

# ***Solutions to I.E. Irodov's Problems in General Physics***

***Volume I***

**Mechanics • Heat • Electrodynamics**

**SECOND EDITION**

**ABHAY KUMAR SINGH**

Director

*Abhay's I.I.T. Physics Teaching Centre*

*Patna-6*



**CBS PUBLISHERS & DISTRIBUTORS**

**4596/1A, 11 DARYAGANJ, NEW DELHI - 110 002 (INDIA)**

*Dedicated to  
my Teacher  
Prof. (Dr.) J. Thakur  
(Department of Physics,  
Patna University,  
Patna-4)*

ISBN : 81-239-0399-5

First Edition : 1995

Reprint : 1997

Second Edition : 1998

Reprint : 2000

Reprint : 2001

Reprint : 2002

Reprint : 2003

Reprint : 2004

Reprint : 2005

Copyright © Author & Publisher

All rights reserved. No part of this book may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system without permission, in writing, from the publisher.

Published by S.K. Jain for CBS Publishers & Distributors,  
4596/1A, 11 Darya Ganj, New Delhi - 110 002 (India)

*Printed at :*

India Binding House, Delhi - 110 032

## FOREWORD

Science, in general, and physics, in particular, have evolved out of man's quest to know beyond unknowns. Matter, radiation and their mutual interactions are basically studied in physics. Essentially, this is an experimental science. By observing appropriate phenomena in nature one arrives at a set of rules which goes to establish some basic fundamental concepts. Entire physics rests on them. Mere knowledge of them is however not enough. Ability to apply them to real day-to-day problems is required. Prof. Irodov's book contains one such set of numerical exercises spread over a wide spectrum of physical disciplines. Some of the problems of the book long appeared to be notorious to pose serious challenges to students as well as to their teachers. This book by Prof. Singh on the solutions of problems of Irodov's book, at the outset, seems to remove the sense of awe which at one time prevailed. Traditionally a difficult exercise to solve continues to draw the attention of concerned persons over a sufficiently long time. Once a logical solution for it becomes available, the difficulties associated with its solutions are forgotten very soon. This statement is not only valid for the solutions of simple physical problems but also to various physical phenomena.

Nevertheless, Prof. Singh's attempt to write a book of this magnitude deserves an all out praise. His ways of solving problems are elegant, straight forward, simple and direct. By writing this book he has definitely contributed to the cause of physics education. A word of advice to its users is however necessary. The solution to a particular problem as given in this book is never to be consulted unless an all out effort in solving it independently has been already made. Only by such judicious uses of this book one would be able to reap better benefits out of it.

As a teacher who has taught physics and who has been in touch with physics curricula at I.I.T., Delhi for over thirty years, I earnestly feel that this book will certainly be of benefit to younger students in their formative years.

Dr. Dilip Kumar Roy  
Professor of Physics  
Indian Institute of Technology, Delhi  
New Delhi-110016.

## FOREWORD

A proper understanding of the physical laws and principles that govern nature require solutions of related problems which exemplify the principle in question and leads to a better grasp of the principles involved. It is only through experiments or through solutions of multifarious problem-oriented questions can a student master the intricacies and fall outs of a physical law. According to Ira M. Freeman, professor of physics of the state university of new Jersey at Rutgers and author of "physic--principles and Insights" -- "In certain situations mathematical formulation actually promotes intuitive understanding..... Sometimes a mathematical formulation is not feasible, so that ordinary language must take the place of mathematics in both roles. However, Mathematics is far more rigorous and its concepts more precise than those of language. Any science that is able to make extensive use of mathematical symbolism and procedures is justly called an exact science". I.E. Irodov's problems in General Physics fulfills such a need. This book originally published in Russia contains about 1900 problems on mechanics, thermodynamics, molecular physics, electrodynamics, waves and oscillations, optics, atomic and nuclear physics. The book has survived the test of class room for many years as is evident from its number of reprint editions, which have appeared since the first English edition of 1981, including an Indian Edition at affordable price for Indian students.

Abhay Kumar Singh's present book containing solutions to Dr. I.E. Irodov's Problems in General Physics is a welcome attempt to develop a student's problem solving skills. The book should be very useful for the students studying a general course in physics and also in developing their skills to answer questions normally encountered in national level entrance examinations conducted each year by various bodies for admissions to professional colleges in science and technology.

B.P. PAL  
Professor of Physics  
I.I.T., Delhi



## **PREFACE TO THE SECOND EDITION**

*Nothing succeeds like success, they say. Now, consequent upon the warm welcome on the part of students and the teaching fraternity this revised and enlarged edition of this volume is before you. In order to make it more up-to-date and viable, a large number of problems have been streamlined with special focus on the complicated and ticklish ones, to cater to the needs of the aspiring students.*

*I extend my deep sense of gratitude to all those who have directly or indirectly engineered the cause of its existing status in the book world.*

*Patna*

*June 1997*

**Abhay Kumar Singh**

## PREFACE TO THE FIRST EDITION

When you envisage to write a book of solutions to problems, one pertinent question crops up in the mind that—why solution! Is this to prove one's erudition? My only defence against this is that the solution is a challenge to save the scientific man hours by channelizing thoughts in a right direction.

The book entitled “Problems in General Physics” authored by I.E. Irodov (a noted Russian physicist and mathematician) contains 1877 intriguing problems divided into six chapters.

After the acceptance of my first book “Problems in Physics”, published by Wiley Eastern Limited, I have got the courage to acknowledge the fact that good and honest ultimately win in the market place. This stimulation provided me insight to come up with my second attempt—“Solutions to I.E. Irodov's Problems in General Physics.”

This first volume encompasses solutions of first three chapters containing 1052 problems. Although a large number of problems can be solved by different methods, I have adopted standard methods and in many of the problems with helping hints for other methods.

In the solutions of chapter three, the emf of a cell is represented by  $\xi$  (xi) in contrast to the notation used in figures and in the problem book, due to some printing difficulty.

I am thankful to my students Mr. Omprakash, Miss Neera and Miss Punam for their valuable co-operation even in my hard days while authoring the present book. I am also thankful to my younger sister Prof. Ranju Singh, my younger brother Mr. Ratan Kumar Singh, my junior friend Miss Anupama Bharti, other well wishers and friends for their emotional support. At last and above all I am grateful to my Ma and Pappaji for their blessings and encouragement.

**ABHAY KUMAR SINGH**

# CONTENTS

<i>Foreword</i>	iii
<i>Preface to the second edition</i>	v
<i>Preface to the first edition</i>	vi

## **PART ONE PHYSICAL FUNDAMENTALS OF MECHANICS**

1.1 Kinematics	1-34
1.2 The Fundamental Equation of Dynamics	35-65
1.3 Laws of Conservation of Energy, Momentum, and Angular Momentum	66-101
1.4 Universal Gravitation	102-117
1.5 Dynamics of a Solid Body	118-143
1.6 Elastic Deformations of a Solid Body	144-155
1.7 Hydrodynamics	156-167
1.8 Relativistic Mechanics	168-183

## **PART TWO THERMODYNAMICS AND MOLECULAR PHYSICS**

2.1 Equation of the Gas State. Processes	184-195
2.2 The first Law of Thermodynamics. Heat Capacity	196-212
2.3 Kinetic theory of Gases. Boltzmann's Law and Maxwell's Distribution	213-226
2.4 The Second Law of Thermodynamics. Entropy	227-241
2.5 Liquids. Capillary Effects	242-247
2.6 Phase Transformations	248-256
2.7 Transport Phenomena	257-266

## **PART THREE ELECTRODYNAMICS**

3.1 Constant Electric Field in Vacuum	267-288
3.2 Conductors and Dielectrics in an Electric Field	289-305
3.3 Electric Capacitance. Energy of an Electric Field	306-324
3.4 Electric Current	325-353
3.5 Constant Magnetic Field. Magnetism	354-379
3.6 Electromagnetic Induction. Maxwell's Equations	380-407
3.7 Motion of Charged Particles in Electric and Magnetic Fields	408-424

## PART ONE

# PHYSICAL FUNDAMENTALS OF MECHANICS

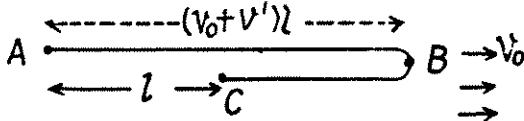
## 1.1 KINEMATICS

- 1.1 Let  $v_0$  be the stream velocity and  $v'$  the velocity of motorboat with respect to water. The motorboat reached point  $B$  while going downstream with velocity  $(v_0 + v')$  and then returned with velocity  $(v' - v_0)$  and passed the raft at point  $C$ . Let  $t$  be the time for the raft (which flows with stream with velocity  $v_0$ ) to move from point  $A$  to  $C$ , during which the motorboat moves from  $A$  to  $B$  and then from  $B$  to  $C$ .

Therefore

$$\frac{l}{v_0} = \tau + \frac{(v_0 + v')\tau - l}{(v' - v_0)}$$

On solving we get  $v_0 = \frac{l}{2\tau}$



- 1.2 Let  $s$  be the total distance traversed by the point and  $t_1$  the time taken to cover half the distance. Further let  $2t$  be the time to cover the rest half of the distance.

Therefore 
$$\frac{s}{2} = v_0 t_1 \quad \text{or} \quad t_1 = \frac{s}{2v_0} \quad (1)$$

and 
$$\frac{s}{2} = (v_1 + v_2) t \quad \text{or} \quad 2t = \frac{s}{v_1 + v_2} \quad (2)$$

Hence the sought average velocity

$$\langle v \rangle = \frac{s}{t_1 + 2t} = \frac{s}{[s/2v_0] + [s/(v_1 + v_2)]} = \frac{2v_0(v_1 + v_2)}{v_1 + v_2 + 2v_0}$$

- 1.3 As the car starts from rest and finally comes to a stop, and the rate of acceleration and deceleration are equal, the distances as well as the times taken are same in these phases of motion.

Let  $\Delta t$  be the time for which the car moves uniformly. Then the acceleration / deceleration time is  $\frac{\tau - \Delta t}{2}$  each. So,

$$\langle v \rangle \tau = 2 \left\{ \frac{1}{2} w \frac{(\tau - \Delta t)^2}{4} \right\} + w \frac{(\tau - \Delta t)}{2} \Delta t$$

or 
$$\Delta t^2 = \tau^2 - \frac{4 \langle v \rangle \tau}{w}$$

Hence 
$$\Delta t = \tau \sqrt{1 - \frac{4 \langle v \rangle}{w \tau}} = 15 \text{ s.}$$

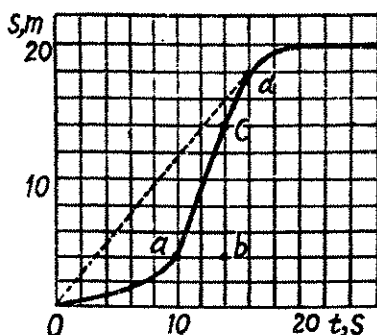
1.4 (a) Sought average velocity

$$\langle v \rangle = \frac{s}{t} = \frac{200 \text{ cm}}{20 \text{ s}} = 10 \text{ cm/s}$$

(b) For the maximum velocity,  $\frac{ds}{dt}$  should be

maximum. From the figure  $\frac{ds}{dt}$  is maximum for all points on the line  $ac$ , thus the sought maximum velocity becomes average velocity for the line  $ac$  and is equal to :

$$\frac{bc}{ab} = \frac{100 \text{ cm}}{4 \text{ s}} = 25 \text{ cm/s}$$



(c) Time  $t_0$  should be such that corresponding to it the slope  $\frac{ds}{dt}$  should pass through the point  $O$  (origin), to satisfy the relationship  $\frac{ds}{dt} = \frac{s}{t_0}$ . From figure the tangent at point  $d$  passes through the origin and thus corresponding time  $t = t_0 = 16 \text{ s}$ .

1.5 Let the particles collide at the point  $A$  (Fig.), whose position vector is  $\vec{r}_3$  (say). If  $t$  be the time taken by each particle to reach at point  $A$ , from triangle law of vector addition :

$$\vec{r}_3 = \vec{r}_1 + \vec{v}_1 t = \vec{r}_2 + \vec{v}_2 t$$

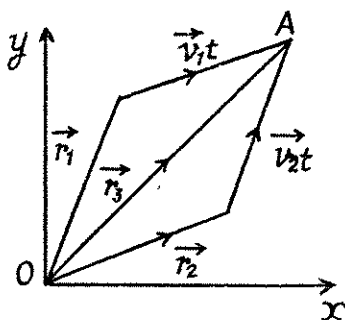
so, 
$$\vec{r}_1 - \vec{r}_2 = (\vec{v}_2 - \vec{v}_1) t \quad (1)$$

therefore, 
$$t = \frac{|\vec{r}_1 - \vec{r}_2|}{|\vec{v}_2 - \vec{v}_1|} \quad (2)$$

From Eqs. (1) and (2)

$$\vec{r}_1 = \vec{r}_2 - (\vec{v}_2 - \vec{v}_1) \frac{|\vec{r}_1 - \vec{r}_2|}{|\vec{v}_2 - \vec{v}_1|}$$

or, 
$$\frac{\vec{r}_1 - \vec{r}_2}{|\vec{r}_1 - \vec{r}_2|} = \frac{\vec{v}_2 - \vec{v}_1}{|\vec{v}_2 - \vec{v}_1|}, \text{ which is the sought relationship.}$$



1.6 We have

$$\vec{v}' = \vec{v} - \vec{v}_0 \quad (1)$$

From the vector diagram [of Eq. (1)] and using properties of triangle

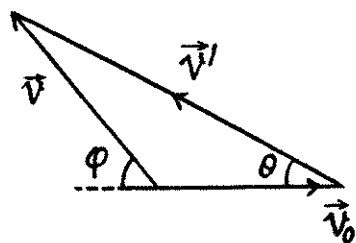
$$v' = \sqrt{v_0^2 + v^2 + 2v_0 v \cos \varphi} = 39.7 \text{ km/hr} \quad (2)$$

$$\text{and } \frac{v'}{\sin(\pi - \varphi)} = \frac{v}{\sin \theta} \quad \text{or, } \sin \theta = \frac{v \sin \varphi}{v'}$$

$$\text{or } \theta = \sin^{-1} \left( \frac{v \sin \varphi}{v'} \right)$$

Using (2) and putting the values of  $v$  and  $d$

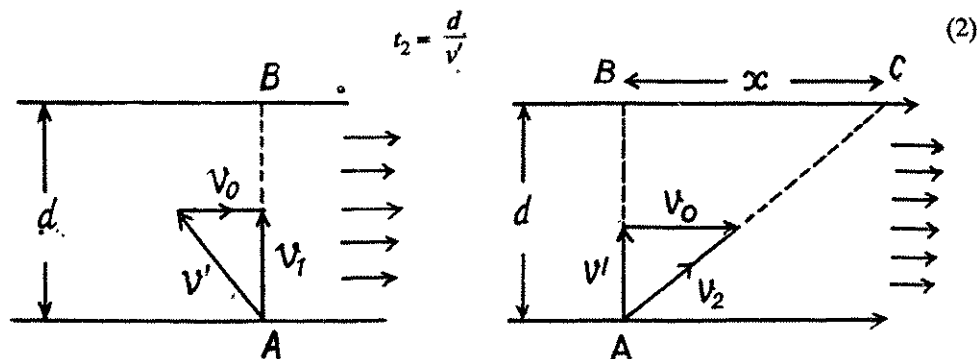
$$\theta = 19.1^\circ$$



1.7 Let one of the swimmer (say 1) cross the river along  $AB$ , which is obviously the shortest path. Time taken to cross the river by the swimmer 1.

$$t_1 = \frac{d}{\sqrt{v'^2 - v_0^2}}, \quad (\text{where } AB = d \text{ is the width of the river}) \quad (1)$$

For the other swimmer (say 2), which follows the quickest path, the time taken to cross the river.



In the time  $t_2$ , drifting of the swimmer 2, becomes

$$x = v_0 t_2 = \frac{v_0}{v'} d, \quad (\text{using Eq. 2}) \quad (3)$$

If  $t_3$  be the time for swimmer 2 to walk the distance  $x$  to come from  $C$  to  $B$  (Fig.), then

$$t_3 = \frac{x}{u} = \frac{v_0 d}{v' u} \quad (\text{using Eq. 3}) \quad (4)$$

According to the problem  $t_1 = t_2 + t_3$

$$\text{or, } \frac{d}{\sqrt{v'^2 - v_0^2}} = \frac{d}{v'} + \frac{v_0 d}{v' u}$$

On solving we get

$$u = \frac{v_0}{\left( \frac{1 - v_0^2}{v'^2} \right)^{-\frac{1}{2}} - 1} = 3 \text{ km/hr.}$$

- 1.8 Let  $l$  be the distance covered by the boat A along the river as well as by the boat B across the river. Let  $v_0$  be the stream velocity and  $v'$  the velocity of each boat with respect to water. Therefore time taken by the boat A in its journey

$$t_A = \frac{l}{v' + v_0} + \frac{l}{v' - v_0}$$

and for the boat B

$$t_B = \frac{l}{\sqrt{v'^2 - v_0^2}} + \frac{l}{\sqrt{v'^2 - v_0^2}} = \frac{2l}{\sqrt{v'^2 - v_0^2}}$$

Hence,

$$\frac{t_A}{t_B} = \frac{v'}{\sqrt{v'^2 - v_0^2}} = \frac{\eta}{\sqrt{\eta^2 - 1}} \quad \left( \text{where } \eta = \frac{v'}{v} \right)$$

On substitution

$$t_A/t_B = 1.8$$

- 1.9 Let  $v_0$  be the stream velocity and  $v'$  the velocity of boat with respect to water. A

$\frac{v_0}{v'} = \eta = 2 > 0$ , some drifting of boat is inevitable.

Let  $\vec{v}'$  make an angle  $\theta$  with flow direction. (Fig.), then the time taken to cross the river

$$t = \frac{d}{v' \sin \theta} \quad (\text{where } d \text{ is the width of the river})$$

In this time interval, the drifting of the boat

$$x = (v' \cos \theta + v_0) t$$

$$= (v' \cos \theta + v_0) \frac{d}{v' \sin \theta} = (\cot \theta + \eta \operatorname{cosec} \theta) d$$

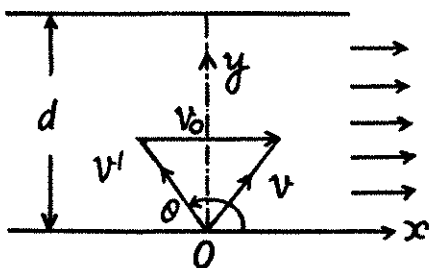
For  $x_{\min}$  (minimum drifting)

$$\frac{d}{d\theta} (\cot \theta + \eta \operatorname{cosec} \theta) = 0, \text{ which yields}$$

$$\cos \theta = -\frac{1}{\eta} = -\frac{1}{2}$$

Hence,

$$\theta = 120^\circ$$



- 1.10 The solution of this problem becomes simple in the frame attached with one of the bodies. Let the body thrown straight up be 1 and the other body be 2, then for the body 1 in the frame of 2 from the kinematic equation for constant acceleration :

$$\vec{r}_{12} = \vec{r}_{0(12)} + \vec{v}_{0(12)} t + \frac{1}{2} \vec{w}_{12} t^2$$

So,  $\vec{r}_{12} = \vec{v}_{0(12)} t$ , (because  $\vec{w}_{12} = 0$  and  $\vec{r}_{0(12)} = 0$ )

$$\text{or, } |\vec{r}_{12}| = |\vec{v}_{0(12)}| t \quad (1)$$

$$\text{But } |\vec{v}_{01}| = |\vec{v}_{02}| = v_0$$

So, from properties of triangle

$$v_{0(12)} = \sqrt{v_0^2 + v_0^2 - 2 v_0 v_0 \cos(\pi/2 - \theta_0)}$$

Hence, the sought distance

$$|\vec{r}_{12}| = v_0 \sqrt{2(1 - \sin \theta)} t = 22 \text{ m.}$$

- 1.11 Let the velocities of the particles (say  $\vec{v}_1'$  and  $\vec{v}_2'$ ) becomes mutually perpendicular after time  $t$ . Then their velocities become

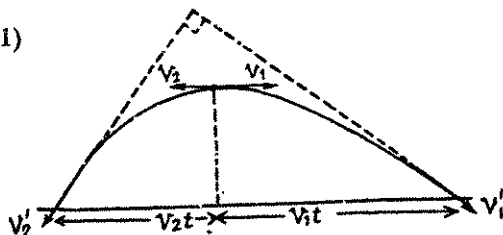
$$\vec{v}_1' = \vec{v}_1 + \vec{g}t; \quad \vec{v}_2' = \vec{v}_2 + \vec{g}t \quad (1)$$

As  $\vec{v}_1' \perp \vec{v}_2'$  so,  $\vec{v}_1' \cdot \vec{v}_2' = 0$

$$\text{or, } (\vec{v}_1 + \vec{g}t) \cdot (\vec{v}_2 + \vec{g}t) = 0$$

$$\text{or, } -v_1 v_2 + g^2 t^2 = 0$$

$$\text{Hence, } t = \frac{\sqrt{v_1 v_2}}{g} \quad (3)$$



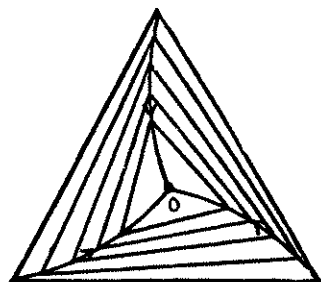
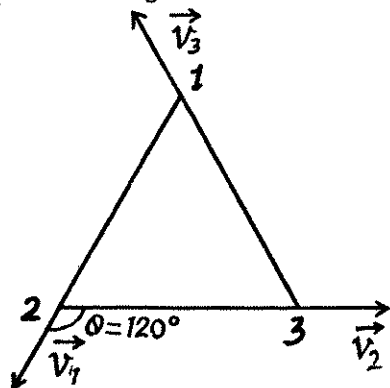
Now from the Eq.  $\vec{r}_{12} = \vec{r}_{0(12)} + \vec{v}_{0(12)}t + \frac{1}{2}\vec{w}_{12}t^2$

$$|\vec{r}_{12}| = |\vec{v}_{0(12)}|t, \quad (\text{because here } \vec{w}_{12} = 0 \text{ and } \vec{r}_{0(12)} = 0)$$

Hence the sought distance

$$|\vec{r}_{12}| = \frac{v_1 + v_2}{g} \sqrt{v_1 v_2} \quad (\text{as } |\vec{v}_{0(12)}| = v_1 + v_2)$$

- 1.12 From the symmetry of the problem all the three points are always located at the vertices of equilateral triangles of varying side length and finally meet at the centroid of the initial equilateral triangle whose side length is  $a$ , in the sought time interval (say  $t$ ).



Let us consider an arbitrary equilateral triangle of edge length  $l$  (say).

Then the rate by which 1 approaches 2, 2 approaches 3, and 3 approaches 1, becomes :

$$\frac{-dl}{dt} = v - v \cos\left(\frac{2\pi}{3}\right)$$

On integrating :

$$-\int_a^0 dl = \frac{3v}{2} \int_0^t dt$$

$$a = \frac{3}{2} vt \quad \text{so} \quad t = \frac{2a}{3v}$$



1.13 Let us locate the points  $A$  and  $B$  at an arbitrary instant of time (Fig.).

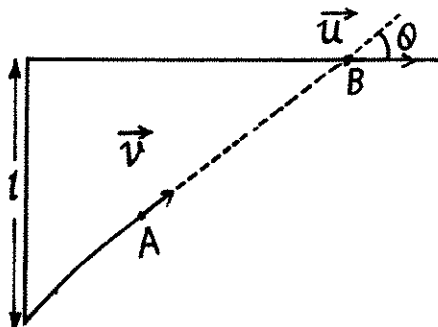
If  $A$  and  $B$  are separated by the distance  $s$  at this moment, then the points converge or point  $A$  approaches  $B$  with velocity  $\frac{-ds}{dt} = v - u \cos \alpha$  where angle  $\alpha$  varies with time.

On integrating,

$$-\int_l^0 ds = \int_0^T (v - u \cos \alpha) dt,$$

(where  $T$  is the sought time.)

$$\text{or} \quad l = \int_0^T (v - u \cos \alpha) dt \quad (1)$$



As both  $A$  and  $B$  cover the same distance in  $x$ -direction during the sought time interval, so the other condition which is required, can be obtained by the equation

$$\Delta x = \int_0^T v_x dt$$

$$\text{So,} \quad uT = \int_0^T v \cos \alpha dt \quad (2)$$

$$\text{Solving (1) and (2), we get } T = \frac{ul}{v^2 - u^2}$$

One can see that if  $u = v$ , or  $u < v$ , point  $A$  cannot catch  $B$ .

1.14 In the reference frame fixed to the train, the distance between the two events is obviously equal to  $l$ . Suppose the train starts moving at time  $t = 0$  in the positive  $x$  direction and take the origin ( $x = 0$ ) at the head-light of the train at  $t = 0$ . Then the coordinate of first event in the earth's frame is

$$x_1 = \frac{1}{2} \omega t^2$$

and similarly the coordinate of the second event is

$$x_2 = \frac{1}{2} \omega (t + \tau)^2 - l$$

The distance between the two events is obviously.

$$x_1 - x_2 = l - \omega \tau (t + \tau/2) = 0.242 \text{ km}$$

in the reference frame fixed on the earth..

For the two events to occur at the same point in the reference frame  $K$ , moving with constant velocity  $V$  relative to the earth, the distance travelled by the frame in the time interval  $T$  must be equal to the above distance.

$$\text{Thus} \quad V\tau = l - \omega \tau (t + \tau/2)$$

$$\text{So,} \quad V = \frac{l}{\tau} - \omega (t + \tau/2) = 4.03 \text{ m/s}$$

The frame  $K$  must clearly be moving in a direction opposite to the train so that if (for example) the origin of the frame coincides with the point  $x_1$  on the earth at time  $t$ , it coincides with the point  $x_2$  at time  $t + \tau$ .

- 1.15 (a) One good way to solve the problem is to work in the elevator's frame having the observer at its bottom (Fig.).

Let us denote the separation between floor and ceiling by  $h = 2.7$  m. and the acceleration of the elevator by  $w = 1.2$  m/s<sup>2</sup>

From the kinematical formula

$$y = y_0 + v_{0y}t + \frac{1}{2}w_y t^2 \quad (1)$$

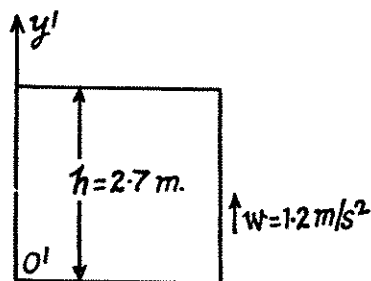
Here  $y = 0, y_0 = +h, v_{0y} = 0$

and  $w_y = w_{\text{bolt}}(y) - w_{\text{ele}}(y)$

$$= (-g) - (w) = -(g + w)$$

So,  $0 = h + \frac{1}{2}[-(g + w)]t^2$

$$\text{or, } t = \sqrt{\frac{2h}{g + w}} = 0.7 \text{ s.}$$



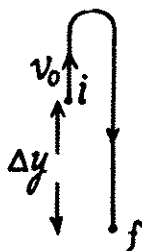
(b) At the moment the bolt loses contact with the elevator, it has already acquired the velocity equal to elevator, given by :

$$v_0 = (1.2)(2) = 2.4 \text{ m/s}$$

In the reference frame attached with the elevator shaft (ground) and pointing the  $y$ -axis upward, we have for the displacement of the bolt,

$$\begin{aligned} \Delta y &= v_{0y}t + \frac{1}{2}w_y t^2 \\ &= v_0 t + \frac{1}{2}(-g)t^2 \end{aligned}$$

$$\text{or, } \Delta y = (2.4)(0.7) + \frac{1}{2}(-9.8)(0.7)^2 = -0.7 \text{ m.}$$



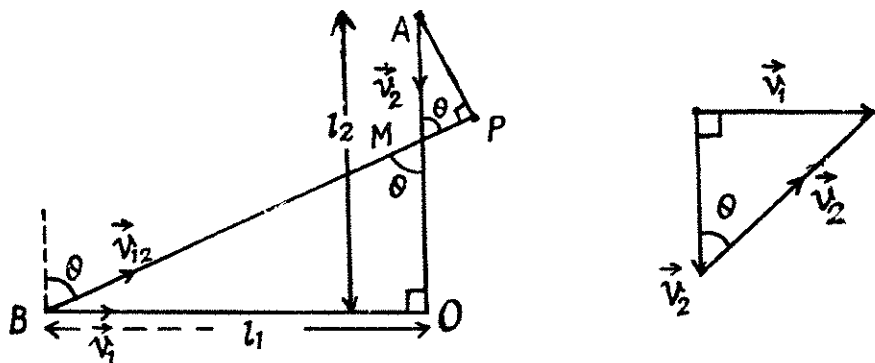
Hence the bolt comes down or displaces downward relative to the point, when it loses contact with the elevator by the amount 0.7 m (Fig.).

Obviously the total distance covered by the bolt during its free fall time

$$s = |\Delta y| + 2\left(\frac{v_0^2}{2g}\right) = 0.7 \text{ m} + \frac{(2.4)^2}{(9.8)} \text{ m} = 1.3 \text{ m.}$$

- 1.16 Let the particle 1 and 2 be at points  $B$  and  $A$  at  $t = 0$  at the distances  $l_1$  and  $l_2$  from intersection point  $O$ .

Let us fix the inertial frame with the particle 2. Now the particle 1 moves in relative to this reference frame with a relative velocity  $\vec{v}_{12} = \vec{v}_1 - \vec{v}_2$  and its trajectory is the straight line  $BP$ . Obviously, the minimum distance between the particles is equal to the length of the perpendicular  $AP$  dropped from point  $A$  on to the straight line  $BP$  (Fig.).



From Fig. (b),  $v_{12} = \sqrt{v_1^2 + v_2^2}$ , and  $\tan \theta = \frac{v_1}{v_2}$  (1)

The shortest distance

$$AP = AM \sin \theta = (OA - OM) \sin \theta = (l_2 - l_1 \cot \theta) \sin \theta$$

or  $AP = \left( l_2 - l_1 \frac{v_2}{v_1} \right) \frac{v_1}{\sqrt{v_1^2 + v_2^2}} = \frac{v_1 l_2 - v_2 l_1}{\sqrt{v_1^2 + v_2^2}}$  (using 1)

The sought time can be obtained directly from the condition that  $(l_1 - v_1 t)^2 + (l_2 - v_2 t)^2$  is minimum. This gives  $t = \frac{l_1 v_1 + l_2 v_2}{v_1^2 + v_2^2}$ .

1.17 Let the car turn off the highway at a distance  $x$  from the point  $D$ .

So,  $CD = x$ , and if the speed of the car in the field is  $v$ , then the time taken by the car to cover the distance  $AC = AD - x$  on the highway

$$t_1 = \frac{AD - x}{\eta v} \quad (1)$$

and the time taken to travel the distance  $CB$  in the field

$$t_2 = \frac{\sqrt{l^2 + x^2}}{v} \quad (2)$$

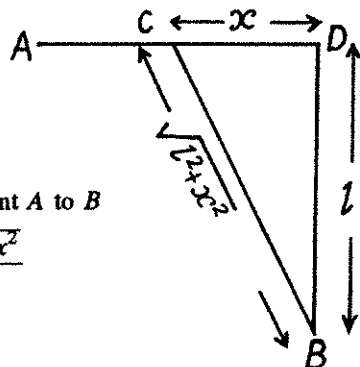
So, the total time elapsed to move the car from point  $A$  to  $B$

$$t = t_1 + t_2 = \frac{AD - x}{\eta v} + \frac{\sqrt{l^2 + x^2}}{v}$$

For  $t$  to be minimum

$$\frac{dt}{dx} = 0 \quad \text{or} \quad \frac{1}{v} \left[ -\frac{1}{\eta} + \frac{x}{\sqrt{l^2 + x^2}} \right] = 0$$

or  $\eta^2 x^2 = l^2 + x^2 \quad \text{or} \quad x = \frac{l}{\sqrt{\eta^2 - 1}}$



1.18 To plot  $x(t)$ ,  $s(t)$  and  $w_x(t)$  let us partition the given plot  $v_x(t)$  into five segments (for detailed analysis) as shown in the figure.

For the part  $oa$ :  $w_x = 1$  and  $v_x = t = v$

$$\text{Thus, } \Delta x_1(t) = \int v_x dt = \int_0^t dt = \frac{t^2}{2} = s_1(t)$$

Putting  $t = 1$ , we get,  $\Delta x_1 = s = \frac{1}{2}$  unit

For the part  $ab$ :

$$w_x = 0 \text{ and } v_x = v = \text{constant} = 1$$

$$\text{Thus } \Delta x_2(t) = \int v_x dt = \int_1^t dt = (t - 1) = s_2(t)$$

Putting  $t = 3$ ,  $\Delta x_2 = s_2 = 2$  unit

For the part  $b4$ :  $w_x = 1$  and  $v_x = 1 - (t - 3) = 4 - t = v$

$$\text{Thus } \Delta x_3(t) = \int_3^t (4 - t) dt = 4t - \frac{t^2}{2} - \frac{15}{2} = s_3(t)$$

Putting  $t = 4$ ,  $\Delta x_3 = x_3 = \frac{1}{2}$  unit

For the part  $4d$ :  $v_x = -1$  and  $v_x = -(1 - 4) = 4 - 1$

So,  $v = |v_x| = t - 4$  for  $t > 4$

$$\text{Thus } \Delta x_4(t) = \int_4^t (1 - t) dt = 4t - \frac{t^2}{2} - 8$$

Putting  $t = 6$ ,  $\Delta x_4 = -1$

$$\text{Similarly } s_4(t) = \int_4^t |v_x| dt = \int_4^t (t - 4) dt = \frac{t^2}{2} - 4t + 8$$

Putting  $t = 6$ ,  $s_4 = 2$  unit

For the part  $d7$ :  $w_x = 2$  and  $v_x = -2 + 2(t - 6) = 2(t - 7)$

$$v = |v_x| = 2(7 - t) \text{ for } t \leftarrow 7$$

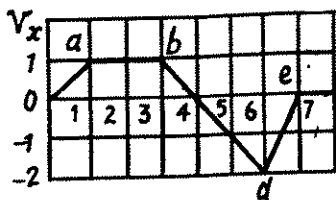
$$\text{Now, } \Delta x(t) = \int_6^t 2(7 - t) dt = t^2 - 14t + 48$$

Putting  $t = 4$ ,  $\Delta x_5 = -1$

$$\text{Similarly } s_5(t) = \int_6^t 2(7 - t) dt = 14t - t^2 - 48$$

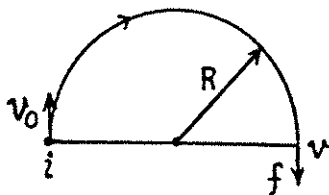
Putting  $t = 7$ ,  $s_5 = 1$

On the basis of these obtained expressions  $w_x(t)$ ,  $x(t)$  and  $s(t)$  plots can be easily plotted as shown in the figure of answersheet.



## 1.19 (a) Mean velocity

$$\begin{aligned}\langle v \rangle &= \frac{\text{Total distance covered}}{\text{Time elapsed}} \\ &= \frac{s}{t} = \frac{\pi R}{\tau} = 50 \text{ cm/s} \quad (1)\end{aligned}$$



## (b) Modulus of mean velocity vector

$$|\langle \vec{v} \rangle| = \frac{|\Delta \vec{r}|}{\Delta t} = \frac{2R}{\tau} = 32 \text{ cm/s} \quad (2)$$

(c) Let the point moves from  $i$  to  $f$  along the half circle (Fig.) and  $v_0$  and  $v$  be the spe at the points respectively.

We have  $\frac{dv}{dt} = w_t$

or,  $v = v_0 + w_t t$  (as  $w_t$  is constant, according to the problem)

$$\text{So, } \langle v \rangle = \frac{\int_0^t (v_0 + w_t t) dt}{\int_0^t dt} = \frac{v_0 + (v_0 + w_t t)}{2} = \frac{v_0 + v}{2} \quad (3)$$

So, from (1) and (3)

$$\frac{v_0 + v}{2} = \frac{\pi R}{\tau} \quad (3)$$

Now the modulus of the mean vector of total acceleration

$$|\langle \vec{w} \rangle| = \frac{|\Delta \vec{v}|}{\Delta t} = \frac{|\vec{v} - \vec{v}_0|}{\tau} = \frac{v_0 + v}{\tau} \quad (\text{see Fig.}) \quad (5)$$

Using (4) in (5), we get :

$$|\langle \vec{w} \rangle| = \frac{2\pi R}{\tau^2}$$

## 1.20 (a) we have

$$\vec{r} = \vec{a} t (1 - \alpha t)$$

So,

$$\vec{v} = \frac{d\vec{r}}{dt} = \vec{a}(1 - 2\alpha t)$$

and

$$\vec{w} = \frac{d\vec{v}}{dt} = -2\alpha \vec{a}$$

(b) From the equation

$$\vec{r} = \vec{a} t (1 - \alpha t),$$

$$\vec{r} = 0, \text{ at } t = 0 \text{ and also at } t = \Delta t = \frac{1}{\alpha}$$

So, the sought time  $\Delta t = \frac{1}{\alpha}$

As

$$\vec{v} = \vec{a}(1 - 2\alpha t)$$

So,

$$v = |\vec{v}| = \begin{cases} a(1 - 2\alpha t) & \text{for } t \leq \frac{1}{2\alpha} \\ a(2\alpha t - 1) & \text{for } t > \frac{1}{2\alpha} \end{cases}$$

Hence, the sought distance

$$s = \int_0^{1/2\alpha} v \, dt = \int_0^{1/2\alpha} a(1 - 2\alpha t) \, dt + \int_{1/2\alpha}^{1/\alpha} a(2\alpha t - 1) \, dt$$

Simplifying, we get,  $s = \frac{a}{2\alpha}$

**1.21 (a)** As the particle leaves the origin at  $t = 0$

$$\text{So,} \quad \Delta x = x = \int v_x \, dt \quad (1)$$

$$\text{As} \quad \vec{v} = \vec{v}_0 \left(1 - \frac{t}{\tau}\right),$$

where  $\vec{v}_0$  is directed towards the +ve  $x$ -axis

$$\text{So,} \quad v_x = v_0 \left(1 - \frac{t}{\tau}\right) \quad (2)$$

From (1) and (2),

$$x = \int_0^t v_0 \left(1 - \frac{t}{\tau}\right) dt = v_0 t \left(1 - \frac{t}{2\tau}\right) \quad (3)$$

Hence  $x$  coordinate of the particle at  $t = 6$  s.

$$x = 10 \times 6 \left(1 - \frac{6}{2 \times 5}\right) = 24 \text{ cm} = 0.24 \text{ m}$$

Similarly at

$$t = 10 \text{ s}$$

$$x = 10 \times 10 \left(1 - \frac{10}{2 \times 5}\right) = 0$$

and at

$$t = 20 \text{ s}$$

$$x = 10 \times 20 \left(1 - \frac{20}{2 \times 5}\right) = -200 \text{ cm} = -2 \text{ m}$$

(b) At the moments the particle is at a distance of 10 cm from the origin,  $x = \pm 10$  cm.

Putting

$$x = +10 \text{ in Eq. (3)}$$

$$10 = 10t \left(1 - \frac{t}{10}\right) \text{ or, } t^2 - 10t + 10 = 0,$$

So,

$$t = t = \frac{10 \pm \sqrt{100 - 40}}{2} = 5 \pm \sqrt{15} \text{ s}$$

Now putting

$$x = -10 \text{ in Eqn (3)}$$

$$-10 = 10 \left(1 - \frac{t}{10}\right),$$

On solving,

$$t = 5 \pm \sqrt{35} \text{ s}$$

As  $t$  cannot be negative, so,

$$t = (5 + \sqrt{35}) \text{ s}$$

Hence the particle is at a distance of 10 cm from the origin at three moments of time :

$$t = 5 \pm \sqrt{15} \text{ s}, 5 + \sqrt{35} \text{ s}$$

(c) We have  $\vec{v} = \vec{v}_0 \left(1 - \frac{t}{\tau}\right)$

So,  $v = |\vec{v}| = \begin{cases} v_0 \left(1 - \frac{t}{\tau}\right) & \text{for } t \leq \tau \\ v_0 \left(\frac{t}{\tau} - 1\right) & \text{for } t > \tau \end{cases}$

So  $s = \int_0^t v_0 \left(1 - \frac{t}{\tau}\right) dt \text{ for } t \leq \tau = v_0 t \left(1 - \frac{1}{2}\tau\right)$

and  $s = \int_0^{\tau} v_0 \left(1 - \frac{t}{\tau}\right) dt + \int_{\tau}^t v_0 \left(\frac{t}{\tau} - 1\right) dt \text{ for } t > \tau$

$$= v_0 \tau \left[1 + \left(1 - \frac{1}{2}\right)^2\right] / 2 \text{ for } t > \tau \quad (\text{A})$$

$$s = \int_0^4 v_0 \left(1 - \frac{t}{\tau}\right) dt = \int_0^4 10 \left(1 - \frac{t}{5}\right) dt = 24 \text{ cm.}$$

And for  $t = 8 \text{ s}$

$$s = \int_0^5 10 \left(1 - \frac{t}{5}\right) dt + \int_5^8 10 \left(\frac{t}{5} - 1\right) dt$$

On integrating and simplifying, we get

$$s = 34 \text{ cm.}$$

On the basis of Eqs. (3) and (4),  $x(t)$  and  $s(t)$  plots can be drawn as shown in the answer sheet.

**1.22** As particle is in unidirectional motion it is directed along the  $x$ -axis all the time. As at  $t = 0$ ,  $x = 0$

So,  $\Delta x = x = s$ , and  $\frac{dv}{dt} = w$

Therefore,  $v = \alpha \sqrt{x} = \alpha \sqrt{s}$

or,  $w = \frac{dv}{dt} = \frac{\alpha}{2\sqrt{s}} \frac{ds}{dt} = \frac{\alpha}{2\sqrt{s}}$

$$= \frac{\alpha v}{2\sqrt{s}} = \frac{\alpha \alpha \sqrt{s}}{2\sqrt{s}} = \frac{\alpha^2}{2} \quad (1)$$

As,  $w = \frac{dv}{dt} = \frac{\alpha^2}{2}$

On integrating,  $\int_0^v dv = \int_0^t \frac{\alpha^2}{2} dt \text{ or, } v = \frac{\alpha^2}{2} t \quad (2)$

(b) Let  $s$  be the time to cover first  $s$  m of the path. From the Eq.

$$s = \int v dt$$

$$s = \int_0^t \frac{\alpha^2}{2} dt = \frac{\alpha^2}{2} \frac{t^2}{2} \quad (\text{using 2})$$

$$\text{or} \quad t = \frac{2}{\alpha} \sqrt{s} \quad (3)$$

The mean velocity of particle

$$\langle v \rangle = \frac{\int v(t) dt}{\int dt} = \frac{\int_0^{2\sqrt{s}/\alpha} \frac{\alpha^2}{2} t dt}{2\sqrt{s}/\alpha} = \frac{\alpha \sqrt{s}}{2}$$

1.23 According to the problem

$$-\frac{v dv}{ds} = a \sqrt{v} \quad (\text{as } v \text{ decreases with time})$$

$$\text{or,} \quad -\int_{v_0}^0 \sqrt{v} dv = a \int_0^s ds$$

$$\text{On integrating we get } s = \frac{2}{3a} v_0^{3/2}$$

Again according to the problem

$$-\frac{dv}{dt} = a \sqrt{v} \quad \text{or} \quad -\frac{dv}{\sqrt{v}} = a dt$$

$$\text{or,} \quad \int_{v_0}^0 \frac{dv}{\sqrt{v}} = a \int_0^t dt$$

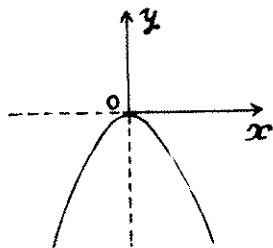
$$\text{Thus} \quad t = \frac{2\sqrt{v_0}}{a}$$

1.24 (a) As

So,

and therefore

$$\begin{aligned} \vec{r} &= a t \vec{i} - b t^2 \vec{j} \\ x &= a t, \quad y = -b t^2 \\ y &= \frac{-b x^2}{a^2} \end{aligned}$$





which is Eq. of a parabola, whose graph is shown in the Fig.

(b) As 
$$\vec{r} = a t \vec{i} - b t^2 \vec{j}$$
$$\vec{v} = \frac{d\vec{r}}{dt} = a \vec{i} - 2 b t \vec{j}$$
 (1)

So, 
$$v = \sqrt{a^2 + (-2 b t)^2} = \sqrt{a^2 + 4 b^2 t^2}$$

Diff. Eq. (1) w.r.t. time, we get

$$\vec{w} = \frac{d\vec{v}}{dt} = -2 b \vec{j}$$

So, 
$$|\vec{w}| = w = 2 b$$

(c) 
$$\cos \alpha = \frac{\vec{v} \cdot \vec{w}}{v w} = \frac{(a \vec{i} - 2 b t \vec{j}) \cdot (-2 b \vec{j})}{(\sqrt{a^2 + 4 b^2 t^2}) 2 b}$$

or, 
$$\cos \alpha = \frac{2 b t}{\sqrt{a^2 + 4 b^2 t^2}},$$

so, 
$$\tan \alpha = \frac{a}{2 b t}$$

or, 
$$\alpha = \tan^{-1} \left( \frac{a}{2 b t} \right)$$

(d) The mean velocity vector

$$\langle \vec{v} \rangle = \frac{\int \vec{v} dt}{\int dt} = \frac{\int_0^t (a \vec{i} - 2 b t \vec{j}) dt}{t} = a \vec{i} - b t \vec{j}$$

Hence, 
$$|\langle \vec{v} \rangle| = \sqrt{a^2 + (-b t)^2} = \sqrt{a^2 + b^2 t^2}$$

1.25 (a) We have

$$x = a t \text{ and } y = a t (1 - \alpha t) \quad (1)$$

Hence,  $y(x)$  becomes,

$$y = \frac{a x}{a} \left( 1 - \frac{\alpha x}{a} \right) = x - \frac{\alpha}{a} x^2 \text{ (parabola)}$$

(b) Differentiating Eq. (1) we get

$$v_x = a \text{ and } v_y = a (1 - 2 \alpha t) \quad (2)$$

So, 
$$v = \sqrt{v_x^2 + v_y^2} = a \sqrt{1 + (1 - 2\alpha t)^2}$$

Diff. Eq. (2) with respect to time

$$w_x = 0 \text{ and } w_y = -2a\alpha$$

So, 
$$w = \sqrt{w_x^2 + w_y^2} = 2a\alpha$$

(c) From Eqs. (2) and (3)

We have 
$$\vec{v} = a\vec{i} + a(1 - 2\alpha t)\vec{j} \text{ and } \vec{w} = 2a\alpha\vec{j}$$

So, 
$$\cos \frac{\pi}{4} = \frac{1}{\sqrt{2}} = \frac{\vec{v} \cdot \vec{w}}{vw} = \frac{-a(1 - 2\alpha t_0)2a\alpha}{a\sqrt{1 + (1 - 2\alpha t_0)^2}2a\alpha}$$

On simplifying, 
$$1 - 2\alpha t_0 = \pm 1$$

As, 
$$t_0 \neq 0, \quad t_0 = \frac{1}{\alpha}$$

1.26 Differentiating motion law :  $x = a \sin \omega t$ ,  $y = a(1 - \cos \omega t)$ , with respect to time,  
 $v_x = a\omega \cos \omega t$ ,  $v_y = a\omega \sin \omega t$

So, 
$$\vec{v} = a\omega \cos \omega t \vec{i} + a\omega \sin \omega t \vec{j} \quad (1)$$

and 
$$v = a\omega = \text{Const.} \quad (2)$$

Differentiating Eq. (1) with respect to time

$$\vec{w} = \frac{d\vec{v}}{dt} = -a\omega^2 \sin \omega t \vec{i} + a\omega^2 \cos \omega t \vec{j} \quad (3)$$

(a) The distance  $s$  traversed by the point during the time  $\tau$  is given by

$$s = \int_0^\tau v dt = \int_0^\tau a\omega dt = a\omega\tau \quad (\text{using 2})$$

(b) Taking inner product of  $\vec{v}$  and  $\vec{w}$

We get, 
$$\vec{v} \cdot \vec{w} = (a\omega \cos \omega t \vec{i} + a\omega \sin \omega t \vec{j}) \cdot (a\omega^2 \sin \omega t (-\vec{i}) + a\omega^2 \cos \omega t \vec{j})$$

So, 
$$\vec{v} \cdot \vec{w} = -a^2\omega^2 \sin \omega t \cos \omega t + a^2\omega^3 \sin \omega t \cos \omega t = 0$$

Thus,  $\vec{v} \perp \vec{w}$ , i.e., the angle between velocity vector and acceleration vector equals  $\frac{\pi}{2}$ .

1.27 According to the problem

$$\vec{w} = w(-\vec{j})$$

So, 
$$w_x = \frac{dv_x}{dt} = 0 \text{ and } w_y = \frac{dv_y}{dt} = -w \quad (1)$$

Differentiating Eq. of trajectory,  $y = ax - bx^2$ , with respect to time

$$\frac{dy}{dt} = a \frac{dx}{dt} - 2bx \frac{dx}{dt} \quad (2)$$

So, 
$$\left. \frac{dy}{dt} \right|_{x=0} = a \left. \frac{dx}{dt} \right|_{x=0}$$

Again differentiating with respect to time

$$\frac{d^2 y}{dt^2} = \frac{a d^2 x}{dt^2} - 2b \left( \frac{dx}{dt} \right)^2 - 2bx \frac{d^2 x}{dt^2}$$

or, 
$$-w = a(0) - 2b \left( \frac{dx}{dt} \right)^2 - 2bx(0) \text{ (using 1)}$$

or, 
$$\frac{dx}{dt} = \sqrt{\frac{w}{2b}} \text{ (using 1)} \quad (3)$$

Using (3) in (2) 
$$\left. \frac{dy}{dt} \right|_{x=0} = a \sqrt{\frac{w}{2b}} \quad (4)$$

Hence, the velocity of the particle at the origin

$$v = \sqrt{\left( \left. \frac{dx}{dt} \right|_{x=0} \right)^2 + \left( \left. \frac{dy}{dt} \right|_{x=0} \right)^2} = \sqrt{\frac{w}{2b} + a^2 \frac{w}{2b}} \text{ (using Eqns (3) and (4))}$$

Hence, 
$$v = \sqrt{\frac{w}{2b} (1 + a^2)}$$

**1.28** As the body is under gravity of constant acceleration  $\vec{g}$ , its velocity vector and displacement vectors are:

$$\vec{v} = \vec{v}_0 + \vec{g}t \quad (1)$$

and 
$$\Delta \vec{r} = \vec{r} = \vec{v}_0 t + \frac{1}{2} \vec{g} t^2 \quad (\vec{r} = 0 \text{ at } t = 0) \quad (2)$$

So,  $\langle \vec{v} \rangle$  over the first  $t$  seconds

$$\langle \vec{v} \rangle = \frac{\Delta \vec{r}}{\Delta t} = \frac{\vec{r}}{t} = \vec{v}_0 + \frac{\vec{g}t}{2} \quad (3)$$

Hence from Eq. (3),  $\langle \vec{v} \rangle$  over the first  $t$  seconds

$$\langle \vec{v} \rangle = \vec{v}_0 + \frac{\vec{g}}{2} t \quad (4)$$

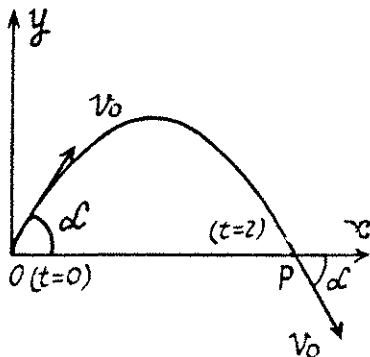
For evaluating  $t$ , take

$$\vec{v} \cdot \vec{v} = (\vec{v}_0 + \vec{g}t) \cdot (\vec{v}_0 + \vec{g}t) = v_0^2 + 2(\vec{v}_0 \cdot \vec{g})t + g^2 t^2$$

or,  $v^2 = v_0^2 + (\vec{v}_0 \cdot \vec{g})t + g^2 t^2$

But we have  $v = v_0$  at  $t = 0$  and

Also at  $t = \tau$  (Fig.) (also from energy conservation)



Hence using this property in Eq. (5)

$$v_0^2 = v_0^2 + 2(\vec{v}_0 \cdot \vec{g})\tau + g^2\tau^2$$

As  $\tau \neq 0$ , so,  $\tau = -\frac{2(\vec{v}_0 \cdot \vec{g})}{g^2}$

Putting this value of  $\tau$  in Eq. (4), the average velocity over the time of flight

$$\langle \vec{v} \rangle = \vec{v}_0 - \vec{g} \frac{(\vec{v}_0 \cdot \vec{g})}{g^2}$$

1.29 The body thrown in air with velocity  $v_0$  at an angle  $\alpha$  from the horizontal lands at point  $P$  on the Earth's surface at same horizontal level (Fig.). The point of projection is taken as origin, so,  $\Delta x = x$  and  $\Delta y = y$

(a) From the Eq.  $\Delta y = v_{0y}t + \frac{1}{2}w_y t^2$

$$0 = v_0 \sin \alpha \tau - \frac{1}{2}g\tau^2$$

As  $\tau \neq 0$ , so, time of motion  $\tau = \frac{2v_0 \sin \alpha}{g}$

(b) At the maximum height of ascent,  $v_y = 0$

so, from the Eq.  $v_y^2 = v_{0y}^2 + 2w_y \Delta y$

$$0 = (v_0 \sin \alpha)^2 - 2gH$$

Hence maximum height  $H = \frac{v_0^2 \sin^2 \alpha}{2g}$

During the time of motion the net horizontal displacement or horizontal range, will be obtained by the equation

$$\Delta x = v_{0x}t + \frac{1}{2}w_x \tau^2$$

or,  $R = v_0 \cos \alpha \tau - \frac{1}{2}(0)\tau^2 = v_0 \cos \alpha \tau = \frac{v_0^2 \sin 2\alpha}{g}$

when

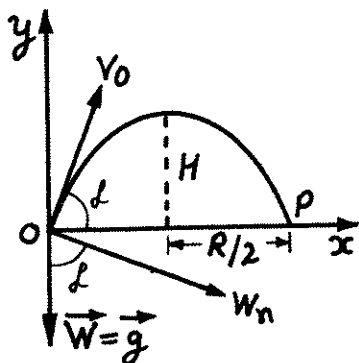
$$R = H$$

$$\frac{v_0^2 \sin^2 \alpha}{g} = \frac{v_0^2 \sin^2 \alpha}{2g} \quad \text{or} \quad \tan \alpha = 4, \quad \text{so, } \alpha = \tan^{-1} 4$$

(c) For the body,  $x(t)$  and  $y(t)$  are

$$x = v_0 \cos \alpha t$$

(1)



and 
$$y = v_0 \sin \alpha t - \frac{1}{2} g t^2 \quad (2)$$

Hence putting the value of  $t$  from (1) into (2) we get,

$$y = v_0 \sin \alpha \left( \frac{x}{v_0 \cos \alpha} \right) - \frac{1}{2} g \left( \frac{x}{v_0 \cos \alpha} \right)^2 = x \tan \alpha - \frac{g x^2}{2 v_0^2 \cos^2 \alpha},$$

Which is the sought equation of trajectory i.e.  $y(x)$

(d) As the body thrown in air follows a curve, it has some normal acceleration at all the moments of time during its motion in air.

At the initial point ( $x = 0, y = 0$ ), from the equation :

$$w_n = \frac{v^2}{R}, \text{ (where } R \text{ is the radius of curvature)}$$

$$g \cos \alpha = \frac{v_0^2}{R_0} \text{ (see Fig.) or } R_0 = \frac{v_0^2}{g \cos \alpha}$$

At the peak point  $v_y = 0$ ,  $v = v_x = v_0 \cos \alpha$  and the angular acceleration is zero.

Now from the Eq. 
$$w_n = \frac{v^2}{R}$$

$$g = \frac{v_0^2 \cos^2 \alpha}{R}, \text{ or } R = \frac{v_0^2 \cos^2 \alpha}{g}$$

**Note :** We may use the formula of curvature radius of a trajectory  $y(x)$ , to solve part (d),

$$R = \frac{\left[ 1 + (dy/dx)^2 \right]^{\frac{3}{2}}}{\left| d^2 y / dx^2 \right|}$$

1.30 We have,  $v_x = v_0 \cos \alpha$ ,  $v_y = v_0 \sin \alpha - gt$

As  $\vec{v} \uparrow \uparrow \hat{u}_t$  all the moments of time.

Thus 
$$v^2 = v_t^2 - 2gt v_0 \sin \alpha + g^2 t^2$$

Now, 
$$w_t = \frac{dv_t}{dt} = \frac{1}{2 v_t} \frac{d}{dt} (v_t^2) = \frac{1}{v_t} (g^2 t - g v_0 \sin \alpha)$$

$$= -\frac{g}{v_t} (v_0 \sin \alpha - g t) = -g \frac{v_y}{v_t}$$

Hence 
$$|w_t| = g \frac{|v_y|}{v}$$

Now 
$$w_n = \sqrt{w^2 - w_t^2} = \sqrt{g^2 - g^2 \frac{v_y^2}{v_t^2}}$$

or 
$$w_n = g \frac{v_x}{v_t} \text{ (where } v_x = \sqrt{v_t^2 - v_y^2})$$

As  $\vec{v} \uparrow \hat{v}$ , during time of motion

$$w_y = w_t = -g \frac{v_y}{v}$$

On the basis of obtained expressions or facts the sought plots can be drawn as shown in the figure of answer sheet.

- 1.31 The ball strikes the inclined plane ( $Ox$ ) at point  $O$  (origin) with velocity  $v_0 = \sqrt{2gh}$  (1)

As the ball elastically rebounds, it recalls with same velocity  $v_0$ , at the same angle  $\alpha$  from the normal or  $y$  axis (Fig.). Let the ball strikes the incline second time at  $P$ , which is at a distance  $l$  (say) from the point  $O$ , along the incline. From the equation

$$y = v_{0y}t + \frac{1}{2}w_y t^2$$

$$0 = v_0 \cos \alpha \tau - \frac{1}{2}g \cos \alpha \tau^2$$

where  $\tau$  is the time of motion of ball in air while moving from  $O$  to  $P$ .

As  $\tau \neq 0$ , so,  $\tau = \frac{2v_0}{g}$  (2)

Now from the equation.

$$x = v_{0x}t + \frac{1}{2}w_x t^2$$

$$l = v_0 \sin \alpha \tau + \frac{1}{2}g \sin \alpha \tau^2$$

so, 
$$l = v_0 \sin \alpha \left( \frac{2v_0}{g} \right) + \frac{1}{2}g \sin \alpha \left( \frac{2v_0}{g} \right)^2$$

$$= \frac{4v_0^2 \sin \alpha}{g} \quad (\text{using 2})$$

Hence the sought distance,  $l = \frac{4(2gh) \sin \alpha}{g} = 8h \sin \alpha$  (Using Eq. 1)

- 1.32 Total time of motion

$$\tau = \frac{2v_0 \sin \alpha}{g} \quad \text{or} \quad \sin \alpha = \frac{\tau g}{2v_0} = \frac{9.8 \tau}{2 \times 240} \quad (1)$$

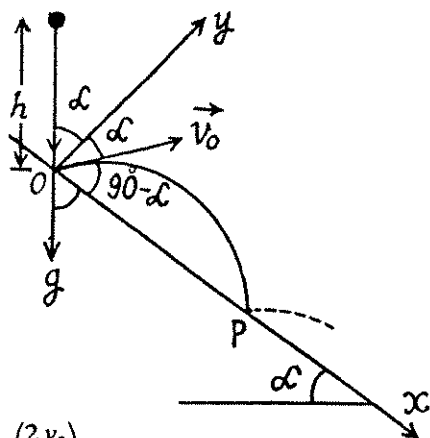
and horizontal range

$$R = v_0 \cos \alpha \tau \quad \text{or} \quad \cos \alpha = \frac{R}{v_0 \tau} = \frac{5100}{240 \tau} = \frac{85}{4 \tau} \quad (2)$$

From Eqs. (1) and (2)

$$\frac{(9.8)^2 \tau^2}{(480)^2} + \frac{(85)^2}{(4 \tau^2)^2} = 1$$

On simplifying  $\tau^4 - 2400 \tau^2 + 1083750 = 0$



Solving for  $\tau^2$  we get :

$$\tau^2 = \frac{2400 \pm \sqrt{1425000}}{2} = \frac{2400 \pm 1194}{2}$$

Thus  $\tau = 42.39 \text{ s} = 0.71 \text{ min}$  and

$\tau = 24.55 \text{ s} = 0.41 \text{ min}$  depending on the angle  $\alpha$ .

1.33 Let the shells collide at the point  $P(x, y)$ . If the first shell takes  $t$  s to collide with second and  $\Delta t$  be the time interval between the firings, then

$$x = v_0 \cos \theta_1 t = v_0 \cos \theta_2 (t - \Delta t) \quad (1)$$

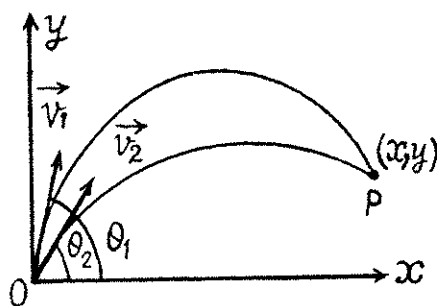
$$\text{and } y = v_0 \sin \theta_1 t - \frac{1}{2} g t^2$$

$$= v_0 \sin \theta_2 (t - \Delta t) - \frac{1}{2} g (t - \Delta t)^2 \quad (2)$$

$$\text{From Eq. (1) } t = \frac{\Delta t \cos \theta_2}{\cos \theta_2 - \cos \theta_1} \quad (3)$$

From Eqs. (2) and (3)

$$\Delta t = \frac{2 v_0 \sin (\theta_1 - \theta_2)}{g (\cos \theta_2 + \cos \theta_1)} \text{ as } \Delta t \neq 0$$



1.34 According to the problem

$$(a) \frac{dy}{dt} = v_0 \text{ or } dy = v_0 dt$$

$$\text{Integrating } \int_0^y dy = v_0 \int_0^t dt \text{ or } y = v_0 t \quad (1)$$

$$\text{And also we have } \frac{dx}{dt} = ay \text{ or } dx = a y dt = a v_0 t dt \text{ (using 1)}$$

$$\text{So, } \int_0^x dx = a v_0 \int_0^t t dt, \text{ or, } x = \frac{1}{2} a v_0 t^2 = \frac{1}{2} \frac{a y^2}{v_0} \text{ (using 1)}$$

(b) According to the problem

$$v_y = v_0 \text{ and } v_x = a y \quad (2)$$

$$\text{So, } v = \sqrt{v_x^2 + v_y^2} = \sqrt{v_0^2 + a^2 y^2}$$

$$\text{Therefore } w_t = \frac{dv}{dt} = \frac{a^2 y}{\sqrt{v_0^2 + a^2 y^2}} \frac{dy}{dt} = \frac{a^2 y}{\sqrt{1 + (ay/v_0)^2}}$$

Diff. Eq. (2) with respect to time.

$$\frac{dv_y}{dt} = w_y = 0 \text{ and } \frac{dv_x}{dt} = w_x = a \frac{dy}{dt} = a v_0$$

$$\text{So, } w = |w_x| = a v_0$$

$$\text{Hence } w_n = \sqrt{w^2 - w_t^2} = \sqrt{a^2 v_0^2 - \frac{a^4 y^2}{1 + (ay/v_0)^2}} = \frac{a v_0}{\sqrt{1 + (ay/v_0)^2}}$$

1.35 (a) The velocity vector of the particle

$$\vec{v} = a \vec{i} + bx \vec{j}$$

$$\text{So, } \frac{dx}{dt} = a : \frac{dy}{dt} = bx \quad (1)$$

$$\text{From (1) } \int_0^x dx = a \int_0^t dt \text{ or, } x = at \quad (2)$$

$$\text{And } dy = bx \, dt = bat \, dt$$

$$\text{Integrating } \int_0^y dy = ab \int_0^t t \, dt \text{ or, } y = \frac{1}{2} ab t^2 \quad (3)$$

$$\text{From Eqs. (2) and (3), we get, } y = \frac{b}{2a} x^2 \quad (4)$$

(b) The curvature radius of trajectory  $y(x)$  is :

$$R = \frac{\left[ 1 + (dy/dx)^2 \right]^{\frac{3}{2}}}{\left| d^2 y / dx^2 \right|} \quad (5)$$

Let us differentiate the path Eq.  $y = \frac{b}{2a} x^2$  with respect to  $x$ ,

$$\frac{dy}{dx} = \frac{b}{a} x \text{ and } \frac{d^2 y}{dx^2} = \frac{b}{a} \quad (6)$$

From Eqs. (5) and (6), the sought curvature radius :

$$R = \frac{a}{b} \left[ 1 + \left( \frac{b}{a} x \right)^2 \right]^{\frac{3}{2}}$$

1.36 In accordance with the problem

$$w_t = \vec{a} \cdot \vec{v}$$

$$\text{But } w_t = \frac{v \, dv}{ds} \text{ or } v \, dv = w_t \, ds$$

$$\text{So, } v \, dv = (\vec{a} \cdot \vec{v}) \, ds = \vec{a} \cdot d\vec{r}$$

$$\text{or, } v \, dv = a \vec{i} \cdot d\vec{r} = a \, dx \text{ (because } \vec{a} \text{ is directed towards the x-axis)}$$

$$\text{So, } \int_0^v v \, dv = a \int_0^x dx$$

$$\text{Hence } v^2 = 2ax \text{ or, } v = \sqrt{2ax}$$



1.37 The velocity of the particle  $v = at$

So, 
$$\frac{dv}{dt} = w_t = a \quad (1)$$

And 
$$w_n = \frac{v^2}{R} = \frac{a^2 t^2}{R} \quad (\text{using } v = at) \quad (2)$$

From 
$$s = \int v dt$$

$$2\pi R \eta = a \int_0^t v dt = \frac{1}{2} at^2$$

So, 
$$\frac{4\pi\eta}{a} = \frac{t^2}{R} \quad (3)$$

From Eqs. (2) and (3)  $w_n = 4\pi a \eta$

Hence  $w = \sqrt{w_t^2 + w_n^2}$

$$= \sqrt{a^2 + (4\pi a \eta)^2} = a \sqrt{1 + 16\pi^2 \eta^2} = 0.8 \text{ m/s}^2$$

1.38 According to the problem

$$|w_t| = |w_n|$$

For  $v(t)$ , 
$$\frac{-dv}{dt} = \frac{v^2}{R}$$

Integrating this equation from  $v_0 \leq v \leq v$  and  $0 \leq t \leq t$

$$-\int_{v_0}^v \frac{dv}{v^2} = \frac{1}{R} \int_0^t dt \quad \text{or, } v = \frac{v_0}{\left(1 + \frac{v_0 t}{R}\right)}$$

Now for  $v(s)$ ,  $-\frac{v dv}{ds} = \frac{v^2}{R}$ , Integrating this equation from  $v_0 \leq v \leq v$  and  $0 \leq s \leq s$

So, 
$$\int_{v_0}^v \frac{dv}{v} = -\frac{1}{R} \int_0^s ds \quad \text{or, } \ln \frac{v}{v_0} = -\frac{s}{R}$$

Hence 
$$v = v_0 e^{-s/R} \quad (2)$$

(b) The normal acceleration of the point

$$w_n = \frac{v^2}{R} = \frac{v_0^2 e^{-2s/R}}{R} \quad (\text{using 2})$$

And as accordance with the problem

$$|w_t| = |w_n| \quad \text{and} \quad w_t \hat{u}_t \perp w_n \hat{u}_n$$

so, 
$$w = \sqrt{2} w_n = \sqrt{2} \frac{v_0^2}{R} e^{-2s/R} = \sqrt{2} \frac{v^2}{R}$$

1.39 From the equation  $v = a\sqrt{s}$

$$w_t = \frac{dv}{dt} = \frac{a}{2\sqrt{s}} \frac{ds}{dt} = \frac{a}{2\sqrt{s}} a\sqrt{s} = \frac{a^2}{2}, \text{ and}$$

$$w_n = \frac{v^2}{R} = \frac{a^2 s}{R}$$

As  $w_t$  is a positive constant, the speed of the particle increases with time, and the tangential acceleration vector and velocity vector coincides in direction.

Hence the angle between  $\vec{v}$  and  $\vec{w}$  is equal to between  $w_t \hat{u}_t$  and  $\vec{w}$ , and  $\alpha$  can be found

by means of the formula :  $\tan \alpha = \frac{|w_n|}{|w_t|} = \frac{a^2 s/R}{a^2/2} = \frac{2s}{R}$

1.40 From the equation  $l = a \sin \omega t$

$$\frac{dl}{dt} = v = a \omega \cos \omega t$$

$$\text{So, } w_t = \frac{dv}{dt} = -a \omega^2 \sin \omega t, \text{ and} \quad (1)$$

$$w_n = \frac{v^2}{R} = \frac{a^2 \omega^2 \cos^2 \omega t}{R} \quad (2)$$

(a) At the point  $l = 0$ ,  $\sin \omega t = 0$  and  $\cos \omega t = \pm 1$  so,  $\omega t = 0, \pi$  etc.

$$\text{Hence } w = w_n = \frac{a^2 \omega^2}{R}$$

Similarly at  $l = \pm a$ ,  $\sin \omega t = \pm 1$  and  $\cos \omega t = 0$ , so,  $w_n = 0$

$$\text{Hence } w = |w_t| = a \omega^2$$

1.41 As  $w_t = a$  and at  $t = 0$ , the point is at rest

$$\text{So, } v(t) \text{ and } s(t) \text{ are, } v = at \text{ and } s = \frac{1}{2} at^2 \quad (1)$$

Let  $R$  be the curvature radius, then

$$w_n = \frac{v^2}{R} = \frac{a^2 t^2}{R} = \frac{2as}{R} \text{ (using 1)}$$

But according to the problem

$$w_n = bt^4$$

$$\text{So, } bt^4 = \frac{a^2 t^2}{R} \text{ or, } R = \frac{a^2}{bt^2} = \frac{a^2}{2bs} \text{ (using 1)} \quad (2)$$

$$\text{Therefore } w = \sqrt{w_t^2 + w_n^2} = \sqrt{a^2 + (2as/R)^2} = \sqrt{a^2 + (4bs^2/a^2)^2} \text{ (using 2)}$$

$$\text{Hence } w = a \sqrt{1 + (4bs^2/a^3)^2}$$

1.42 (a) Let us differentiate twice the path equation  $y(x)$  with respect to time.

$$\frac{dy}{dt} = 2ax \frac{dx}{dt}; \quad \frac{d^2y}{dt^2} = 2a \left[ \left( \frac{dx}{dt} \right)^2 + x \frac{d^2x}{dt^2} \right]$$

Since the particle moves uniformly, its acceleration at all points of the path is normal and at the point  $x = 0$  it coincides with the direction of derivative  $d^2y/dt^2$ . Keeping in mind

that at the point  $x = 0$ ,  $\left| \frac{dx}{dt} \right| = v$ ,

We get 
$$w = \left| \frac{d^2y}{dt^2} \right|_{x=0} = 2av^2 = w_n$$

So, 
$$w_n = 2av^2 = \frac{v^2}{R}, \text{ or } R = \frac{1}{2a}$$

Note that we can also calculate it from the formula of problem (1.35 b)

(b) Differentiating the equation of the trajectory with respect to time we see that

$$b^2x \frac{dx}{dt} + a^2y \frac{dy}{dt} = 0 \quad (1)$$

which implies that the vector  $(b^2x \vec{i} + a^2y \vec{j})$  is normal to the velocity vector  $\vec{v} = \frac{dx}{dt} \vec{i} + \frac{dy}{dt} \vec{j}$  which, of course, is along the tangent. Thus the former vector is along the normal and the normal component of acceleration is clearly

$$w_n = \frac{b^2x \frac{d^2x}{dt^2} + a^2y \frac{d^2y}{dt^2}}{(b^4x^2 + a^4y^2)^{1/2}}$$

on using  $w_n = \vec{w} \cdot \vec{n} / |\vec{n}|$ . At  $x = 0$ ,  $y = \pm b$  and so at  $x = 0$

$$w_n = \pm \frac{d^2y}{dt^2} \Big|_{x=0}$$

Differentiating (1)

$$b^2 \left( \frac{dx}{dt} \right)^2 + b^2x \left( \frac{d^2x}{dt^2} \right) + a^2 \left( \frac{dy}{dt} \right)^2 + a^2y \left( \frac{d^2y}{dt^2} \right) = 0$$

Also from (1) 
$$\frac{dy}{dt} = 0 \text{ at } x = 0$$

So 
$$\left( \frac{dx}{dt} \right) = \pm v \text{ (since tangential velocity is constant } = v \text{)}$$

Thus 
$$\left( \frac{d^2y}{dt^2} \right) = \pm \frac{b}{a^2} v^2$$

and

$$|w_n| = \frac{bv^2}{a^2} = \frac{v^2}{R}$$

This gives  $R = a^2/b$ .

- 1.43 Let us fix the co-ordinate system at the point  $O$  as shown in the figure, such that the radius vector  $\vec{r}$  of point  $A$  makes an angle  $\theta$  with  $x$  axis at the moment shown.

Note that the radius vector of the particle  $A$  rotates clockwise and we here take line  $ox$  as reference line, so in this case obviously the angular velocity  $\omega = \left(-\frac{d\theta}{dt}\right)$  taking anticlockwise sense of angular displacement as positive.

Also from the geometry of the triangle  $OAC$

$$\frac{R}{\sin \theta} = \frac{r}{\sin(\pi - 2\theta)} \quad \text{or, } r = 2R \cos \theta.$$

Let us write,

$$\vec{r} = r \cos \theta \vec{i} + r \sin \theta \vec{j} = 2R \cos^2 \theta \vec{i} + R \sin 2\theta \vec{j}$$

Differentiating with respect to time.

$$\frac{d\vec{r}}{dt} \quad \text{or } \vec{v} = 2R \cos \theta (-\sin \theta) \frac{d\theta}{dt} \vec{i} + 2R \cos 2\theta \frac{d\theta}{dt} \vec{j}$$

$$\text{or, } \vec{v} = 2R \left( \frac{-d\theta}{dt} \right) [\sin 2\theta \vec{i} - \cos 2\theta \vec{j}]$$

$$\text{or, } \vec{v} = 2R \omega (\sin 2\theta \vec{i} - \cos^2 \theta \vec{j})$$

$$\text{So, } |\vec{v}| \quad \text{or } v = 2\omega R = 0.4 \text{ m/s.}$$

As  $\omega$  is constant,  $v$  is also constant and  $w_t = \frac{dv}{dt} = 0$ ,

$$\text{So, } w = w_n = \frac{v^2}{R} = \frac{(2\omega R)^2}{R} = 4\omega^2 R = 0.32 \text{ m/s}^2$$

**Alternate :** From the Fig. the angular velocity of the point  $A$ , with respect to centre of the circle  $C$  becomes

$$-\frac{d(2\theta)}{dt} = 2 \left( \frac{-d\theta}{dt} \right) = 2\omega = \text{constant}$$

Thus we have the problem of finding the velocity and acceleration of a particle moving along a circle of radius  $R$  with constant angular velocity  $2\omega$ .

Hence

$$v = 2\omega R \quad \text{and}$$

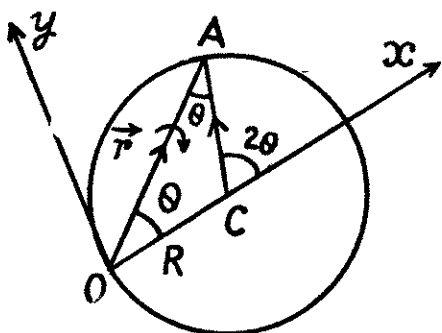
$$w = w_n = \frac{v^2}{R} = \frac{(2\omega R)^2}{R} = 4\omega^2 R$$

- 1.44 Differentiating  $\varphi(t)$  with respect to time

$$\frac{d\varphi}{dt} = \omega_z = 2at \quad (1)$$

For fixed axis rotation, the speed of the point  $A$ :

$$v = \omega R = 2atR \quad \text{or } R = \frac{v}{2at} \quad (2)$$



Differentiating with respect to time

$$w_t = \frac{dv}{dt} = 2at = \frac{v}{t}, \text{ (using 1)}$$

But 
$$w_n = \frac{v^2}{R} = \frac{v^2}{v/2at} = 2atv \text{ (using 2)}$$

So, 
$$w = \sqrt{w_t^2 + w_n^2} = \sqrt{(v/t)^2 + (2atv)^2}$$
  

$$= \frac{v}{t} \sqrt{1 + 4a^2 t^4}$$

- 1.45 The shell acquires a constant angular acceleration at the same time as it accelerates linearly. The two are related by (assuming both are constant)

$$\frac{w}{l} = \frac{\beta}{2\pi n}$$

Where  $w$  = linear acceleration and  $\beta$  = angular acceleration

Then, 
$$\omega = \sqrt{2\beta 2\pi n} = \sqrt{2 \cdot \frac{w}{l} (2\pi n)^2}$$

But  $v^2 = 2wl$ , hence finally

$$\omega = \frac{2\pi n v}{l}$$

- 1.46 Let us take the rotation axis as z-axis whose positive direction is associated with the positive direction of the coordinate  $\varphi$ , the rotation angle, in accordance with the right-hand screw rule (Fig.)

(a) Differentiating  $\varphi(t)$  with respect to time.

$$\frac{d\varphi}{dt} = a - 3bt^2 = \omega_z \quad (1) \text{ and}$$

$$\frac{d^2\varphi}{dt^2} = \frac{d\omega_z}{dt} = \beta_z = -6bt \quad (2)$$

From (1) the solid comes to stop at  $\Delta t = t = \sqrt{\frac{a}{3b}}$

The angular velocity  $\omega = a - 3bt^2$ , for  $0 \leq t \leq \sqrt{a/3b}$

So, 
$$\langle \omega \rangle = \frac{\int \omega dt}{\int dt} = \frac{\int_0^{\sqrt{a/3b}} (a - 3bt^2) dt}{\int_0^{\sqrt{a/3b}} dt} = [at - bt^3]_0^{\sqrt{a/3b}} / \sqrt{a/3b} = 2a/3$$

Similarly  $\beta = |\beta_z| = 6bt$  for all values of  $t$ .



So, 
$$\langle \beta \rangle = \frac{\int \beta dt}{\int dt} = \frac{\int_0^{\sqrt{a/3b}} 6bt dt}{\int_0^{\sqrt{a/3b}} dt} = \sqrt{3ab}$$

(b) From Eq. (2)  $\beta_z = -6bt$

So, 
$$(\beta_z)_t = \sqrt{a/3b} = -6b \sqrt{\frac{a}{3b}} = -2\sqrt{ab}$$

Hence 
$$\beta = |(\beta_z)_t - \sqrt{a/3b}| = 2\sqrt{3ab}$$

1.47 Angle  $\alpha$  is related with  $|w_t|$  and  $w_n$  by means of the formula :

$$\tan \alpha = \frac{w_n}{|w_t|}, \text{ where } w_n = \omega^2 R \text{ and } |w_t| = \beta R \quad (1)$$

where  $R$  is the radius of the circle which an arbitrary point of the body circumscribes.

From the given equation  $\beta = \frac{d\omega}{dt} = at$  (here  $\beta = \frac{d\omega}{dt}$ , as  $\beta$  is positive for all values of  $t$ )

Integrating within the limit  $\int_0^\omega d\omega = a \int_0^t t dt$  or,  $\omega = \frac{1}{2} at^2$

So, 
$$w_n = \omega^2 R = \left(\frac{at^2}{2}\right)^2 R = \frac{a^2 t^4}{4} R$$

and  $|w_t| = \beta R = atR$

Putting the values of  $|w_t|$  and  $w_n$  in Eq. (1), we get,

$$\tan \alpha = \frac{a^2 t^4 R/4}{atR} = \frac{at^3}{4} \text{ or, } t = \left[ \left( \frac{4}{a} \right) \tan \alpha \right]^{1/3}$$

1.48 In accordance with the problem,  $\beta_z < 0$

Thus  $-\frac{d\omega}{dt} = k\sqrt{\omega}$ , where  $k$  is proportionality constant

or, 
$$-\int_{\omega_0}^{\omega} \frac{d\omega}{\sqrt{\omega}} = k \int_0^t dt \text{ or, } \sqrt{\omega} = \sqrt{\omega_0} - \frac{kt}{2} \quad (1)$$

When  $\omega = 0$ , total time of rotation  $t = \tau = \frac{2\sqrt{\omega_0}}{k}$

$$\text{Average angular velocity } \langle \omega \rangle = \frac{\int \omega dt}{\int dt} = \frac{\int_0^{2\sqrt{\omega_0}/k} \left( \omega_0 + \frac{k^2 t^2}{4} - k t \sqrt{\omega_0} \right) dt}{2\sqrt{\omega_0}/k}$$

$$\text{Hence } \langle \omega \rangle = \left[ \omega_0 t + \frac{k^2 t^3}{12} - \frac{k}{2} \sqrt{\omega_0} t^2 \right]_0^{2\sqrt{\omega_0}/k} / \frac{2\sqrt{\omega_0}}{k} = \omega_0/3$$

1.49 We have  $\omega = \omega_0 - a\varphi = \frac{d\varphi}{dt}$

Integratin this Eq. within its limit for  $(\varphi) t$

$$\int_0^\varphi \frac{d\varphi}{\omega_0 - k\varphi} = \int_0^t dt \text{ or, } \ln \frac{\omega_0 - k\varphi}{\omega_0} = -kt$$

Hence 
$$\varphi = \frac{\omega_0}{k} (1 - e^{-kt}) \quad (1)$$

(b) From the Eq.,  $\omega = \omega_0 - k\varphi$  and Eq. (1) or by differentiating Eq. (1)

$$\omega = \omega_0 e^{-kt}$$

1.50 Let us choose the positive direction of z-axis (stationary rotation axis) along the vector  $\beta_0$ . In accordance with the equation

$$\frac{d\omega_z}{dt} = \beta_z \text{ or } \omega_z \frac{d\omega_z}{d\varphi} = \beta_z$$

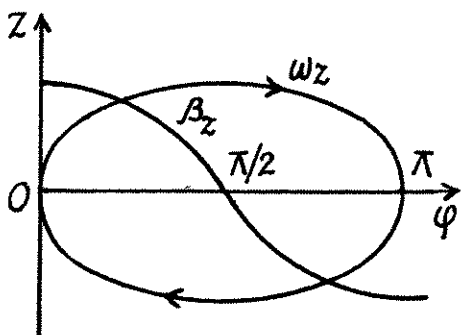
or,  $\omega_z d\omega_z = \beta_z d\varphi = \beta \cos \varphi d\varphi$ ,

Integrating this Eq. within its limit for  $\omega_z(\varphi)$

or, 
$$\int_0^{\omega_z} d\omega_z = \beta_0 \int_0^\varphi \cos \varphi d\varphi$$

or, 
$$\frac{\omega_z^2}{2} = \beta_0 \sin \varphi$$

Hence 
$$\omega_z = \pm \sqrt{2\beta_0 \sin \varphi}$$



The plot  $\omega_z(\varphi)$  is shown in the Fig. It can be seen that as the angle  $\varphi$  grows, the vector  $\vec{\omega}$  first increases, coinciding with the direction of the vector  $\vec{\beta}_0$  ( $\omega_z > 0$ ), reaches the maximum at  $\varphi = \varphi/2$ , then starts decreasing and finally turns into zero at  $\varphi = \pi$ . After that the body starts rotating in the opposite direction in a similar fashion ( $\omega_z < 0$ ). As a result, the body will oscillate about the position  $\varphi = \varphi/2$  with an amplitude equal to  $\pi/2$ .

- 1.51 Rotating disc moves along the  $x$ -axis, in plane motion in  $x-y$  plane. Plane motion of a solid can be imagined to be in pure rotation about a point (say  $I$ ) at a certain instant known as instantaneous centre of rotation. The instantaneous axis whose positive sense is directed along  $\vec{\omega}$  of the solid and which passes through the point  $I$ , is known as instantaneous axis of rotation.

Therefore the velocity vector of an arbitrary point ( $P$ ) of the solid can be represented as :

$$\vec{v}_P = \vec{\omega} \times \vec{r}_{PI} \quad (1)$$

On the basis of Eq. (1) for the C. M. ( $C$ ) of the disc

$$\vec{v}_C = \vec{\omega} \times \vec{r}_{CI} \quad (2)$$

According to the problem  $\vec{v}_C \uparrow \uparrow \vec{i}$  and  $\vec{\omega} \uparrow \uparrow \vec{k}$  i.e.  $\vec{\omega} \perp x-y$  plane, so to satisfy the Eqn. (2)  $\vec{r}_{CI}$  is directed along  $(-\vec{j})$ . Hence point  $I$  is at a distance  $r_{CI} = y$ , above the centre of the disc along  $y$ -axis. Using all these facts in Eq. (2), we get

$$v_C = \omega y \text{ or } y = \frac{v_C}{\omega} \quad (3)$$

(a) From the angular kinematical equation

$$\omega_z = \omega_{0z} + \beta_z t \quad (4)$$

$$\omega = \beta t.$$

On the other hand  $x = vt$ , (where  $x$  is the  $x$  coordinate of the C.M.)

$$\text{or, } t = \frac{x}{v} \quad (5)$$

From Eqs. (4) and (5),  $\omega = \frac{\beta x}{v}$

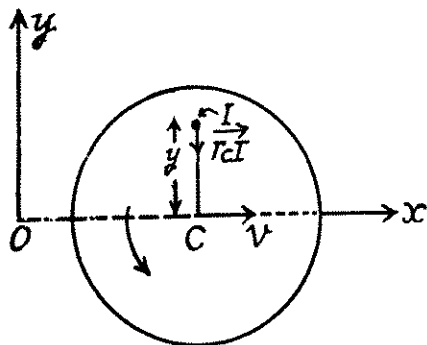
Using this value of  $\omega$  in Eq. (3) we get  $y = \frac{v_C}{\omega} = \frac{v}{\beta x/v} = \frac{v^2}{\beta x}$  (hyperbola)

(b) As centre  $C$  moves with constant acceleration  $w$ , with zero initial velocity

$$\text{So, } x = \frac{1}{2} w t^2 \text{ and } v_C = w t$$

$$\text{Therefore, } v_C = w \sqrt{\frac{2x}{w}} = \sqrt{2wx}$$

$$\text{Hence } y = \frac{v_C}{\omega} = \frac{\sqrt{2wx}}{\omega} \text{ (parabola)}$$





- 1.52** The plane motion of a solid can be imagined as the combination of translation of the C.M. and rotation about C.M.

So, we may write  $\vec{v}_A = \vec{v}_C + \vec{v}_{AC}$

$$= \vec{v}_C + \vec{\omega} \times \vec{r}_{AC} \quad (1) \text{ and}$$

$$\vec{w}_A = \vec{w}_C + \vec{w}_{AC}$$

$$= \vec{w}_C + \omega^2 (-\vec{r}_{AC}) + (\vec{\beta} \times \vec{r}_{AC}) \quad (2)$$

$\vec{r}_{AC}$  is the position of vector of A with respect to C.

In the problem  $v_C = v = \text{constant}$ , and the rolling is without slipping i.e.,  $v_C = v = \omega R$ ,

So,  $w_C = 0$  and  $\beta = 0$ . Using these conditions in Eq. (2)

$$\vec{w}_A = \omega^2 (-\vec{r}_{AC}) = \omega^2 R (-\hat{u}_{AC}) = \frac{v^2}{R} (-\hat{u}_{AC})$$

Here,  $\hat{u}_{AC}$  is the unit vector directed along  $\vec{r}_{AC}$ .

Hence  $w_A = \frac{v^2}{R}$  and  $\vec{w}_A$  is directed along  $(-\hat{u}_{AC})$  or directed toward the centre of the wheel.

(b) Let the centre of the wheel move toward right (positive x-axis) then for pure rolling on the rigid horizontal surface, wheel will have to rotate in clockwise sense. If  $\omega$  be the angular velocity of the wheel then  $\omega = \frac{v_C}{R} = \frac{v}{R}$ .

Let the point A touches the horizontal surface at  $t = 0$ , further let us locate the point A at  $t = t$ ,

When it makes  $\theta = \omega t$  at the centre of the wheel.

From Eqn. (1) 
$$\vec{v}_A = \vec{v}_C + \vec{\omega} \times \vec{r}_{AC}$$

$$= v \vec{i} + \omega (-\vec{k}) \times [R \cos \theta (-\vec{j}) + R \sin \theta (-\vec{i})]$$

or, 
$$\vec{v}_A = v \vec{i} + \omega R [\cos \omega t (-\vec{i}) + \sin \omega t \vec{j}]$$

$$= (v - \cos \omega t) \vec{i} + v \sin \omega t \vec{j} \quad (\text{as } v = \omega R)$$

So, 
$$v_A = \sqrt{(v - v \cos \omega t)^2 + (v \sin \omega t)^2}$$

$$= v \sqrt{2(1 - \cos \omega t)} = 2v \sin(\omega t/2)$$

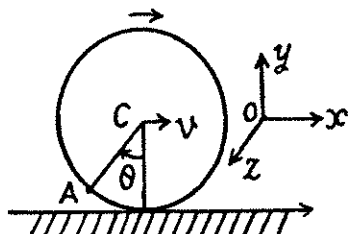
Hence distance covered by the point A during  $T = 2\pi/\omega$

$$s = \int_0^{2\pi/\omega} v_A dt = \int_0^{2\pi/\omega} 2v \sin(\omega t/2) dt = \frac{8v}{\omega} = 8R.$$

- 1.53** Let us fix the co-ordinate axis  $xyz$  as shown in the fig. As the ball rolls without slipping along the rigid surface so, on the basis of the solution of problem 1.52 :

Thus 
$$\vec{v}_0 = \vec{v}_C + \vec{\omega} \times \vec{r}_{C0} = 0$$

$$v_C = \omega R \text{ and } \vec{\omega} \uparrow \uparrow (-\vec{k}) \text{ as } \vec{v}_C \uparrow \uparrow \vec{i} \quad (1)$$



$$\left. \begin{aligned} & \vec{\omega}_c + \vec{\beta} \times \vec{r}_{oc} = 0 \\ & \text{and } w_c = \beta R \text{ and } \vec{\beta} \uparrow \uparrow (-\vec{k}) \text{ as } \vec{w}_c \uparrow \uparrow \vec{i} \end{aligned} \right\}$$

At the position corresponding to that of Fig., in accordance with the problem,

$$w_c = w, \text{ so } v_c = w t$$

$$\text{and } \omega = \frac{v_c}{R} = \frac{w t}{R} \text{ and } \beta = \frac{w}{R} \text{ (using 1)}$$

(a) Let us fix the co-ordinate system with the frame attached with the rigid surface as shown in the Fig.

As point  $O$  is the instantaneous centre of rotation of the ball at the moment shown in Fig.

$$\text{so, } \vec{v}_O = 0,$$

Now,

$$\begin{aligned} \vec{v}_A &= \vec{v}_C + \vec{\omega} \times \vec{r}_{AC} \\ &= v_C \vec{i} + \omega (-\vec{k}) \times R (\vec{j}) = (v_C + \omega R) \vec{i} \end{aligned}$$

$$\text{So, } \vec{v}_A = 2 v_C \vec{i} = 2 w t \vec{i} \text{ (using 1)}$$

$$\begin{aligned} \text{Similarly } \vec{v}_B &= \vec{v}_C + \vec{\omega} \times \vec{r}_{BC} = v_C \vec{i} + \omega (-\vec{k}) \times R (\vec{i}) \\ &= v_C \vec{i} + \omega R (-\vec{j}) = v_C \vec{i} + v_C (-\vec{j}) \end{aligned}$$

So,  $v_B = \sqrt{2} v_C = \sqrt{2} w t$  and  $\vec{v}_B$  is at an angle  $45^\circ$  from both  $\vec{i}$  and  $\vec{j}$  (Fig.)

$$\begin{aligned} \text{(b) } \vec{w}_0 &= \vec{w}_C + \omega^2 (-\vec{r}_{oc}) + \vec{\beta} \times \vec{r}_{oc} \\ &= \omega^2 (-\vec{r}_{oc}) = \frac{v_C^2}{R} (-\hat{u}_{oc}) \text{ (using 1)} \end{aligned}$$

where  $\hat{u}_{oc}$  is the unit vector along  $\vec{r}_{oc}$

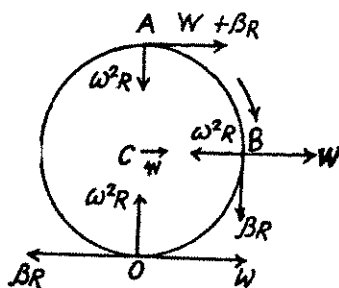
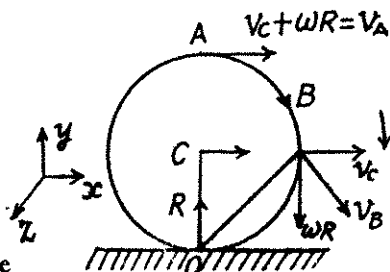
so,  $w_0 = \frac{v_0^2}{R} = \frac{w^2 t^2}{R}$  (using 2) and  $\vec{w}_0$  is directed towards the centre of the ball

$$\begin{aligned} \text{Now } \vec{w}_A &= \vec{w}_C + \omega^2 (-\vec{r}_{AC}) + \vec{\beta} \times \vec{r}_{AC} \\ &= w \vec{i} + \omega^2 R (-\vec{j}) + \beta (-\vec{k}) \times R \vec{j} \\ &= (w + \beta R) \vec{i} + \frac{v_C^2}{R} (-\vec{j}) \text{ (using 1)} = 2w \vec{i} + \frac{w^2 t^2}{R} (-\vec{j}) \end{aligned}$$

$$\text{So, } w_A = \sqrt{4w^2 + \frac{w^4 t^4}{R^2}} = 2w \sqrt{1 + \left(\frac{w t^2}{2R}\right)^2}$$

Similarly

$$\begin{aligned} \vec{w}_B &= \vec{w}_C + \omega^2 (-\vec{r}_{BC}) + \vec{\beta} \times \vec{r}_{BC} \\ &= w \vec{i} + \omega^2 R (-\vec{i}) + \beta (-\vec{k}) \times R (\vec{i}) \\ &= \left(v - \frac{v_C^2}{R}\right) \vec{i} + \beta R (-\vec{j}) \text{ (using 1)} \end{aligned}$$

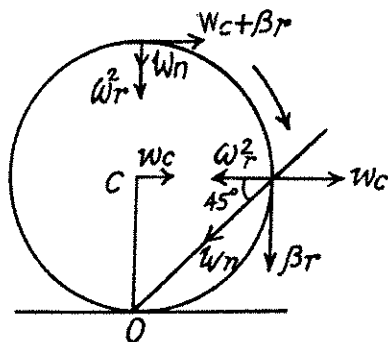
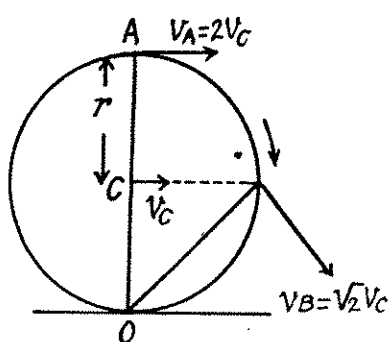


$$= \left( \omega - \frac{\omega^2 t^2}{R} \right) \vec{i} + \omega (-j) \quad (\text{using 2})$$

So,

$$\omega_B = \sqrt{\left( \omega - \frac{\omega^2 t^2}{R} \right)^2 + \omega^2}$$

**1.54** Let us draw the kinematical diagram of the rolling cylinder on the basis of the solution of problem 1.53.



As, an arbitrary point of the cylinder follows a curve, its normal acceleration and radius of curvature are related by the well known equation

$$\omega_n = \frac{v^2}{R}$$

so, for point A,

$$\omega_{A(n)} = \frac{v_A^2}{R_A}$$

or,

$$R_A = \frac{4 v_c^2}{\omega^2 r} = 4r \quad (\text{because } v_c = \omega r, \text{ for pure rolling})$$

Similarly for point B,

$$\omega_{B(n)} = \frac{v_B^2}{R_B}$$

$$\omega^2 r \cos 45^\circ = \frac{(\sqrt{2} v_c)^2}{R_B},$$

or,

$$R_B = 2\sqrt{2} \frac{v_c^2}{\omega^2 r} = 2\sqrt{2} r$$

**1.55** The angular velocity is a vector as infinitesimal rotation commute. Then the relative angular velocity of the body 1 with respect to the body 2 is clearly.

$$\vec{\omega}_{12} = \vec{\omega}_1 - \vec{\omega}_2$$

as for relative linear velocity. The relative acceleration of 1 w.r.t. 2 is

$$\left( \frac{d\vec{\omega}_1}{dt} \right)_{S'}$$

where  $S'$  is a frame corotating with the second body and  $S$  is a space fixed frame with origin coinciding with the point of intersection of the two axes,

but 
$$\left( \frac{d\vec{\omega}_1}{dt} \right)_S = \left( \frac{d\vec{\omega}_1}{dt} \right)_{S'} + \vec{\omega}_2 \times \vec{\omega}_1$$

Since  $S'$  rotates with angular velocity  $\vec{\omega}_2$ . However  $\left( \frac{d\vec{\omega}_1}{dt} \right)_{S'} = 0$  as the first body rotates with constant angular velocity in space, thus

$$\vec{\beta}_{12} = \vec{\omega}_1 \times \vec{\omega}_2.$$

Note that for any vector  $\vec{b}$ , the relation in space fixed frame ( $k$ ) and a frame ( $k'$ ) rotating with angular velocity  $\vec{\omega}$  is

$$\left. \frac{d\vec{b}}{dt} \right|_K = \left. \frac{d\vec{b}}{dt} \right|_{K'} + \vec{\omega} \times \vec{b}$$

1.56 We have  $\vec{\omega} = at\vec{i} + bt^2\vec{j}$  (1)

So,  $\omega = \sqrt{(at)^2 + (bt^2)^2}$ , thus,  $\omega|_{t=10s} = 7.81 \text{ rad/s}$

Differentiating Eq. (1) with respect to time

$$\vec{\beta} = \frac{d\vec{\omega}}{dt} = a\vec{i} + 2bt\vec{j} \quad (2)$$

So,  $\beta = \sqrt{a^2 + (2bt)^2}$

and  $\beta|_{t=10s} = 1.3 \text{ rad/s}^2$

(b) 
$$\cos \alpha = \frac{\vec{\omega} \cdot \vec{\beta}}{\omega \beta} = \frac{(at\vec{i} + bt^2\vec{j}) \cdot (a\vec{i} + 2bt\vec{j})}{\sqrt{(at)^2 + (bt^2)^2} \sqrt{a^2 + (2bt)^2}}$$

Putting the values of (a) and (b) and taking  $t = 10s$ , we get  $\alpha = 17^\circ$

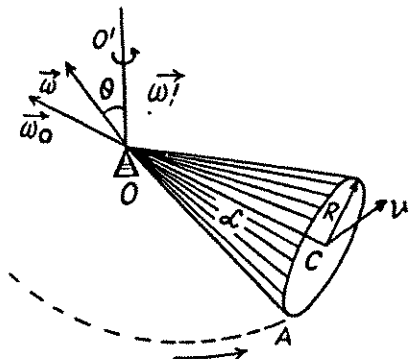
- 1.57 (a) Let the axis of the cone ( $OC$ ) rotates in anticlockwise sense with constant angular velocity  $\vec{\omega}'$  and the cone itself about it's own axis ( $OC$ ) in clockwise sense with angular velocity  $\vec{\omega}_0$  (Fig.). Then the resultant angular velocity of the cone.

$$\vec{\omega} = \vec{\omega}' + \vec{\omega}_0 \quad (1)$$

As the rolling is pure the magnitudes of the vectors  $\vec{\omega}'$  and  $\vec{\omega}_0$  can be easily found from Fig.

$$\omega' = \frac{v}{R \cot \alpha}, \quad \omega_0 = v/R \quad (2)$$

As  $\vec{\omega}' \perp \vec{\omega}_0$  from Eq. (1) and (2)



$$\omega = \sqrt{\omega'^2 + \omega_0^2}$$

$$\sqrt{\left(\frac{v}{R \cot \alpha}\right)^2 + \left(\frac{v}{R}\right)^2} = \frac{v}{R \cos \alpha} = 2.3 \text{ rad/s}$$

(b) Vector of angular acceleration

$$\vec{\beta} = \frac{d\vec{\omega}}{dt} = \frac{d(\vec{\omega}' + \vec{\omega}_0)}{dt} \quad (\text{as } \vec{\omega}' = \text{constant.})$$

The vector  $\vec{\omega}_0$  which rotates about the  $OO'$  axis with the angular velocity  $\vec{\omega}'$ , retains its magnitude. This increment in the time interval  $dt$  is equal to

$$|d\vec{\omega}_0| = \omega_0 \omega' dt \text{ or in vector form } d\vec{\omega}_0 = (\vec{\omega}' \times \vec{\omega}_0) dt.$$

Thus  $\vec{\beta} = \vec{\omega}' \times \vec{\omega}_0$

The magnitude of the vector  $\vec{\beta}$  is equal to

$$\beta = \omega' \omega_0 \text{ (as } \vec{\omega}' \perp \vec{\omega}_0 \text{)}$$

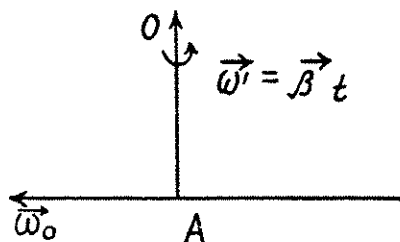
So, 
$$\beta = \frac{v}{R \cot \alpha} \frac{v}{R} = \frac{v^2}{R^2} \tan \alpha = 2.3 \text{ rad/s}$$

1.58 The axis  $AB$  acquired the angular velocity

$$\vec{\omega}' = \vec{\beta}_0 t \quad (1)$$

Using the facts of the solution of 1.57, the angular velocity of the body

$$\begin{aligned} \omega &= \sqrt{\omega_0^2 + \omega'^2} \\ &= \sqrt{\omega_0^2 + \beta_0^2 t^2} = 0.6 \text{ rad/s} \end{aligned}$$



And the angular acceleration.

$$\vec{\beta} = \frac{d\vec{\omega}}{dt} = \frac{d(\vec{\omega}' + \vec{\omega}_0)}{dt} = \frac{d\vec{\omega}'}{dt} + \frac{d\vec{\omega}_0}{dt}$$

But  $\frac{d\vec{\omega}_0}{dt} = \vec{\omega}' \times \vec{\omega}_0$ , and  $\frac{d\vec{\omega}'}{dt} = \vec{\beta}_0 t$

So, 
$$\vec{\beta} = (\vec{\beta}_0 t \times \vec{\omega}_0) + \vec{\beta}_0$$

As,  $\vec{\beta}_0 \perp \vec{\omega}_0$  so,  $\beta = \sqrt{(\omega_0 \beta_0 t)^2 + \beta_0^2} = \beta_0 \sqrt{1 + (\omega_0 t)^2} = 0.2 \text{ rad/s}^2$

## 1.2 THE FUNDAMENTAL EQUATION OF DYNAMICS

1.59 Let  $R$  be the constant upward thrust on the aerostat of mass  $m$ , coming down with a constant acceleration  $w$ . Applying Newton's second law of motion for the aerostat in projection form

$$F_y = mw_y$$

$$mg - R = mw \quad (1)$$

Now, if  $\Delta m$  be the mass, to be dumped, then using the Eq.  $F_y = mw_y$

$$R - (m - \Delta m)g = (m - \Delta m)w, \quad (2)$$

From Eqs. (1) and (2), we get,  $\Delta m = \frac{2mw}{g+w}$

1.60 Let us write the fundamental equation of dynamics for all the three blocks in terms of projections, having taken the positive direction of  $x$  and  $y$  axes as shown in Fig; and using the fact that kinematical relation between the accelerations is such that the blocks move with same value of acceleration (say  $w$ )

$$m_0 g - T_1 = m_0 w \quad (1)$$

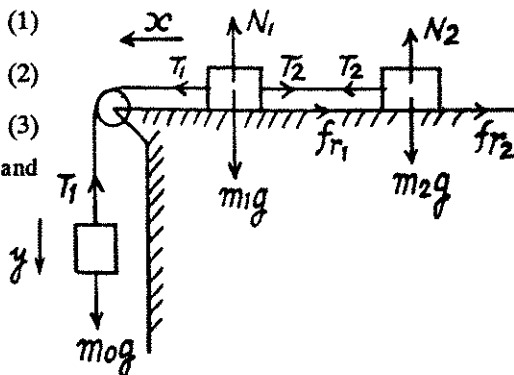
$$T_1 - T_2 - km_1 g = m_1 w \quad (2)$$

$$\text{and } T_2 - km_2 g = m_2 w \quad (3)$$

The simultaneous solution of Eqs. (1), (2) and (3) yields,

$$w = g \frac{[m_0 - k(m_1 + m_2)]}{m_0 + m_1 + m_2}$$

$$\text{and } T_2 = \frac{(1+k)m_0}{m_0 + m_1 + m_2} m_2 g$$

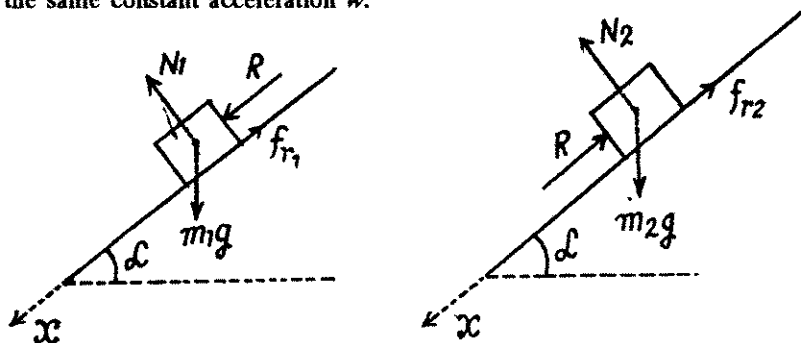


As the block  $m_0$  moves down with acceleration  $w$ , so in vector form

$$\vec{w} = \frac{[m_0 - k(m_1 + m_2)] \vec{g}}{m_0 + m_1 + m_2}$$

1.61 Let us indicate the positive direction of  $x$ -axis along the incline (Fig.). Figures show the force diagram for the blocks.

Let,  $R$  be the force of interaction between the bars and they are obviously sliding down with the same constant acceleration  $w$ .



Newton's second law of motion in projection form along  $x$ -axis for the blocks gives :

$$m_1 g \sin \alpha - k_1 m_1 g \cos \alpha + R = m_1 w \quad (1)$$

$$m_2 g \sin \alpha - R - k_2 m_2 g \cos \alpha = m_2 w \quad (2)$$

Solving Eqs. (1) and (2) simultaneously, we get

$$w = g \sin \alpha - g \cos \alpha \frac{k_1 m_1 + k_2 m_2}{m_1 + m_2} \text{ and}$$

$$R = \frac{m_1 m_2 (k_1 - k_2) g \cos \alpha}{m_1 + m_2} \quad (3)$$

(b) when the blocks just slide down the plane,  $w = 0$ , so from Eqn. (3)

$$g \sin \alpha - g \cos \alpha \frac{k_1 m_1 + k_2 m_2}{m_1 + m_2} = 0$$

$$\text{or, } (m_1 + m_2) \sin \alpha = (k_1 m_1 + k_2 m_2) \cos \alpha$$

Hence 
$$\tan \alpha = \frac{(k_1 m_1 + k_2 m_2)}{m_1 + m_2}$$

#### 1.62 Case 1. When the body is launched up :

Let  $k$  be the coefficient of friction,  $u$  the velocity of projection and  $l$  the distance traversed along the incline. Retarding force on the block =  $mg \sin \alpha + k mg \cos \alpha$  and hence the retardation =  $g \sin \alpha + k g \cos \alpha$ .

Using the equation of particle kinematics along the incline,

$$0 = u^2 - 2 (g \sin \alpha + k g \cos \alpha) l$$

or, 
$$l = \frac{u^2}{2 (g \sin \alpha + k g \cos \alpha)} \quad (1)$$

and 
$$0 = u - (g \sin \alpha + k g \cos \alpha) t$$

or, 
$$u = (g \sin \alpha + k g \cos \alpha) t \quad (2)$$

Using (2) in (1) 
$$l = \frac{1}{2} (g \sin \alpha + k g \cos \alpha) t^2 \quad (3)$$

Case (2). When the block comes downward, the net force on the body =  $mg \sin \alpha - k mg \cos \alpha$  and hence its acceleration =  $g \sin \alpha - k g \cos \alpha$

Let,  $t$  be the time required then,

$$l = \frac{1}{2} (g \sin \alpha - k g \cos \alpha) t'^2 \quad (4)$$

From Eqs. (3) and (4)

$$\frac{t^2}{t'^2} = \frac{\sin \alpha + k \cos \alpha}{\sin \alpha - k \cos \alpha}$$

But  $\frac{t}{t'} = \frac{1}{\eta}$  (according to the question),

Hence on solving we get

$$k = \frac{(\eta^2 - 1)}{(\eta^2 + 1)} \tan \alpha = 0.16$$

1.63 At the initial moment, obviously the tension in the thread connecting  $m_1$  and  $m_2$  equals the weight of  $m_2$ .

(a) For the block  $m_2$  to come down or the block  $m_1$  to go up, the conditions is

$$m_2 g - T \geq 0 \quad \text{and} \quad T - m_1 g \sin \alpha - f_r \geq 0$$

where  $T$  is tension and  $f_r$  is friction which in the limiting case equals  $k m_1 g \cos \alpha$ . Then

$$\text{or} \quad m_2 g - m_1 g \sin \alpha > k m_1 g \cos \alpha$$

$$\text{or} \quad \frac{m_2}{m_1} > (k \cos \alpha + \sin \alpha)$$

(b) Similarly in the case

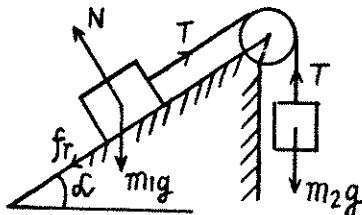
$$m_1 g \sin \alpha - m_2 g > f_{r \text{ lim}}$$

$$\text{or, } m_1 g \sin \alpha - m_2 g > k m_1 g \cos \alpha$$

$$\text{or, } \frac{m_2}{m_1} < (\sin \alpha - k \cos \alpha)$$

(c) For this case, neither kind of motion is possible, and  $f_r$  need not be limiting.

$$\text{Hence, } (k \cos \alpha + \sin \alpha) > \frac{m_2}{m_1} > (\sin \alpha - k \cos \alpha)$$



1.64 From the conditions, obtained in the previous problem, first we will check whether the mass  $m_2$  goes up or down.

Here,  $m_2/m_1 = \eta > \sin \alpha + k \cos \alpha$ , (substituting the values). Hence the mass  $m_2$  will come down with an acceleration (say  $w$ ). From the free body diagram of previous problem,

$$m_2 - g - T = m_2 w \quad (1)$$

$$\text{and} \quad T - m_1 g \sin \alpha - k m_1 g \cos \alpha = m_1 w \quad (2)$$

Adding (1) and (2), we get,

$$m_2 g - m_1 g \sin \alpha - k m_1 g \cos \alpha = (m_1 + m_2) w$$

$$w = \frac{(m_2/m_1 - \sin \alpha - k \cos \alpha) g}{(1 + m_2/m_1)} = \frac{(\eta - \sin \alpha - k \cos \alpha) g}{1 + \eta}$$

Substituting all the values,  $w = 0.048 g = 0.05 g$

As  $m_2$  moves down with acceleration of magnitude  $w = 0.05 g > 0$ , thus in vector form acceleration of  $m_2$ :

$$\vec{w}_2 = \frac{(\eta - \sin \alpha - k \cos \alpha) \vec{g}}{1 + \eta} = 0.05 \vec{g}$$

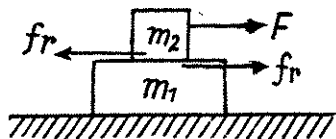
1.65 Let us write the Newton's second law in projection form along positive  $x$ -axis for the plank and the bar

$$f_r = m_1 w_1, \quad f_r = m_2 w_2 \quad (1)$$



At the initial moment,  $fr$  represents the static friction, and as the force  $F$  grows so does the friction force  $fr$ , but up to its limiting value i.e.  $fr = fr_{s(max)} = kN = km_2g$ .

Unless this value is reached, both bodies move as a single body with equal acceleration. But as soon as the force  $fr$  reaches the limit, the bar starts sliding over the plank i.e.  $w_2 \neq w_1$ .



Substituting here the values of  $w_1$  and  $w_2$  taken from Eq. (1) and taking into account that

$fr = km_2g$ , we obtain,  $(at - km_2g)/m_2 \geq \frac{km_2}{m_1}g$ , where the sign "=" corresponds to the moment

$t = t_0$  (say)

Hence,

$$t_0 = \frac{k g m_2 (m_1 + m_2)}{a m_1}$$

If  $t \leq t_0$ , then  $w_1 = \frac{km_2g}{m_1}$  (constant). and

$$w_2 = (at - km_2g)/m_2$$

On this basis  $w_1(t)$  and  $w_2(t)$ , plots are as shown in the figure of answersheet.

**1.66** Let us designate the  $x$ -axis (Fig.) and apply  $F_x = m w_x$  for body A :

$$mg \sin \alpha - k m g \cos \alpha = m w$$

or,  $w = g \sin \alpha - k g \cos \alpha$

Now, from kinematical equation :

$$l \sec \alpha = 0 + (1/2) w t^2$$

or,  $t = \sqrt{2 l \sec \alpha / (g (\sin \alpha - k \cos \alpha))}$

$$= \sqrt{2 l / (\sin 2 \alpha / 2 - k \cos^2 \alpha) g}$$

(using Eq. (1)).

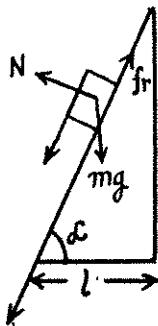
$$\frac{d \left( \frac{\sin 2 \alpha}{2} - k \cos^2 \alpha \right)}{d \alpha} = 0$$

for  $t_{\min}$ ,

i.e.  $\frac{2 \cos 2 \alpha}{2} + 2 k \cos \alpha \sin \alpha = 0$

or,  $\tan 2 \alpha = -\frac{1}{k} \Rightarrow \alpha = 49^\circ$

and putting the values of  $\alpha$ ,  $k$  and  $l$  in Eq. (2) we get  $t_{\min} = 1s$ .



**1.67** Let us fix the  $x$ - $y$  co-ordinate system to the wedge, taking the  $x$ -axis up, along the incline and the  $y$ -axis perpendicular to it (Fig.).

Now, we draw the free body diagram for the bar.

Let us apply Newton's second law in projection form along  $x$  and  $y$  axis for the bar :

$$T \cos \beta - m g \sin \alpha - f_r = 0 \quad (1)$$

$$T \sin \beta + N - m g \cos \alpha = 0$$

$$\text{or, } N = m g \cos \alpha - T \sin \beta \quad (2)$$

But  $f_r = kN$  and using (2) in (1), we get

$$T = m g \sin \alpha + k m g \cos \alpha / (\cos \beta + k \sin \beta) \quad (3)$$

For  $T_{\min}$  the value of  $(\cos \beta + k \sin \beta)$  should be maximum

$$\text{So, } \frac{d(\cos \beta + k \sin \beta)}{d\beta} = 0 \quad \text{or} \quad \tan \beta = k$$

Putting this value of  $\beta$  in Eq. (3) we get,

$$T_{\min} = \frac{m g (\sin \alpha + k \cos \alpha)}{1 / \sqrt{1+k^2} + k^2 / \sqrt{1+k^2}} = \frac{m g (\sin \alpha + k \cos \alpha)}{\sqrt{1+k^2}}$$

- 1.68 First of all let us draw the free body diagram for the small body of mass  $m$  and indicate  $x$ -axis along the horizontal plane and  $y$ -axis, perpendicular to it, as shown in the figure. Let the block breaks off the plane at  $t = t_0$  i.e.  $N = 0$

$$\text{So, } N = m g - a t_0 \sin \alpha = 0$$

$$\text{or, } t_0 = \frac{m g}{a \sin \alpha} \quad (1)$$

From  $F_x = m w_x$ , for the body under investigation :

$m d v / dt = a t \cos \alpha$  ; Integrating within the limits for  $v(t)$

$$m \int_0^v dv_x = a \cos \alpha \int_0^t t dt \quad (\text{using Eq. 1})$$

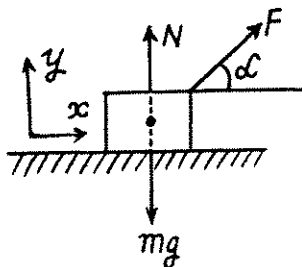
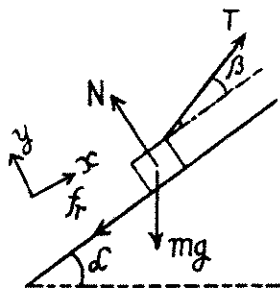
$$\text{So, } v = \frac{ds}{dt} = \frac{a \cos \alpha}{2m} t^2 \quad (2)$$

Integrating, Eqn. (2) for  $s(t)$

$$s = \frac{a \cos \alpha}{2m} \frac{t^3}{3} \quad (3)$$

Using the value of  $t = t_0$  from Eq. (1), into Eqs. (2) and (3)

$$v = \frac{m g^2 \cos \alpha}{2 a \sin^2 \alpha} \quad \text{and} \quad s = \frac{m^2 g^3 \cos \alpha}{6 a^2 \sin^3 \alpha}$$



- 1.69 Newton's second law of motion in projection form, along horizontal or  $x$ -axis i.e.  $F_x = m w_x$  gives.

$$F \cos(\alpha s) = m v \frac{dv}{ds} \quad (\text{as } \alpha = \alpha s)$$

$$\text{or, } F \cos(\alpha s) ds = m v dv$$

Integrating, over the limits for  $v(s)$

$$\frac{F}{m} \int_0^{\infty} \cos(\alpha s) ds = \frac{v^2}{2}$$

$$\text{or } v = \sqrt{\frac{2 F \sin \alpha}{m a}}$$

$$= \sqrt{2 g \sin \alpha / 3 a} \quad (\text{using } F = \frac{m g}{3})$$

which is the sought relationship.

- 1.70 From the Newton's second law in projection from :

For the bar,

$$T - 2 kmg = (2m) w \quad (1)$$

For the motor,

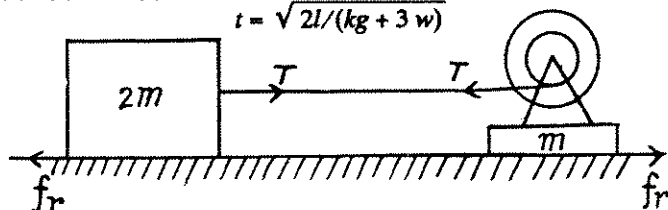
$$T - kmg = m w' \quad (2)$$

Now, from the equation of kinematics in the frame of bar or motor :

$$l = \frac{1}{2} (w + w') t^2 \quad (3)$$

From (1), (2) and (3) we get on eliminating  $T$  and  $w'$

$$t = \sqrt{2l / (kg + 3 w)}$$



- 1.71 Let us write Newton's second law in vector form  $\vec{F} = m \vec{w}$ , for both the blocks (in the frame of ground).

$$\vec{T} + m_1 \vec{g} = m_1 \vec{w}_1 \quad (1)$$

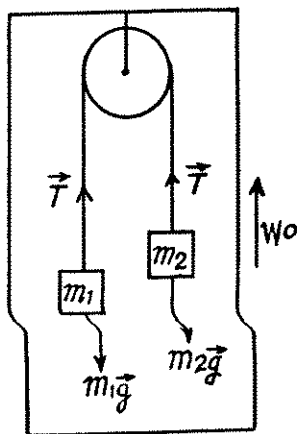
$$\vec{T} + m_2 \vec{g} = m_2 \vec{w}_2 \quad (2)$$

These two equations contain three unknown quantities  $\vec{w}_1$ ,  $\vec{w}_2$  and  $\vec{T}$ . The third equation is provided by the kinematic relationship between the accelerations :

$$\vec{w}_1 = \vec{w}_0 + \vec{w}', \quad \vec{w}_2 = \vec{w}_0 - \vec{w}' \quad (3)$$

where  $\vec{w}'$  is the acceleration of the mass  $m_1$  with respect to the pulley or elevator car.

Summing up termwise the left hand and the right-hand sides of these kinematical equations, we get



$$\vec{w}_1 + \vec{w}_2 = 2 \vec{w}_0 \quad (4)$$

The simultaneous solution of Eqs. (1), (2) and (4) yields

$$\vec{w}_1 = \frac{(m_1 - m_2) \vec{g} + 2 m_2 \vec{w}_0}{m_1 + m_2}$$

Using this result in Eq. (3), we get,

$$\vec{w} = \frac{m_1 - m_2}{m_1 + m_2} (\vec{g} - \vec{w}_0) \quad \text{and} \quad \vec{T} = \frac{2 m_1 m_2}{m_1 + m_2} (\vec{w}_0 - \vec{g})$$

Using the results in Eq. (3) we get  $\vec{w} = \frac{m_1 - m_2}{m_1 + m_2} (\vec{g} - \vec{w}_0)$

(b) obviously the force exerted by the pulley on the ceiling of the car

$$\vec{F} = -2 \vec{T} = \frac{4 m_1 m_2}{m_1 + m_2} (\vec{g} - \vec{w}_0)$$

*Note : one could also solve this problem in the frame of elevator car.*

- 1.72 Let us write Newton's second law for both, bar 1 and body 2 in terms of projection having taken the positive direction of  $x_1$  and  $x_2$  as shown in the figure and assuming that body 2 starts sliding, say, upward along the incline

$$T_1 - m_1 g \sin \alpha = m_1 w_1 \quad (1)$$

$$m_2 g - T_2 = m_2 w \quad (2)$$

For the pulley, moving in vertical direction from the equation  $F_x = m w_x$

$$2 T_2 - T_1 = (m_p) w_1 = 0$$

(as mass of the pulley  $m_p = 0$ )

$$\text{or} \quad T_1 = 2 T_2 \quad (3)$$

As the length of the threads are constant, the kinematical relationship of accelerations becomes

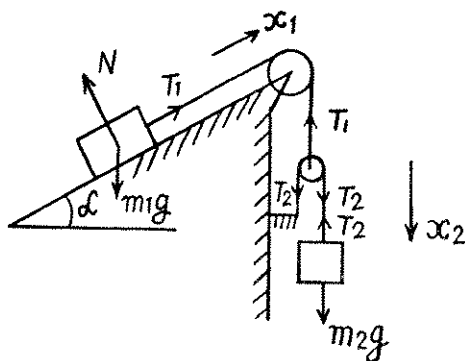
$$w = 2 w_1 \quad (4)$$

Simultaneous solutions of all these equations yields :

$$w = \frac{2 g \left( 2 \frac{m_2}{m_1} - \sin \alpha \right)}{\left( 4 \frac{m_2}{m_1} + 1 \right)} = \frac{2 g (2 \eta - \sin \alpha)}{(4 \eta + 1)}$$

As  $\eta > 1$ ,  $w$  is directed vertically downward, and hence in vector form

$$\vec{w} = \frac{2 \vec{g} (2 \eta - \sin \alpha)}{4 \eta + 1}$$



- 1.73 Let us write Newton's second law for masses  $m_1$  and  $m_2$  and moving pulley in vertical direction along positive  $x$  - axis (Fig.) :

$$m_1 g - T = m_1 w_{1x} \quad (1)$$

$$m_2 g - T = m_2 w_{2x} \quad (2)$$

$$T_1 - 2T = 0 \text{ (as } m = 0 \text{)}$$

$$\text{or} \quad T_1 = 2T \quad (3)$$

Again using Newton's second law in projection form for mass  $m_0$  along positive  $x_1$  direction (Fig.), we get

$$T_1 = m_0 w_0 \quad (4)$$

The kinematical relationship between the accelerations of masses gives in terms of projection on the  $x$  - axis

$$w_{1x} + w_{2x} = 2 w_0 \quad (5)$$

Simultaneous solution of the obtained five equations yields :

$$w_1 = \frac{[4 m_1 m_2 + m_0 (m_1 - m_2)] g}{4 m_1 m_2 + m_0 (m_1 + m_2)}$$

In vector form

$$\vec{w}_1 = \frac{[4 m_1 m_2 + m_0 (m_1 - m_2)] \vec{g}}{4 m_1 m_2 + m_0 (m_1 + m_2)}$$

- 1.74 As the thread is not tied with  $m$ , so if there were no friction between the thread and the ball  $m$ , the tension in the thread would be zero and as a result both bodies will have free fall motion. Obviously in the given problem it is the friction force exerted by the ball on the thread, which becomes the tension in the thread. From the condition or language of the problem  $w_M > w_m$  and as both are directed downward so, relative acceleration of  $M = w_M - w_m$  and is directed downward. Kinematical equation for the ball in the frame of rod in projection form along upward direction gives :

$$l = \frac{1}{2} (w_M - w_m) t^2 \quad (1)$$

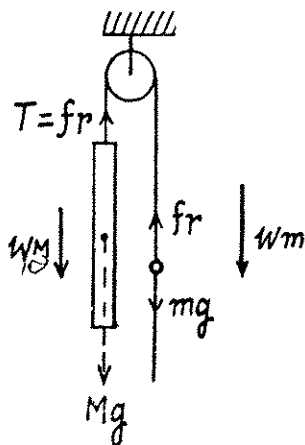
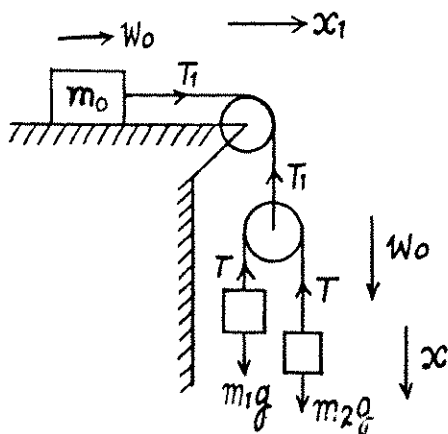
Newton's second law in projection form along vertically down direction for both, rod and ball gives,

$$Mg - fr = M w_M \quad (2)$$

$$mg - fr = m w_m \quad (3)$$

Multiplying Eq. (2) by  $m$  and Eq. (3) by  $M$  and then subtracting Eq. (3) from (2) and after using Eq. (1) we get

$$fr = \frac{2 l M m}{(M - m) t^2}$$



1.75 Suppose, the ball goes up with acceleration  $w_1$  and the rod comes down with the acceleration  $w_2$ .

As the length of the thread is constant,  $2w_1 = w_2$  (1)

From Newton's second law in projection form along vertically upward for the ball and vertically downward for the rod respectively gives,

$$T - mg = mw_1 \quad (2)$$

$$\text{and } Mg - T' = Mw_2 \quad (3)$$

$$\text{but } T = 2T' \quad (\text{because pulley is massless}) \quad (4)$$

From Eqs. (1), (2), (3) and (4)

$$w_1 = \frac{(2M - m)g}{m + 4M} = \frac{(2 - \eta)g}{\eta + 4} \quad (\text{in upward direction})$$

$$\text{and } w_2 = \frac{2(2 - \eta)g}{(\eta + 4)} \quad (\text{downwards})$$

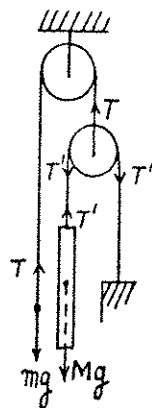
From kinematical equation in projection form, we get

$$l = \frac{1}{2}(w_1 + w_2)t^2$$

as,  $w_1$  and  $w_2$  are in the opposite direction.

Putting the values of  $w_1$  and  $w_2$ , the sought time becomes

$$t = \sqrt{2l(\eta + 4) / 3(2 - \eta)g} = 1.4 \text{ s}$$



1.76 Using Newton's second law in projection form along  $x$ -axis for the body 1 and along negative  $x$ -axis for the body 2 respectively, we get

$$m_1g - T_1 = m_1w_1 \quad (1)$$

$$T_2 - m_2g = m_2w_2 \quad (2)$$

For the pulley lowering in downward direction from Newton's law along  $x$  axis,

$$T_1 - 2T_2 = 0 \quad (\text{as pulley is massless})$$

$$\text{or, } T_1 = 2T_2 \quad (3)$$

As the length of the thread is constant so,

$$w_2 = 2w_1 \quad (4)$$

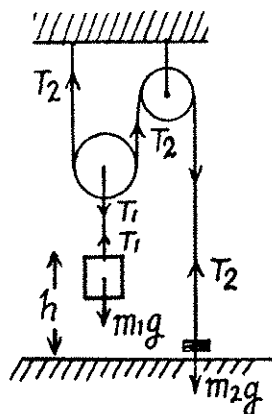
The simultaneous solution of above equations yields,

$$w_2 = \frac{2(m_1 - 2m_2)g}{4m_2 + m_1} = \frac{2(\eta - 2)}{\eta + 4} \quad (\text{as } \frac{m_1}{m_2} = \eta) \quad (5)$$

Obviously during the time interval in which the body 1 comes to the horizontal floor covering the distance  $h$ , the body 2 moves upward the distance  $2h$ . At the moment when the body 2 is at the height  $2h$  from the floor its velocity is given by the expression :

$$v_2^2 = 2w_2(2h) = 2 \left[ \frac{2(\eta - 2)g}{\eta + 4} \right] 2h = \frac{8h(\eta - 2)g}{\eta + 4}$$

After the body  $m_1$  touches the floor the thread becomes slack or the tension in the thread zero, thus as a result body 2 is only under gravity for its subsequent motion.



Owing to the velocity  $v_2$  at that moment or at the height  $2h$  from the floor, the body 2 further goes up under gravity by the distance,

$$h' = \frac{v_2^2}{2g} = \frac{4h(\eta - 2)}{\eta + 4}$$

Thus the sought maximum height attained by the body 2 :

$$H = 2h + h' = 2h + \frac{4h(\eta - 2)}{(\eta + 4)} = \frac{6\eta h}{\eta + 4}$$

- 1.77 Let us draw free body diagram of each body, i.e. of rod  $A$  and of wedge  $B$  and also draw the kinematical diagram for accelerations, after analysing the directions of motion of  $A$  and  $B$ . Kinematical relationship of accelerations is :

$$\tan \alpha = \frac{w_A}{w_B} \quad (1)$$

Let us write Newton's second law for both bodies in terms of projections having taken positive directions of  $y$  and  $x$  axes as shown in the figure.

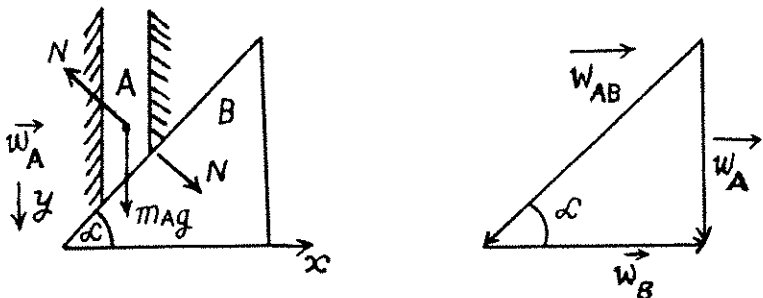
$$m_A g - N \cos \alpha = m_A w_A \quad (2)$$

and 
$$N \sin \alpha = m_B w_B \quad (3)$$

Simultaneous solution of (1), (2) and (3) yields :

$$w_A = \frac{m_A g \sin \alpha}{m_A \sin \alpha + m_B \cot \alpha \cos \alpha} = \frac{g}{(1 + \eta \cot^2 \alpha)} \text{ and}$$

$$w_B = \frac{w_A}{\tan \alpha} = \frac{g}{(\tan \alpha + \eta \cot \alpha)}$$



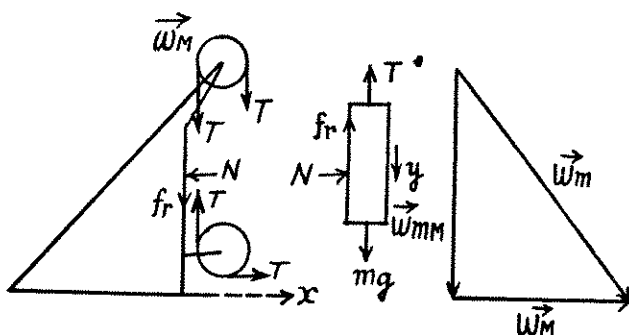
**Note :** We may also solve this problem using conservation of mechanical energy instead of Newton's second law.

- 1.78 Let us draw free body diagram of each body and fix the coordinate system, as shown in the figure. After analysing the motion of  $M$  and  $m$  on the basis of force diagrams, let us draw the kinematical diagram for accelerations (Fig.).

As the length of threads are constant so,

$ds_{mM} = ds_M$  and as  $\vec{v}_{mM}$  and  $\vec{v}_M$  do not change their directions that why

$$\begin{aligned} |\vec{w}_{mM}| &= |\vec{w}_M| = w \text{ (say) and} \\ \vec{w}_{mM} \uparrow \uparrow \vec{v}_M &\text{ and } \vec{w}_M \uparrow \uparrow \vec{v}_M \end{aligned}$$



$$\text{As } \vec{w}_m = \vec{w}_{mM} + \vec{w}_M$$

so, from the triangle law of vector addition

$$w_m = \sqrt{2} w \quad (1)$$

From the Eq.  $F_x = m w_x$ , for the wedge and block :

$$T - N = M w, \quad (2)$$

and

$$N = m w \quad (3)$$

Now, from the Eq.  $F_y = m w_y$ , for the block

$$mg - T - kN = m w \quad (4)$$

Simultaneous solution of Eqs. (2), (3) and (4) yields :

$$w = \frac{mg}{(km + 2m + M)} = \frac{g}{(k + 2 + M/m)}$$

Hence using Eq. (1)

$$w_m = \frac{g\sqrt{2}}{(2 + k + M/m)}$$

- 1.79 Bodies 1 and 2 will remain at rest with respect to bar A for  $w_{\min} \leq w \leq w_{\max}$ , where  $w_{\min}$  is the sought minimum acceleration of the bar. Beyond these limits there will be a relative motion between bar and the bodies. For  $0 \leq w \leq w_{\min}$ , the tendency of body 1 in relation to the bar A is to move towards right and is in the opposite sense for  $w \geq w_{\max}$ . On the basis of above argument the static friction on 2 by A is directed upward and on 1 by A is directed towards left for the purpose of calculating  $w_{\min}$ .

Let us write Newton's second law for bodies 1 and 2 in terms of projection along positive x - axis (Fig.).

$$T - fr_1 = m w \quad \text{or, } fr_1 = T - mw \quad (1)$$

$$N_2 = mw \quad (2)$$

As body 2 has no acceleration in vertical direction, so

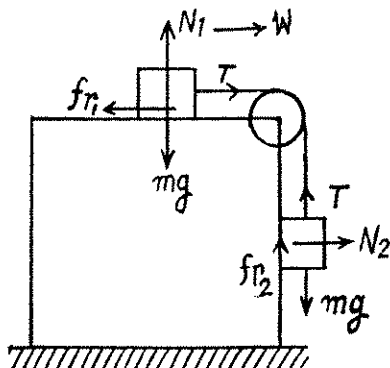
$$fr_2 = mg - T \quad (3)$$

From (1) and (3)

$$(fr_1 + fr_2) = m(g - w) \quad (4)$$

$$\text{But } fr_1 + fr_2 \leq k(N_1 + N_2)$$

$$\text{or } fr_1 + fr_2 \leq k(mg + mw) \quad (5)$$





From (4) and (5)

$$m(g - w) \leq mk(g + w), \text{ or } w \geq \frac{g(1-k)}{(1+k)}$$

Hence

$$w_{\min} = \frac{g(1-k)}{(1+k)}$$

- 1.80 On the basis of the initial argument of the solution of 1.79, the tendency of bar 2 with respect to 1 will be to move up along the plane.

Let us fix  $(x-y)$  coordinate system in the frame of ground as shown in the figure.

From second law of motion in projection form along  $y$  and  $x$  axes :

$$mg \cos \alpha - N = mw \sin \alpha$$

$$\text{or, } N = m(g \cos \alpha - w \sin \alpha) \quad (1)$$

$$mg \sin \alpha + fr = mw \cos \alpha$$

$$\text{or, } fr = m(w \cos \alpha - g \sin \alpha) \quad (2)$$

but  $fr \leq kN$ , so from (1) and (2)

$$(w \cos \alpha - g \sin \alpha) \leq k(g \cos \alpha + w \sin \alpha)$$

$$\text{or, } w(\cos \alpha - k \sin \alpha) \leq g(k \cos \alpha + \sin \alpha)$$

$$\text{or, } w \leq g \frac{(\cos \alpha + \sin \alpha)}{\cos \alpha - k \sin \alpha},$$

So, the sought maximum acceleration of the wedge :

$$w_{\max} = \frac{(k \cos \alpha + \sin \alpha)g}{\cos \alpha - k \sin \alpha} = \frac{(k \cot \alpha + 1)g}{\cot \alpha - k} \text{ where } \cot \alpha > k$$

- 1.81 Let us draw the force diagram of each body, and on this basis we observe that the prism moves towards right say with an acceleration  $w_1$  and the bar 2 of mass  $m_2$  moves down the plane with respect to 1, say with acceleration  $w_{21}$ , then,  $\vec{w}_2 = \vec{w}_{21} + \vec{w}_1$  (Fig.)

Let us write Newton's second law for both bodies in projection form along positive  $y_2$  and  $x_1$  axes as shown in the Fig.

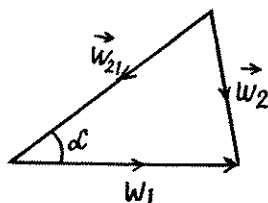
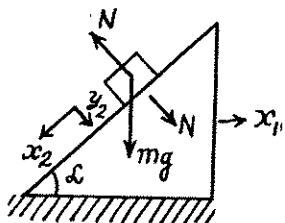
$$m_2 g \cos \alpha - N = m_2 w_{2(y_2)} = m_2 [w_{21(y_2)} + w_{1(y_2)}] = m_2 [0 + w_1 \sin \alpha]$$

$$\text{or, } m_2 g \cos \alpha - N = m_2 w_1 \sin \alpha \quad (1)$$

$$\text{and } N \sin \alpha = m_1 w_1 \quad (2)$$

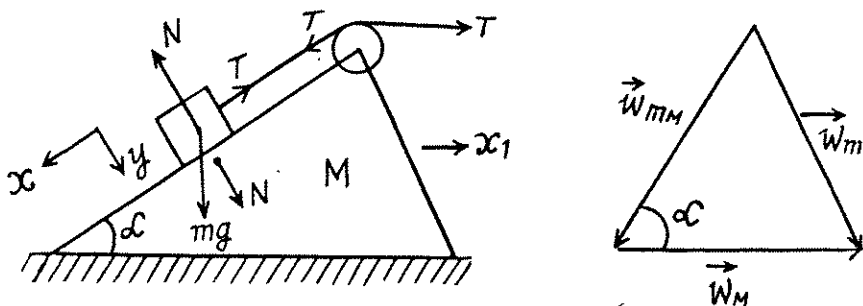
Solving (1) and (2), we get

$$w_1 = \frac{m_2 g \sin \alpha \cos \alpha}{m_1 + m_2 \sin^2 \alpha} = \frac{g \sin \alpha \cos \alpha}{(m_1/m_2) + \sin^2 \alpha}$$



- 1.82 To analyse the kinematic relations between the bodies, sketch the force diagram of each body as shown in the figure.

On the basis of force diagram, it is obvious that the wedge  $M$  will move towards right and the block will move down along the wedge. As the length of the thread is constant, the distance travelled by the block on the wedge must be equal to the distance travelled by the wedge on the floor. Hence  $ds_{mM} = ds_M$ . As  $\vec{v}_{mM}$  and  $\vec{v}_M$  do not change their directions and acceleration that's why  $\vec{w}_{mM} \uparrow \uparrow \vec{v}_{mM}$  and  $\vec{w}_M \uparrow \uparrow \vec{v}_M$  and  $w_{mM} = w_M = w$  (say) and accordingly the diagram of kinematical dependence is shown in figure.



As  $\vec{w}_m = \vec{w}_{mM} + \vec{w}_M$ , so from triangle law of vector addition.

$$w_m = \sqrt{w_M^2 + w_{mM}^2 - 2 w_{mM} w_M \cos \alpha} = w \sqrt{2(1 - \cos \alpha)} \quad (1)$$

From  $F_x = m w_x$ , (for the wedge),

$$T = T \cos \alpha + N \sin \alpha = M w \quad (2)$$

For the bar  $m$  let us fix  $(x - y)$  coordinate system in the frame of ground Newton's law in projection form along  $x$  and  $y$  axes (Fig.) gives

$$\begin{aligned} mg \sin \alpha - T &= m w_{m(x)} = m [w_{mM(x)} + w_{M(x)}] \\ &= m [w_{mM} + w_M \cos (\pi - \alpha)] = m w (1 - \cos \alpha) \end{aligned} \quad (3)$$

$$m g \cos \alpha - N = m w_{m(y)} = m [w_{mM(y)} + w_{M(y)}] = m [0 + w \sin \alpha] \quad (4)$$

Solving the above Eqs. simultaneously, we get

$$w = \frac{m g \sin \alpha}{M + 2m (1 - \cos \alpha)}$$

**Note :** We can study the motion of the block  $m$  in the frame of wedge also, alternately we may solve this problem using conservation of mechanical energy.

- 1.83 Let us sketch the diagram for the motion of the particle of mass  $m$  along the circle of radius  $R$  and indicate  $x$  and  $y$  axis, as shown in the figure.

(a) For the particle, change in momentum  $\Delta \vec{p} = m \vec{v}(-\vec{i}) - m \vec{v}(\vec{j})$

so,  $|\Delta \vec{p}| = \sqrt{2} m v$

and time taken in describing quarter of the circle,

$$\Delta t = \frac{\pi R}{2v}$$

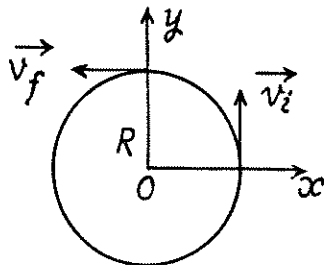
$$\text{Hence, } \langle \vec{F} \rangle = \frac{|\Delta \vec{p}|}{\Delta t} = \frac{\sqrt{2}mv}{\pi R/2v} = \frac{2\sqrt{2}mv^2}{\pi R}$$

(b) In this case

$$\vec{p}_i = 0 \text{ and } \vec{p}_f = m\omega_i t(-\vec{i}),$$

$$\text{so } |\Delta \vec{p}| = m\omega_i t$$

$$\text{Hence, } |\langle \vec{F} \rangle| = \frac{|\Delta \vec{p}|}{t} = m\omega_i$$



1.84 While moving in a loop, normal reaction exerted by the flyer on the loop at different points and uncompensated weight if any contribute to the weight of flyer at those points.

(a) When the aircraft is at the lowermost point, Newton's second law of motion in projection form  $F_n = m\omega_n$  gives

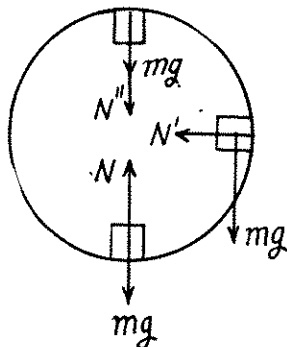
$$N - mg = \frac{mv^2}{R}$$

$$\text{or, } N = mg + \frac{mv^2}{R} = 2.09 \text{ kN}$$

(b) When it is at the upper most point, again from  $F_n = m\omega_n$  we get

$$N'' + mg = \frac{mv^2}{R}$$

$$N'' = \frac{mv^2}{R} - mg = 0.7 \text{ kN}$$



(c) When the aircraft is at the middle point of the loop, again from  $F_n = m\omega_n$

$$N' = \frac{mv^2}{R} = 1.4 \text{ kN}$$

The uncompensated weight is  $mg$ . Thus effective weight  $= \sqrt{N'^2 + m^2 g^2} = 1.56 \text{ kN}$  acts obliquely.

1.85 Let us depict the forces acting on the small sphere  $m$ , (at an arbitrary position when the thread makes an angle  $\theta$  from the vertical) and write equation  $\vec{F} = m\vec{w}$  via projection on the unit vectors  $\hat{u}_t$  and  $\hat{u}_n$ . From  $F_t = m\omega_t$ , we have

$$\begin{aligned} mg \sin \theta &= m \frac{dv}{dt} \\ &= m \frac{v dv}{ds} = m \frac{v dv}{l(-d\theta)} \end{aligned}$$

(as vertical is reference line of angular position)

or  $v dv = -gl \sin \theta d\theta$

Integrating both the sides :

$$\int_0^v v dv = -gl \int_{\pi/2}^{\theta} \sin \theta d\theta$$

or, 
$$\frac{v^2}{2} = gl \cos \theta$$

Hence  $\frac{v^2}{l} = 2g \cos \theta = \omega_n^2$  (1)

(Eq. (1) can be easily obtained by the conservation of mechanical energy).

From  $F_n = m \omega_n^2$

$$T - mg \cos \theta = \frac{mv^2}{l}$$

Using (1) we have

$$T = 3mg \cos \theta \quad (2)$$

Again from the Eq.  $F_t = m \omega_t^2$ :

$$mg \sin \theta = m \omega_t^2 \text{ or } \omega_t^2 = g \sin \theta \quad (3)$$

Hence  $\omega = \sqrt{\omega_t^2 + \omega_n^2} = \sqrt{(g \sin \theta)^2 + (2g \cos \theta)^2}$  (using 1 and 3)

$$= g \sqrt{1 + 3 \cos^2 \theta}$$

(b) Vertical component of velocity,  $v_y = v \sin \theta$

So,  $v_y^2 = v^2 \sin^2 \theta = 2gl \cos \theta \sin^2 \theta$  (using 1)

For maximum  $v_y$  or  $v_y^2$ ,  $\frac{d(\cos \theta \sin^2 \theta)}{d\theta} = 0$

which yields  $\cos \theta = \frac{1}{\sqrt{3}}$

Therefore from (2)  $T = 3mg \frac{1}{\sqrt{3}} = \sqrt{3} mg$

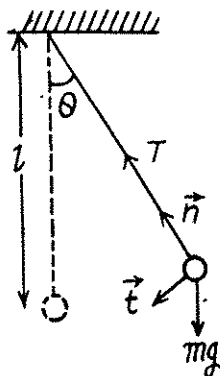
(c) We have  $\vec{\omega} = \omega_t \hat{u}_t + \omega_n \hat{u}_n$  thus  $\omega_y = \omega_{t(y)} + \omega_{n(y)}$

But in accordance with the problem  $\omega_y = 0$

So,  $\omega_{t(y)} + \omega_{n(y)} = 0$

or,  $g \sin \theta \sin \theta + 2g \cos^2 \theta (-\cos \theta) = 0$

or,  $\cos \theta = \frac{1}{\sqrt{3}} \text{ or } \theta = 54.7^\circ$



- 1.86 The ball has only normal acceleration at the lowest position and only tangential acceleration at any of the extreme position. Let  $v$  be the speed of the ball at its lowest position and  $l$  be the length of the thread, then according to the problem

$$\frac{v^2}{l} = g \sin \alpha \quad (1)$$

where  $\alpha$  is the maximum deflection angle

From Newton's law in projection form :  $F_t = mw_t$

$$-mg \sin \theta = mv \frac{dv}{l d\theta}$$

$$\text{or, } -gl \sin \theta d\theta = v dv$$

On integrating both the sides within their limits.

$$-gl \int_0^\alpha \sin \theta d\theta = \int_v^0 v dv$$

$$\text{or, } v^2 = 2gl (1 - \cos \alpha) \quad (2)$$

Note : Eq. (2) can easily be obtained by the conservation of mechanical energy of the ball in the uniform field of gravity.

From Eqs. (1) and (2) with  $\theta = \alpha$

$$2gl (1 - \cos \alpha) = lg \cos \alpha$$

$$\text{or, } \cos \alpha = \frac{2}{3} \text{ so, } \alpha = 53^\circ$$

- 1.87 Let us depict the forces acting on the body  $A$  (which are the force of gravity  $m\vec{g}$  and the normal reaction  $\vec{N}$ ) and write equation  $\vec{F} = m\vec{w}$  via projection on the unit vectors  $\hat{u}_t$  and  $\hat{u}_n$  (Fig.)

From  $F_t = mw_t$

$$\begin{aligned} mg \sin \theta &= m \frac{dv}{dt} \\ &= m \frac{v dv}{ds} = m \frac{v dv}{R d\theta} \end{aligned}$$

$$\text{or, } gR \sin \theta d\theta = v dv$$

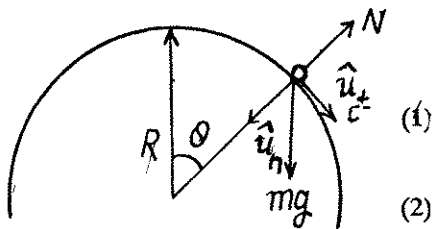
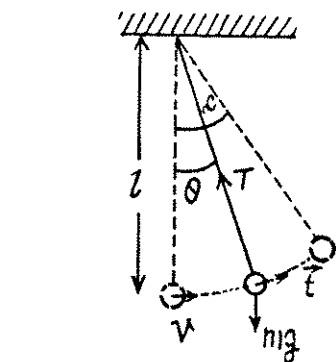
Integrating both side for obtaining  $v(\theta)$

$$\int_0^\theta gR \sin \theta d\theta = \int_v^0 v dv$$

$$\text{or, } v^2 = 2gR (1 - \cos \theta)$$

From  $F_n = mw_n$

$$mg \cos \theta - N = m \frac{v^2}{R}$$



At the moment the body loses contact with the surface,  $N = 0$  and therefore the Eq. (2) becomes

$$v^2 = gR \cos \theta \quad (3)$$

where  $v$  and  $\theta$  correspond to the moment when the body loses contact with the surface.

Solving Eqs. (1) and (3) we obtain  $\cos \theta = \frac{2}{3}$  or,  $\theta = \cos^{-1}(2/3)$  and  $v = \sqrt{2gR/3}$ .

- 1.88 At first draw the free body diagram of the device as, shown. The forces, acting on the sleeve are its weight, acting vertically downward, spring force, along the length of the spring and normal reaction by the rod, perpendicular to its length.

Let  $F$  be the spring force, and  $\Delta l$  be the elongation.

From,  $F_n = m\omega_n^2 r$ :

$$N \sin \theta + F \cos \theta = m\omega^2 r \quad (1)$$

where  $r \cos \theta = (l_0 + \Delta l)$ .

Similarly from  $F_t = m\omega_t^2 r$ ,

$$N \cos \theta - F \sin \theta = 0 \quad \text{or,} \quad N = F \sin \theta / \cos \theta \quad (2)$$

From (1) and (2)

$$\begin{aligned} F (\sin \theta / \cos \theta) \cdot \sin \theta + F \cos \theta &= m\omega^2 r \\ &= m\omega^2 (l_0 + \Delta l) / \cos \theta \end{aligned}$$

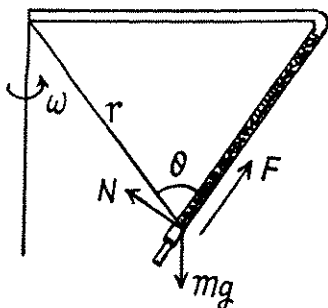
On putting  $F = \kappa \Delta l$ ,

$$\kappa \Delta l \sin^2 \theta + \kappa \Delta l \cos^2 \theta = m\omega^2 (l_0 + \Delta l)$$

on solving, we get,

$$\Delta l = m\omega^2 \frac{l_0}{\kappa - m\omega^2} = \frac{l_0}{(\kappa/m\omega^2 - 1)}$$

and it is independent of the direction of rotation.



- 1.89 According to the question, the cyclist moves along the circular path and the centripetal force is provided by the frictional force. Thus from the equation  $F_n = m\omega_n^2 r$

$$fr = \frac{mv^2}{r} \quad \text{or} \quad kmg = \frac{mv^2}{r}$$

$$\text{or} \quad k_0 \left(1 - \frac{r}{R}\right) g = \frac{v^2}{r} \quad \text{or} \quad v^2 = k_0 \left(r - \frac{r^2}{R}\right) g \quad (1)$$

$$\text{For } v_{\max}, \text{ we should have } \frac{d\left(r - \frac{r^2}{R}\right)}{dr} = 0$$

$$\text{or,} \quad 1 - \frac{2r}{R} = 0, \quad \text{so } r = R/2$$

$$\text{Hence } v_{\max} = \frac{1}{2} \sqrt{k_0 g R}$$

- 1.90 As initial velocity is zero thus

$$v^2 = 2w_t s \quad (1)$$

As  $w_t > 0$  the speed of the car increases with time or distance. Till the moment, sliding starts, the static friction provides the required centripetal acceleration to the car.

Thus

$$fr = mw, \quad \text{but } fr \leq kmg$$

So,  $w^2 \leq k^2 g^2$  or,  $w_i^2 + \frac{v^2}{R} \leq k^2 g^2$

or,  $v^2 \leq (k^2 g^2 - w_i^2) R$

Hence  $v_{\max} = \sqrt{(k^2 g^2 - w_i^2) R}$

so, from Eqn. (1), the sought distance  $s = \frac{v_{\max}^2}{2 w_i} = \frac{1}{2} \sqrt{\left(\frac{kg}{w_i}\right)^2 - 1} = 60 \text{ m.}$

- 1.91 Since the car follows a curve, so the maximum velocity at which it can ride without sliding at the point of minimum radius of curvature is the sought velocity and obviously in this case the static friction between the car and the road is limiting.

Hence from the equation  $F_n = mw$

$$kmg \geq \frac{m v^2}{R} \quad \text{or} \quad v \leq \sqrt{k R g}$$

so

$$v_{\max} = \sqrt{k R_{\min} g} \quad (1)$$

We know that, radius of curvature for a curve at any point  $(x, y)$  is given as,

$$R = \left| \frac{[1 + (dy/dx)^2]^{3/2}}{(d^2 y) / dx^2} \right| \quad (2)$$

For the given curve,

$$\frac{dy}{dx} = \frac{a}{\alpha} \cos\left(\frac{x}{\alpha}\right) \quad \text{and} \quad \frac{d^2 y}{dx^2} = \frac{-a}{\alpha^2} \sin \frac{x}{\alpha}$$

Substituting this value in (2) we get,

$$R = \frac{[1 + (a^2/\alpha^2) \cos^2(x/\alpha)]^{3/2}}{(a/\alpha^2) \sin(x/\alpha)}$$

For the minimum  $R$ ,  $\frac{x}{\alpha} = \frac{\pi}{2}$

and therefore, corresponding radius of curvature

$$R_{\min} = \frac{\alpha^2}{a} \quad (3)$$

Hence from (1) and (2)

$$v_{\max} = \alpha \sqrt{kg/a}$$

- 1.92 The sought tensile stress acts on each element of the chain. Hence divide the chain into small, similar elements so that each element may be assumed as a particle. We consider one such element of mass  $dm$ , which subtends angle  $d\alpha$  at the centre. The chain moves along a circle of known radius  $R$  with a known angular speed  $\omega$  and certain forces act on it. We have to find one of these forces.

From Newton's second law in projection form,  $F_x = mw_x$  we get

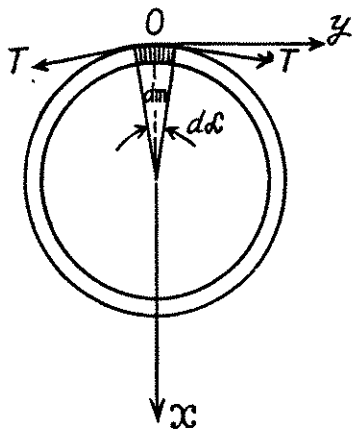
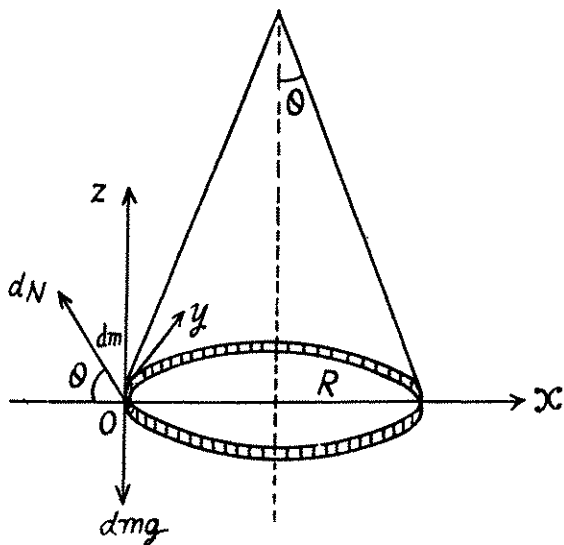
$$2 T \sin(d\alpha/2) - dN \cos \theta = dm \omega^2 R$$

and from  $F_z = mw_z$  we get

$$dN \sin \theta = g dm$$

Then putting  $dm = m d\alpha / 2\pi$  and  $\sin(d\alpha/2) = d\alpha/2$  and solving, we get,

$$T = \frac{m(\omega^2 R + g \cot \theta)}{2\pi}$$



1.93 Let us consider a small element of the thread and draw free body diagram for this element.

(a) Applying Newton's second law of motion in projection form,  $F_n = m\omega_n^2 R$  for this element,

$$(T + dT) \sin(d\theta/2) + T \sin(d\theta/2) - dN = dm \omega^2 R = 0$$

$$\text{or, } 2T \sin(d\theta/2) = dN, \text{ [neglecting the term } (dT \sin d\theta/2) \text{]}$$

$$\text{or, } T d\theta = dN, \text{ as } \sin \frac{d\theta}{2} = \frac{d\theta}{2} \quad (1)$$

$$\text{Also, } dfr = k dN = (T + dT) - T = dT \quad (2)$$

From Eqs. (1) and (2),

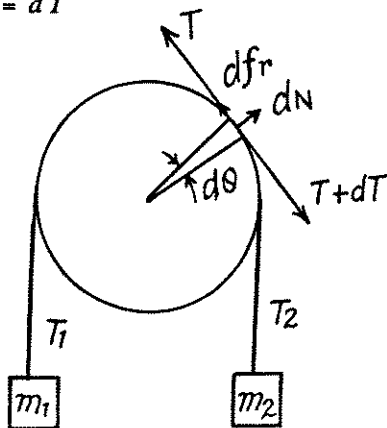
$$k T d\theta = dT \text{ or } \frac{dT}{T} = k d\theta$$

In this case  $Q = \pi$  so,

$$\text{or, } \ln \frac{T_2}{T_1} = k \pi \quad (3)$$

$$\text{So, } k = \frac{1}{\pi} \ln \frac{T_2}{T_1} = \frac{1}{\pi} \ln \eta_0$$

$$\text{as } \frac{T_2}{T_1} = \frac{m_2 g}{m_1 g} = \frac{m_2}{m_1} = \eta_0$$



(b) When  $\frac{m_2}{m_1} = \eta$ , which is greater than  $\eta_0$ , the blocks will move with same value of acceleration. (say  $w$ ) and clearly  $m_2$  moves downward. From Newton's second law in projection form (downward for  $m_2$  and upward for  $m_1$ ) we get :

$$m_2 g - T_2 = m_2 w \quad (4)$$

$$\text{and } T_1 - m_1 g = m_1 w \quad (5)$$



Also 
$$\frac{T_2}{T_1} = \eta_0 \quad (6)$$

Simultaneous solution of Eqs. (4), (5) and (6) yields :

$$w = \frac{(m_2 - \eta_0 m_1)g}{(m_2 + \eta_0 m_1)} = \frac{(\eta - \eta_0)}{(\eta + \eta_0)}g \left( \text{as } \frac{m_2}{m_1} = \eta \right)$$

- 1.94** The force with which the cylinder wall acts on the particle will provide centripetal force necessary for the motion of the particle, and since there is no acceleration acting in the horizontal direction, horizontal component of the velocity will remain constant throughout the motion.

So 
$$v_x = v_0 \cos \alpha$$

Using,  $F_n = m w_n$ , for the particle of mass  $m$ ,

$$N = \frac{m v_x^2}{R} = \frac{m v_0^2 \cos^2 \alpha}{R},$$

which is the required normal force.

- 1.95** Obviously the radius vector describing the position of the particle relative to the origin of coordinate is

$$\vec{r} = x\vec{i} + y\vec{j} = a \sin \omega t \vec{i} + b \cos \omega t \vec{j}$$

Differentiating twice with respect the time :

$$\vec{w} = \frac{d^2 \vec{r}}{dt^2} = -\omega^2 (a \sin \omega t \vec{i} + b \cos \omega t \vec{j}) = -\omega^2 \vec{r} \quad (1)$$

Thus 
$$\vec{F} = m \vec{w} = -m \omega^2 \vec{r}$$

**1.96** (a) We have 
$$\Delta \vec{p} = \int \vec{F} dt$$

$$= \int_0^t m \vec{g} dt = m \vec{g} t \quad (1)$$

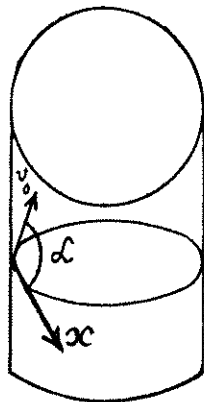
(b) Using the solution of problem 1.28 (b), the total time of motion,  $\tau = -\frac{2(\vec{v}_0 \cdot \vec{g})}{g^2}$

Hence using  $t = \tau$  in (1)

$$\begin{aligned} |\Delta \vec{p}| &= mg\tau \\ &= -2m(\vec{v}_0 \cdot \vec{g})/g \quad (\vec{v}_0 \cdot \vec{g} \text{ is -ve}) \end{aligned}$$

- 1.97** From the equation of the given time dependence force  $\vec{F} = \vec{a} t(\tau - t)$  at  $t = \tau$ , the force vanishes,

(a) Thus 
$$\Delta \vec{p} = \vec{p} = \int_0^\tau \vec{F} dt$$



or, 
$$\vec{p} = \int_0^{\tau} \vec{a} t (\tau - t) dt \frac{\vec{a} \tau^3}{6}$$

but 
$$\vec{p} = m \vec{v} \text{ so } \vec{v} = \frac{\vec{a} \tau^3}{6m}$$

(b) Again from the equation  $\vec{F} = m \vec{w}$

$$\vec{a} t (\tau - t) = m \frac{d\vec{v}}{dt}$$

or, 
$$\vec{a} (t \tau - t^2) dt = m d\vec{v}$$

Integrating within the limits for  $\vec{v}(t)$ ,

$$\int_0^t \vec{a} (t \tau - t^2) dt = m \int_0^{\vec{v}} d\vec{v}$$

or, 
$$\vec{v} = \frac{\vec{a}}{m} \left( \frac{\tau t^2}{2} - \frac{t^3}{3} \right) = \frac{\vec{a} t^2}{m} \left( \frac{\tau}{2} - \frac{t}{3} \right)$$

Thus 
$$v = \frac{a t^2}{m} \left( \frac{\tau}{2} - \frac{t}{3} \right) \text{ for } t \leq \tau$$

Hence distance covered during the time interval  $t = \tau$ ,

$$\begin{aligned} s &= \int_0^{\tau} v dt \\ &= \int_0^{\tau} \frac{a t^2}{m} \left( \frac{\tau}{2} - \frac{t}{3} \right) dt = \frac{a}{m} \frac{\tau^4}{12} \end{aligned}$$

1.98 We have  $F = F_0 \sin \omega t$

or 
$$m \frac{d\vec{v}}{dt} = \vec{F}_0 \sin \omega t \text{ or } m d\vec{v} = \vec{F}_0 \sin \omega t dt$$

On integrating,

$$m\vec{v} = \frac{-\vec{F}_0}{\omega} \cos \omega t + C, \text{ (where } C \text{ is integration constant)}$$

When  $t = 0, v = 0$ , so  $C = \frac{\vec{F}_0}{m\omega}$

Hence, 
$$\vec{v} = \frac{-\vec{F}_0}{m\omega} \cos \omega t + \frac{\vec{F}_0}{m\omega}$$

As  $|\cos \omega t| \leq 1$  so, 
$$v = \frac{F_0}{m\omega} (1 - \cos \omega t)$$

Thus

$$s = \int_0^t v \, dt$$

$$= \frac{F_0 t}{m \omega} - \frac{F_0 \sin \omega t}{m \omega^2} = \frac{F_0}{m \omega^2} (\omega t - \sin \omega t)$$

(Figure in the answer sheet).

1.99 According to the problem, the force acting on the particle of mass  $m$  is,  $\vec{F} = \vec{F}_0 \cos \omega t$

So, 
$$m \frac{d\vec{v}}{dt} = \vec{F}_0 \cos \omega t \quad \text{or} \quad d\vec{v} = \frac{\vec{F}_0}{m} \cos \omega t \, dt$$

Integrating, within the limits.

$$\int_0^{\vec{v}} d\vec{v} = \frac{\vec{F}_0}{m} \int_0^t \cos \omega t \, dt \quad \text{or} \quad \vec{v} = \frac{\vec{F}_0}{m \omega} \sin \omega t$$

It is clear from equation (1), that after starting at  $t = 0$ , the particle comes to rest for the first time at  $t = \frac{\pi}{\omega}$ .

From Eq. (1),  $v = |\vec{v}| = \frac{F_0}{m \omega} \sin \omega t$  for  $t \leq \frac{\pi}{\omega}$  (2)

Thus during the time interval  $t = \pi/\omega$ , the sought distance

$$s = \frac{F_0}{m \omega} \int_0^{\pi/\omega} \sin \omega t \, dt = \frac{2F}{m \omega^2}$$

From Eq. (1)

$$v_{\max} = \frac{F_0}{m \omega} \quad \text{as} \quad |\sin \omega t| \leq 1$$

1.100 (a) From the problem  $\vec{F} = -r\vec{v}$  so  $m \frac{d\vec{v}}{dt} = -r\vec{v}$

Thus 
$$m \frac{dv}{dt} = -rv \quad [\text{as } d\vec{v} \uparrow \downarrow \vec{v}]$$

or, 
$$\frac{dv}{v} = -\frac{r}{m} dt$$

On integrating 
$$\ln v = -\frac{r}{m} t + C$$

But at  $t = 0$ ,  $v = v_0$ , so,  $C = \ln v_0$

or, 
$$\ln \frac{v}{v_0} = -\frac{r}{m} t \quad \text{or,} \quad v = v_0 e^{-\frac{r}{m} t}$$

Thus for 
$$t \rightarrow \infty, v = 0$$

(b) We have  $m \frac{dv}{dt} = -rv$  so  $dv = -\frac{r}{m} ds$

Integrating within the given limits to obtain  $v(s)$ :

$$\text{or, } \int_{v_0}^v dv = -\frac{r}{m} \int_0^s ds \quad \text{or } v = v_0 - \frac{r}{m}s \quad (1)$$

Thus for  $v = 0, s = s_{\text{total}} = \frac{m v_0}{r}$

(c) Let we have  $\frac{m dv}{v} = -r dt$  or  $\frac{dv}{v} = -\frac{r}{m} dt$

$$\text{or, } \int_0^{v_0/\eta} \frac{dv}{v} = -\frac{r}{m} \int_0^t dt, \quad \text{or, } \ln \frac{v_0}{\eta v_0} = -\frac{r}{m} t$$

$$\text{So } t = \frac{-m \ln(1/\eta)}{r} = \frac{m \ln \eta}{r}$$

Now, average velocity over this time interval,

$$\langle v \rangle = \frac{\int_0^{m \ln \eta / r} v dt}{\int_0^{m \ln \eta / r} dt} = \frac{\int_0^{m \ln \eta / r} v_0 e^{-\frac{r}{m} t} dt}{\frac{m}{r} \ln \eta} = \frac{v_0 (\eta - 1)}{\eta \ln \eta}$$

1.101 According to the problem

$$m \frac{dv}{dt} = -k v^2 \quad \text{or, } m \frac{dv}{v^2} = -k dt$$

Integrating, withing the limits,

$$\int_{v_0}^v \frac{dv}{v^2} = -\frac{k}{m} \int_0^t dt \quad \text{or, } t = \frac{m}{k} \frac{(v_0 - v)}{v_0 v} \quad (1)$$

To find the value of  $k$ , rewrite

$$m v \frac{dv}{ds} = -k v^2 \quad \text{or, } \frac{dv}{v} = -\frac{k}{m} ds$$

On integrating

$$\int_{v_0}^v \frac{dv}{v} = -\frac{k}{m} \int_0^h ds$$

$$\text{So, } k = \frac{m}{h} \ln \frac{v_0}{v} \quad (2)$$

Putting the value of  $k$  from (2) in (1), we get

$$t = \frac{h (v_0 - v)}{v_0 v \ln \frac{v_0}{v}}$$

1.102 From Newton's second law for the bar in projection from,  $F_x = m w_x$  along  $x$  direction we get

$$mg \sin \alpha - kmg \cos \alpha = mw$$

$$\text{or, } v \frac{dv}{dx} = g \sin \alpha - ax g \cos \alpha, \text{ (as } k = ax),$$

$$\text{or, } v dv = (g \sin \alpha - ax g \cos \alpha) dx$$

$$\text{or, } \int_0^v v dv = g \int_0^x (\sin \alpha - x \cos \alpha) dx$$

$$\text{So, } \frac{v^2}{2} = g \left( \sin \alpha x - \frac{x^2}{2} a \cos \alpha \right) \quad (1)$$

From (1)  $v = 0$  at either

$$x = 0, \text{ or } x = \frac{2}{a} \tan \alpha$$

As the motion of the bar is unidirectional it stops after going through a distance of  $\frac{2}{a} \tan \alpha$ .

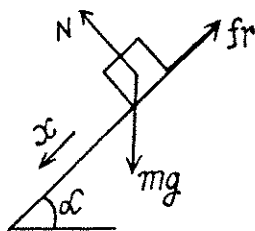
From (1), for  $v_{\max}$ ,

$$\frac{d}{dx} \left( \sin \alpha x - \frac{x^2}{2} a \cos \alpha \right) = 0, \text{ which yields } x = \frac{1}{a} \tan \alpha$$

Hence, the maximum velocity will be at the distance,  $x = \tan \alpha / a$

Putting this value of  $x$  in (1) the maximum velocity,

$$v_{\max} = \sqrt{\frac{g \sin \alpha \tan \alpha}{a}}$$



1.103 Since, the applied force is proportional to the time and the frictional force also exists, the motion does not start just after applying the force. The body starts its motion when  $F$  equals the limiting friction.

Let the motion start after time  $t_0$ , then

$$F = at_0 = kmg \text{ or, } t_0 = \frac{km g}{a}$$

So, for  $t \leq t_0$ , the body remains at rest and for  $t > t_0$  obviously

$$\frac{mdv}{dt} = a(t - t_0) \text{ or, } m dv = a(t - t_0) dt$$

Integrating, and noting  $v = 0$  at  $t = t_0$ , we have for  $t > t_0$

$$\int_0^v m dv = a \int_{t_0}^t (t - t_0) dt \text{ or } v = \frac{a}{2m} (t - t_0)^2$$

$$\text{Thus } s = \int v dt = \frac{a}{2m} \int_{t_0}^t (t - t_0)^2 dt = \frac{a}{6m} (t - t_0)^3$$

1.104 While going upward, from Newton's second law in vertical direction :

$$m \frac{v dv}{ds} = -(mg + kv^2) \quad \text{or} \quad \frac{v dv}{\left(g + \frac{kv^2}{m}\right)} = -ds$$

At the maximum height  $h$ , the speed  $v = 0$ , so

$$\int_{v_0}^0 \frac{v dv}{g + (kv^2/m)} = - \int_0^h ds$$

Integrating and solving, we get,

$$h = \frac{m}{2k} \ln \left( 1 + \frac{kv_0^2}{mg} \right) \quad (1)$$

When the body falls downward, the net force acting on the body in downward direction equals  $(mg - kv^2)$ ,

Hence net acceleration, in downward direction, according to second law of motion

$$\frac{v dv}{ds} = g - \frac{kv^2}{m} \quad \text{or,} \quad \frac{v dv}{g - \frac{kv^2}{m}} = ds$$

Thus

$$\int_0^{v'} \frac{v dv}{g - kv^2/m} = \int_0^h ds$$

Integrating and putting the value of  $h$  from (1), we get,

$$v' = v_0 / \sqrt{1 + kv_0^2/mg}.$$

1.105 Let us fix  $x - y$  co-ordinate system to the given plane, taking  $x$ -axis in the direction along which the force vector was oriented at the moment  $t = 0$ , then the fundamental equation of dynamics expressed via the projection on  $x$  and  $y$ -axes gives,

$$F \cos \omega t = m \frac{dv_x}{dt} \quad (1)$$

and

$$F \sin \omega t = m \frac{dv_y}{dt} \quad (2)$$

$$(a) \text{ Using the condition } v(0) = 0, \text{ we obtain } v_x = \frac{F}{m\omega} \sin \omega t \quad (3)$$

and

$$v_y = \frac{F}{m\omega} (1 - \cos \omega t) \quad (4)$$

Hence, 
$$v = \sqrt{v_x^2 + v_y^2} = \left( \frac{2F}{m\omega} \right) \left| \sin \left( \frac{\omega t}{2} \right) \right|$$

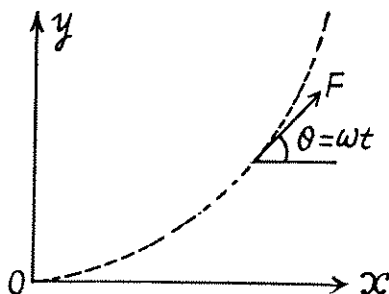
(b) It is seen from this that the velocity  $v$  turns into zero after the time interval  $\Delta t$ , which can be found from the relation,  $\omega \frac{\Delta t}{2} = \pi$ . Consequently,

the sought distance, is

$$s = \int_0^{\Delta t} v dt = \frac{8F}{m\omega^2}$$

Average velocity,  $\langle v \rangle = \frac{\int v dt}{\int dt}$

$$\text{So, } \langle v \rangle = \int_0^{2\pi/\omega} \frac{2F}{m\omega} \sin\left(\frac{\omega t}{2}\right) dt / (2\pi/\omega) = \frac{4F}{\pi m\omega}$$



- 1.106 The acceleration of the disc along the plane is determined by the projection of the force of gravity on this plane  $F_x = mg \sin \alpha$  and the friction force  $fr = kmg \cos \alpha$ . In our case  $k = \tan \alpha$  and therefore

$$fr = F_x = mg \sin \alpha$$

Let us find the projection of the acceleration on the direction of the tangent to the trajectory and on the  $x$ -axis:

$$m w_t = F_x \cos \varphi - fr = mg \sin \alpha (\cos \varphi - 1)$$

$$m w_x = F_x - fr \cos \varphi = mg \sin \alpha (1 - \cos \varphi)$$

It is seen from this that  $w_t = -w_x$ , which means that the velocity  $v$  and its projection  $v_x$  differ only by a constant value  $C$  which does not change with time, i.e.

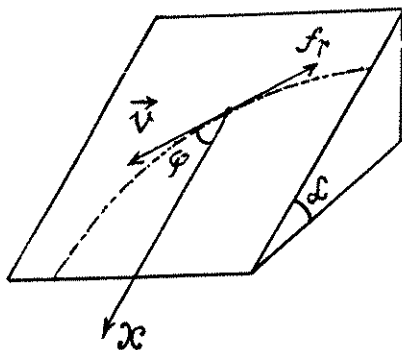
$$v = v_x + C,$$

where  $v_x = v \cos \varphi$ . The constant  $C$  is found from the initial condition  $v = v_0$ , whence

$$C = v_0 \text{ since } \varphi = \frac{\pi}{2} \text{ initially. Finally we obtain}$$

$$v = v_0 / (1 + \cos \varphi).$$

In the course of time  $\varphi \rightarrow 0$  and  $v \rightarrow v_0/2$ . (Motion then is unaccelerated.)



- 1.107 Let us consider an element of length  $ds$  at an angle  $\varphi$  from the vertical diameter. As the speed of this element is zero at initial instant of time, its centripetal acceleration is zero, and hence,  $dN - \lambda ds \cos \varphi = 0$ , where  $\lambda$  is the linear mass density of the chain. Let  $T$  and  $T + dT$  be the tension at the upper and the lower ends of  $ds$ . We have from,  $F_t = m w_t$ ,

$$(T + dT) + \lambda ds g \sin \varphi - T = \lambda ds w_t$$

or,

$$dT + \lambda R d\varphi g \sin \varphi = \lambda ds w_t$$

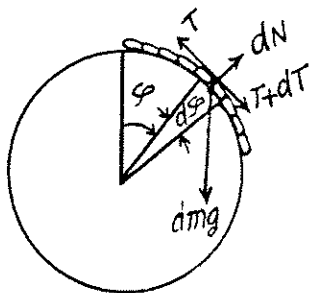
If we sum the above equation for all elements, the term  $\int dT = 0$  because there is no tension at the free ends, so

$$\lambda g R \int_0^{l/R} \sin \varphi d\varphi = \lambda w_t \int ds = \lambda l w_t$$

$$\text{Hence } w_t = \frac{gR}{l} \left( 1 - \cos \frac{l}{R} \right)$$

As  $w_n = a$  at initial moment

$$\text{So, } w = |w_t| = \frac{gR}{l} \left( 1 - \cos \frac{l}{R} \right)$$



- 1.108 In the problem, we require the velocity of the body, relative to the sphere, which itself moves with an acceleration  $w_0$  in horizontal direction (say towards left). Hence it is advisable to solve the problem in the frame of sphere (non-inertial frame).

At an arbitrary moment, when the body is at an angle  $\theta$  with the vertical, we sketch the force diagram for the body and write the second law of motion in projection form  $F_n = mw_n$

$$\text{or, } mg \cos \theta - N - mw_0 \sin \theta = \frac{mv^2}{R} \quad (1)$$

At the break off point,  $N = 0$ ,  $\theta = \theta_0$  and let  $v = v_0$ , so the Eq. (1) becomes,

$$\frac{v_0^2}{R} = g \cos \theta_0 - w_0 \sin \theta_0 \quad (2)$$

From,  $F_t = mw_t$

$$mg \sin \theta - mw_0 \cos \theta = m \frac{v dv}{ds} = m \frac{v dv}{R d\theta}$$

$$\text{or, } v dv = R (g \sin \theta + w_0 \cos \theta) d\theta$$

$$\text{Integrating, } \int_0^{v_0} v dv = \int_0^{\theta_0} R (g \sin \theta + w_0 \cos \theta) d\theta$$

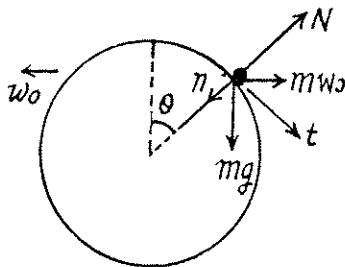
$$\frac{v_0^2}{2R} = g(1 - \cos \theta_0) + w_0 \sin \theta_0 \quad (3)$$

Note that the Eq. (3) can also be obtained by the work-energy theorem  $A = \Delta T$  (in the frame of sphere)

$$\text{therefore, } mgR(1 - \cos \theta_0) + mw_0 R \sin \theta_0 = \frac{1}{2} mv_0^2$$

[here  $mw_0 R \sin \theta_0$  is the work done by the pseudoforce  $(-m\vec{w}_0)$ ]

$$\text{or, } \frac{v_0^2}{2R} = g(1 - \cos \theta_0) + w_0 \sin \theta_0$$





Solving Eqs. (2) and (3) we get,

$$v_0 = \sqrt{2gR/3} \text{ and } \theta_0 = \cos^{-1} \left[ \frac{2 + k\sqrt{5 + 9k^2}}{3(1 + k^2)} \right], \text{ where } k = \frac{w_0}{g}$$

Hence

$$\theta_0 \Big|_{w_0 = g} = 17^\circ$$

- 1.109 This is not central force problem unless the path is a circle about the said point. Rather here  $F_t$  (tangential force) vanishes. Thus equation of motion becomes,

$$v_t = v_0 = \text{constant}$$

and, 
$$\frac{mv_0^2}{r} = \frac{A}{r^2} \text{ for } r = r_0$$

We can consider the latter equation as the equilibrium under two forces. When the motion is perturbed, we write  $r = r_0 + x$  and the net force acting on the particle is,

$$-\frac{A}{(r_0 + x)^n} + \frac{mv_0^2}{r_0 + x} = \frac{-A}{r_0^n} \left( 1 - \frac{nx}{r_0} \right) + \frac{mv_0^2}{r_0} \left( 1 - \frac{x}{r_0} \right) = -\frac{mv_0^2}{r_0^2} (1 - n)x$$

This is opposite to the displacement  $x$ , if  $n < 1$ . ( $\frac{mv_0^2}{r}$  is an outward directed centrifugal force while  $\frac{-A}{r^n}$  is the inward directed external force).

- 1.110 There are two forces on the sleeve, the weight  $F_1$  and the centrifugal force  $F_2$ . We resolve both forces into tangential and normal component then the net downward tangential force on the sleeve is,

$$mg \sin \theta \left( 1 - \frac{\omega^2 R}{g} \cos \theta \right)$$

This vanishes for  $\theta = 0$  and for

$$\theta = \theta_0 = \cos^{-1} \left( \frac{g}{\omega^2 R} \right), \text{ which is real if}$$

$$\omega^2 R > g. \text{ If } \omega^2 R < g, \text{ then } 1 - \frac{\omega^2 R}{g} \cos \theta$$

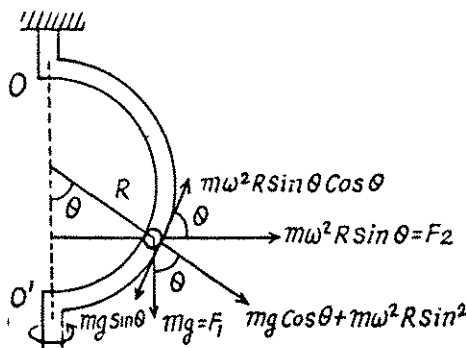
is always positive for small values of  $\theta$  and hence the net tangential force near  $\theta = 0$  opposes any displacement away from it.  $\theta = 0$  is then stable.

If  $\omega^2 R > g$ ,  $1 - \frac{\omega^2 R}{g} \cos \theta$  is negative for small

$\theta$  near  $\theta = 0$  and  $\theta = 0$  is then unstable.

However  $\theta = \theta_0$  is stable because the force tends to bring the sleeve near the equilibrium position  $\theta = \theta_0$ .

If  $\omega^2 R = g$ , the two positions coincide and becomes a stable equilibrium point.



- 1.111 Define the axes as shown with  $z$  along the local vertical,  $x$  due east and  $y$  due north. (We assume we are in the northern hemisphere). Then the Coriolis force has the components.

$$\vec{F}_{cor} = -2m(\vec{\omega} \times \vec{v})$$

$= 2m\omega [v_y \cos\theta - v_z \sin\theta] \vec{i} - v_x \cos\theta \vec{j} + v_x \cos\theta \vec{k}$   
 since  $v_x$  is small when the direction in which the gun is fired is due north. Thus the equation of motion (neglecting centrifugal forces) are

$$\dot{x} = 2m\omega (v_y \sin\varphi - v_z \cos\varphi), \dot{y} = 0 \text{ and } \dot{z} = -g$$

Integrating we get  $\dot{y} = v$  (constant),  $\dot{z} = -gt$

$$\text{and } \dot{x} = 2\omega v \sin\varphi t + \omega g t^2 \cos\varphi$$

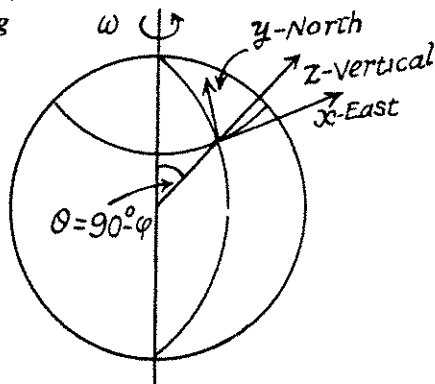
Finally,

$$x = \omega v t^2 \sin\varphi + \frac{1}{3} \omega g t^3 \cos\varphi$$

Now  $v \gg gt$  in the present case. so,

$$x \approx \omega v \sin\varphi \left(\frac{s}{v}\right)^2 = \omega \sin\varphi \frac{s^2}{v}$$

$$\approx 7 \text{ cm (to the east).}$$



- 1.112 The disc exerts three forces which are mutually perpendicular. They are the reaction of the weight,  $mg$ , vertically upward, the Coriolis force  $2mv'\omega$  perpendicular to the plane of the vertical and along the diameter, and  $m\omega^2 r$  outward along the diameter. The resultant force is,

$$F = m\sqrt{g^2 + \omega^4 r^2 + (2v'\omega)^2}$$

- 1.113 The sleeve is free to slide along the rod  $AB$ . Thus only the centrifugal force acts on it. The equation is,

$$m\dot{v} = m\omega^2 r \text{ where } v = \frac{dr}{dt}$$

$$\text{But } \dot{v} = v \frac{dv}{dr} = \frac{d}{dr} \left( \frac{1}{2} v^2 \right)$$

$$\text{so, } \frac{1}{2} v^2 = \frac{1}{2} \omega^2 r^2 + \text{constant}$$

$$\text{or, } v^2 = v_0^2 + \omega^2 r^2$$

$v_0$  being the initial velocity when  $r = 0$ . The Coriolis force is then,

$$2m\omega \sqrt{v_0^2 + \omega^2 r^2} = 2m\omega^2 r \sqrt{1 + v_0^2/\omega^2 r^2}$$

$$= 2.83 \text{ N on putting the values.}$$

- 1.114 The disc  $OBAC$  is rotating with angular velocity  $\omega$  about the axis  $OO'$  passing through the edge point  $O$ . The equation of motion in rotating frame is,

$$m\vec{w} = \vec{F} + m\omega^2 \vec{R} + 2m\vec{v} \times \vec{\omega} = \vec{F} + \vec{F}_{in}$$

where  $\vec{F}_{in}$  is the resultant inertial force (pseudo force) which is the vector sum of centrifugal and Coriolis forces.

- (a) At  $A$ ,  $F_{in}$  vanishes. Thus  $0 = -2m\omega^2 R \hat{n} + 2mv' \omega \hat{n}$

where  $\hat{n}$  is the inward drawn unit vector to the centre from the point in question, here  $A$ . Thus,

$$v' = \omega R$$

$$w = \frac{v'^2}{\rho} = \frac{v'^2}{R} = \omega^2 R.$$

- (b) At  $B$   $\vec{F}_{in} = m\omega^2 \vec{OC} + m\omega^2 \vec{BC}$

its magnitude is  $m\omega^2 \sqrt{4R^2 - r^2}$ , where  $r = OB$ .

- 1.115 The equation of motion in the rotating coordinate system is,

$$m\vec{w} = \vec{F} + m\omega^2 \vec{R} + 2m(\vec{v} \times \vec{\omega})$$

Now,  $\vec{v} = R\dot{\theta} \vec{e}_\theta + R\sin\theta \dot{\phi} \vec{e}_\phi$

and  $\vec{w} = w' \cos\theta \vec{e}_r - w' \sin\theta \vec{e}_\theta$

$$\frac{1}{2m} \vec{F}_{cor} = \begin{vmatrix} \vec{e}_r & \vec{e}_\theta & \vec{e}_\phi \\ 0 & R\dot{\theta} & R\sin\theta \dot{\phi} \\ \omega \cos\theta & -\omega \sin\theta & 0 \end{vmatrix}$$

$$= \vec{e}_r (\omega R \sin^2\theta \dot{\phi}) + \omega R \sin\theta \cos\theta \dot{\phi} \vec{e}_\theta - \omega R \dot{\theta} \cos\theta \vec{e}_\phi$$

Now on the sphere,

$$\vec{v} = (-R\dot{\theta}^2 - R\sin^2\theta \dot{\phi}^2) \vec{e}_r$$

$$+ (R\dot{\theta}' - R\sin\theta \cos\theta \dot{\phi}^2) \vec{e}_\theta$$

$$+ (R\sin\theta \dot{\phi}' + 2R\cos\theta \dot{\theta} \dot{\phi}) \vec{e}_\phi$$

Thus the equation of motion are,

$$m(-R\dot{\theta}^2 - R\sin^2\theta \dot{\phi}^2) = N - mg \cos\theta + m\omega^2 R \sin^2\theta + 2m\omega R \sin^2\theta \dot{\phi}$$

$$m(R\dot{\theta}' - R\sin\theta \cos\theta \dot{\phi}^2) = mg \sin\theta + m\omega^2 R \sin\theta \cos\theta + 2m\omega R \sin\theta \cos\theta \dot{\phi}$$

$$m(R\sin\theta \dot{\phi}' + 2R\cos\theta \dot{\theta} \dot{\phi}) = -2m\omega R \dot{\theta} \cos\theta$$

From the third equation, we get,  $\dot{\phi} = -\omega$

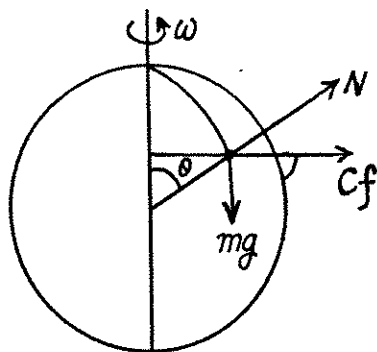
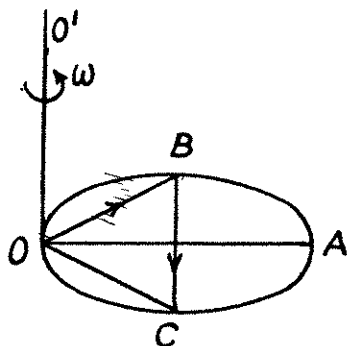
A result that is easy to understand by considering the motion in non-rotating frame. The eliminating  $\dot{\phi}$  we get,

$$mR\dot{\theta}^2 = mg \cos\theta - N$$

$$mR\dot{\theta}' = mg \sin\theta$$

Integrating the last equation,

$$\frac{1}{2} m R \dot{\theta}^2 = mg(1 - \cos\theta)$$



Hence

$$N = (3 - 2 \cos \theta) mg$$

So the body must fly off for  $\theta = \theta_0 = \cos^{-1} \frac{2}{3}$ , exactly as if the sphere were nonrotating.

Now, at this point  $F_{cf}$  = centrifugal force  $= m\omega^2 R \sin \theta_0 = \sqrt{\frac{5}{9}} m\omega^2 R$

$$\begin{aligned} F_{cor} &= \sqrt{\omega^2 R^2 \theta^2 \cos^2 \theta + (\omega^2 R^2)^2 \sin^2 \theta} \times 2m \\ &= \sqrt{\frac{5}{9} (\omega^2 R)^2 + \omega^2 R^2 \times \frac{4}{9} \times \frac{2g}{3R}} \times 2m = \frac{2}{3} m\omega^2 R \sqrt{5 + \frac{8g}{3\omega^2 R}} \end{aligned}$$

1.116 (a) When the train is moving along a meridian only the Coriolis force has a lateral component and its magnitude (see the previous problem) is,

$$2m\omega v \cos \theta = 2m\omega \sin \lambda$$

(Here we have put  $R\dot{\theta} \rightarrow v$ )

$$\begin{aligned} \text{So, } F_{lateral} &= 2 \times 2000 \times 10^3 \times \frac{2\pi}{86400} \times \frac{54000}{3600} \times \frac{\sqrt{3}}{2} \\ &= 3.77 \text{ kN, (we write } \lambda \text{ for the latitude)} \end{aligned}$$

(b) The resultant of the inertial forces acting on the train is,

$$\begin{aligned} \vec{F}_{in} &= -2m\omega R \dot{\theta} \cos \theta \vec{e}_\varphi \\ &+ (m\omega^2 R \sin \theta \cos \theta + 2m\omega R \sin \theta \cos \theta \dot{\varphi}) \vec{e}_\theta \\ &+ (m\omega^2 R \sin^2 \theta + 2m\omega R \sin^2 \theta \dot{\varphi}) \vec{e}_r \end{aligned}$$

This vanishes if  $\dot{\theta} = 0$ ,  $\dot{\varphi} = -\frac{1}{2}\omega$

$$\text{Thus } \vec{v} = v_\varphi \vec{e}_\varphi, v_\varphi = -\frac{1}{2}\omega R \sin \theta = -\frac{1}{2}\omega R \cos \lambda$$

(We write  $\lambda$  for the latitude here)

Thus the train must move from the east to west along the  $60^\text{th}$  parallel with a speed,

$$\frac{1}{2}\omega R \cos \lambda = \frac{1}{4} \times \frac{2\pi}{8.64} \times 10^{-4} \times 6.37 \times 10^6 = 115.8 \text{ m/s} \approx 417 \text{ km/hr}$$

1.117 We go to the equation given in 1.111. Here  $v_y = 0$  so we can take  $y = 0$ , thus we get for the motion in the  $xz$  plane.

$$\ddot{x} = -2\omega v_z \cos \theta$$

and

$$\ddot{z} = -g$$

Integrating,

$$z = -\frac{1}{2}gt^2$$

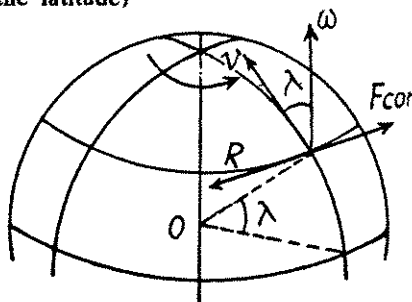
$$\dot{x} = \omega g \cos \varphi t^2$$

So

$$\begin{aligned} x &= \frac{1}{3}\omega g \cos \varphi t^3 = \frac{1}{3}\omega g \cos \varphi \left(\frac{2h}{g}\right)^{3/2} \\ &= \frac{2\omega h}{3} \cos \varphi \sqrt{\frac{2h}{g}} \end{aligned}$$

There is thus a displacement to the east of

$$\frac{2}{3} \times \frac{2\pi}{8} 64 \times 500 \times 1 \times \sqrt{\frac{400}{9.8}} \approx 26 \text{ cm.}$$



### 1.3 Laws of Conservation of Energy, Momentum and Angular Momentum.

1.118 As  $\vec{F}$  is constant so the sought work done

$$A = \vec{F} \cdot \Delta \vec{r} = \vec{F} \cdot (\vec{r}_2 - \vec{r}_1)$$

or,  $A = (3\vec{i} + 4\vec{j}) \cdot [(2\vec{i} - 3\vec{j}) - (\vec{i} + 2\vec{j})] = (3\vec{i} + 4\vec{j}) \cdot (\vec{i} - 5\vec{j}) = 17 \text{ J}$

1.119 Differentiating  $v(s)$  with respect to time

$$\frac{dv}{dt} = \frac{a}{2\sqrt{s}} \frac{ds}{dt} = \frac{a}{2\sqrt{s}} a\sqrt{s} = \frac{a^2}{2} = w$$

(As locomotive is in unidirectional motion)

Hence force acting on the locomotive  $F = mw = \frac{ma^2}{2}$

Let, at  $v = 0$  at  $t = 0$  then the distance covered during the first  $t$  seconds

$$s = \frac{1}{2} wt^2 = \frac{1}{2} \frac{a^2}{2} t^2 = \frac{a^2}{4} t^2$$

Hence the sought work,  $A = Fs = \frac{ma^2}{2} \frac{(a^2 t^2)}{4} = \frac{m a^4 t^2}{8}$

1.120 We have

$$T = \frac{1}{2} mv^2 = as^2 \quad \text{or,} \quad v^2 = \frac{2as^2}{m} \quad (1)$$

Differentiating Eq. (1) with respect to time

$$2v w_t = \frac{4as}{m} v \quad \text{or,} \quad w_t = \frac{2as}{m} \quad (2)$$

Hence net acceleration of the particle

$$w = \sqrt{w_t^2 + w_n^2} = \sqrt{\left(\frac{2as}{m}\right)^2 + \left(\frac{2as^2}{mR}\right)^2} = \frac{2as}{m} \sqrt{1 + (s/R)^2}$$

Hence the sought force,  $F = mw = 2as\sqrt{1 + (s/R)^2}$

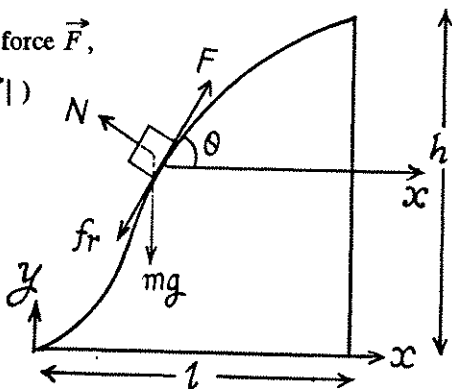
1.121 Let  $\vec{F}$  makes an angle  $\theta$  with the horizontal at any instant of time (Fig.). Newton's second law in projection form along the direction of the force, gives :

$F = kmg \cos \theta + mg \sin \theta$  (because there is no acceleration of the body.)

As  $\vec{F} \uparrow \uparrow d\vec{r}$  the differential work done by the force  $\vec{F}$ ,

$$\begin{aligned} dA &= \vec{F} \cdot d\vec{r} = F ds, \quad (\text{where } ds = |d\vec{r}|) \\ &= kmg ds (\cos \theta) + mg ds \sin \theta \\ &= kmg dx + mg dy. \end{aligned}$$

$$\begin{aligned} \text{Hence, } A &= kmg \int_0^l dx + mg \int_0^h dy \\ &= kmg l + mgh = mg(kl + h). \end{aligned}$$



- 1.122 Let  $s$  be the distance covered by the disc along the incline, from the Eq. of increment of M.E. of the disc in the field of gravity :  $\Delta T + \Delta U = A_{fr}$

$$0 + (-mgs \sin \alpha) = -kmg \cos \alpha s - kmg l$$

$$\text{or, } s = \frac{kl}{\sin \alpha - k \cos \alpha} \quad (1)$$

Hence the sought work

$$A_{fr} = -kmg [s \cos \alpha + l]$$

$$A_{fr} = -\frac{k l mg}{1 - k \cot \alpha} \quad [\text{Using the Eqn. (1)}]$$

On putting the values  $A_{fr} = -0.05 \text{ J}$

- 1.123 Let  $x$  be the compression in the spring when the bar  $m_2$  is about to shift. Therefore at this moment spring force on  $m_2$  is equal to the limiting friction between the bar  $m_2$  and horizontal floor. Hence

$$\kappa x = k m_2 g \quad [\text{where } \kappa \text{ is the spring constant (say)}] \quad (1)$$

For the block  $m_1$  from work-energy theorem :  $A = \Delta T = 0$  for minimum force. (A here includes the work done in stretching the spring.)

$$\text{so, } Fx - \frac{1}{2} \kappa x^2 - kmg x = 0 \quad \text{or } \kappa \frac{x}{2} = F - km_1 g \quad (2)$$

From (1) and (2),

$$F = kg \left( m_1 + \frac{m_2}{2} \right).$$

- 1.124 From the initial condition of the problem the limiting friction between the chain lying on the horizontal table equals the weight of the over hanging part of the chain, i.e.

$$\lambda \eta l g = k \lambda (1 - \eta) l g \quad (\text{where } \lambda \text{ is the linear mass density of the chain})$$

$$\text{So, } k = \frac{\eta}{1 - \eta} \quad (1)$$

Let (at an arbitrary moment of time) the length of the chain on the table is  $x$ . So the net friction force between the chain and the table, at this moment :

$$f_r = kN = k \lambda x g \quad (2)$$

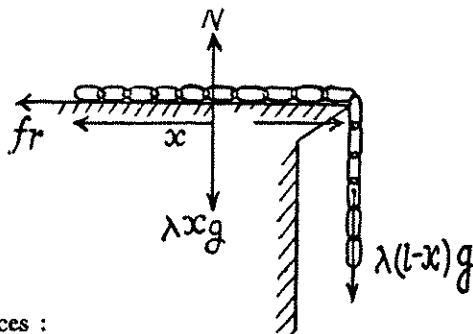
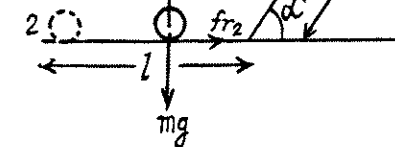
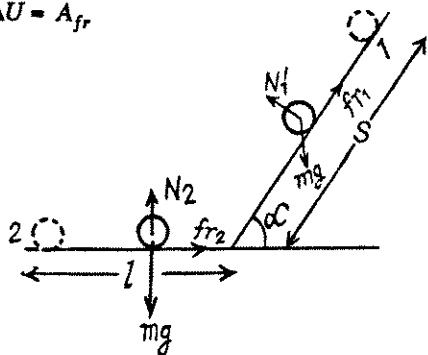
The differential work done by the friction forces :

$$dA = \vec{f}_r \cdot d\vec{r} = -f_r ds = -k \lambda x g (-dx) = \lambda g \left( \frac{\eta}{1 - \eta} \right) x dx \quad (3)$$

(Note that here we have written  $ds = -dx$ , because  $ds$  is essentially a positive term and as the length of the chain decreases with time,  $dx$  is negative)

Hence, the sought work done

$$A = \int_{(1-\eta)l}^0 \lambda g \frac{\eta}{1-\eta} x dx = -(1-\eta) \eta \frac{mgl}{2} = -1.3 \text{ J}$$



- 1.125 The velocity of the body,  $t$  seconds after the beginning of the motion becomes  $\vec{v} = \vec{v}_0 + \vec{g}t$ . The power developed by the gravity ( $m\vec{g}$ ) at that moment, is

$$P = m\vec{g} \cdot \vec{v} = m(\vec{g} \cdot \vec{v}_0 + g^2t) = mg(gt - v_0 \sin \alpha) \quad (1)$$

As  $m\vec{g}$  is a constant force, so the average power

$$\langle P \rangle = \frac{A}{\tau} = \frac{m\vec{g} \cdot \Delta \vec{r}}{\tau}$$

where  $\Delta \vec{r}$  is the net displacement of the body during time of flight.

As,  $m\vec{g} \perp \Delta \vec{r}$  so  $\langle P \rangle = 0$

- 1.126 We have  $w_n = \frac{v^2}{R} = at^2$ , or,  $v = \sqrt{aR}t$ ,

$t$  is defined to start from the beginning of motion from rest.

So,  $w_t = \frac{dv}{dt} = \sqrt{aR}$

Instantaneous power,  $P = \vec{F} \cdot \vec{v} = m(w_t \hat{u}_t + w_n \hat{u}_n) \cdot (\sqrt{aR}t \hat{u}_t)$ ,

(where  $\hat{u}_t$  and  $\hat{u}_n$  are unit vectors along the direction of tangent (velocity) and normal respectively)

So,  $P = mw_t \sqrt{aR}t = maRt$

Hence the sought average power

$$\langle P \rangle = \frac{\int_0^t P dt}{\int_0^t dt} = \frac{\int_0^t maRt dt}{\int_0^t dt}$$

Hence

$$\langle P \rangle = \frac{maRt^2}{2t} = \frac{maRt}{2}$$

- 1.127 Let the body  $m$  acquire the horizontal velocity  $v_0$  along positive  $x$ -axis at the point  $O$ .

(a) Velocity of the body  $t$  seconds after the beginning of the motion,

$$\vec{v} = \vec{v}_0 + \vec{w}t = (v_0 - kg t) \vec{i} \quad (1)$$

Instantaneous power  $P = \vec{F} \cdot \vec{v} = (-kmg \vec{i}) \cdot (v_0 - kg t) \vec{i} = -kmg(v_0 - kgt)$

From Eq. (1), the time of motion  $\tau = v_0/kg$

Hence sought average power during the time of motion

$$\langle P \rangle = \frac{\int_0^\tau -kmg(v_0 - kgt) dt}{\tau} = -\frac{kmg v_0}{2} = -2 \text{ W (On substitution)}$$

From  $F_x = mw_x$

$$-kmg = mw_x = mv_x \frac{dv_x}{dx}$$

or,

$$v_x dv_x = -kg dx = -\alpha g x dx$$

To find  $v(x)$ , let us integrate the above equation

$$\int_{v_0}^v v_x dv_x = -\alpha g \int_0^x x dx \quad \text{or, } v^2 = v_0^2 - \alpha g x^2 \quad (1)$$

Now, 
$$\vec{P} = \vec{F} \cdot \vec{v} = -m\alpha x g \sqrt{v_0^2 - \alpha g x^2} \quad (2)$$

For maximum power,  $\frac{d}{dt}(\sqrt{v_0^2 x^2 - \lambda g x^4}) = 0$  which yields  $x = \frac{v_0}{\sqrt{2\alpha g}}$

Putting this value of  $x$ , in Eq. (2) we get,

$$P_{\max} = -\frac{1}{2} m v_0^2 \sqrt{\alpha g}$$

1.128 Centrifugal force of inertia is directed outward along radial line, thus the sought work

$$A = \int_{r_1}^{r_2} m\omega^2 r dr = \frac{1}{2} m\omega^2 (r_2^2 - r_1^2) = 0.20 \text{ T (On substitution)}$$

1.129 Since the springs are connected in series, the combination may be treated as a single spring of spring constant.

$$\kappa = \frac{\kappa_1 \kappa_2}{\kappa_1 + \kappa_2}$$

From the equation of increment of M.E.,  $\Delta T + \Delta U = A_{\text{ext}}$

$$0 + \frac{1}{2} \kappa \Delta l^2 = A, \quad \text{or, } A = \frac{1}{2} \left( \frac{\kappa \kappa_2}{\kappa_1 + \kappa_2} \right) \Delta l^2$$

1.130 First, let us find the total height of ascent. At the beginning and the end of the path of velocity of the body is equal to zero, and therefore the increment of the kinetic energy of the body is also equal to zero. On the other hand, in according with work-energy theorem  $\Delta T$  is equal to the algebraic sum of the works  $A$  performed by all the forces, i.e. by the force  $F$  and gravity, over this path. However, since  $\Delta T = 0$  then  $A = 0$ . Taking into account that the upward direction is assumed to coincide with the positive direction of the  $y$ -axis, we can write

$$\begin{aligned} A &= \int_0^h (\vec{F} + m\vec{g}) \cdot d\vec{r} = \int_0^h (F_y - mg) dy \\ &= mg \int_0^h (1 - 2ay) dy = mgh(1 - ah) = 0. \end{aligned}$$

whence  $h = 1/a$ .

The work performed by the force  $F$  over the first half of the ascent is

$$A_F = \int_0^{h/2} F_y dy = 2mg \int_0^{h/2} (1 - ay) dy = 3mg/4a.$$

The corresponding increment of the potential energy is

$$\Delta U = mgh/2 = mg/2a.$$



1.131 From the equation  $F_r = -\frac{dU}{dr}$  we get  $F_r = \left[ -\frac{2a}{r^3} + \frac{b}{r^2} \right]$

(a) we have at  $r = r_0$ , the particle is in equilibrium position. i.e.  $F_r = 0$  so,  $r_0 = \frac{2a}{b}$

To check, whether the position is steady (the position of stable equilibrium), we have to satisfy

$$\frac{d^2 U}{dr^2} > 0$$

We have 
$$\frac{d^2 U}{dr^2} = \left[ \frac{6a}{r^4} - \frac{2b}{r^3} \right]$$

Putting the value of  $r = r_0 = \frac{2a}{b}$ , we get

$$\frac{d^2 U}{dr^2} = \frac{b^4}{8a^3}, \text{ (as } a \text{ and } b \text{ are positive constant)}$$

So, 
$$\frac{d^2 U}{dr^2} = \frac{b^2}{8a^3} > 0,$$

which indicates that the potential energy of the system is minimum, hence this position is steady.

(b) We have 
$$F_r = -\frac{dU}{dr} = \left[ -\frac{2a}{r^3} + \frac{b}{r^2} \right]$$

For  $F_r$  to be maximum, 
$$\frac{dF_r}{dr} = 0$$

So,  $r = \frac{3a}{b}$  and then  $F_{r(\max)} = \frac{-b^3}{27a^2}$ ,

As  $F_r$  is negative, the force is attractive.

1.132 (a) We have

$$F_x = -\frac{\partial U}{\partial x} = -2\alpha x \text{ and } F_y = -\frac{\partial U}{\partial y} = -2\beta y$$

So, 
$$\vec{F} = 2\alpha x \vec{i} - 2\beta y \vec{j} \text{ and, } F = 2\sqrt{\alpha^2 x^2 + \beta^2 y^2} \quad (1)$$

For a central force,  $\vec{r} \times \vec{F} = 0$

Here, 
$$\begin{aligned} \vec{r} \times \vec{F} &= (x\vec{i} + y\vec{j}) \times (-2\alpha x \vec{i} - 2\beta y \vec{j}) \\ &= -2\beta xy \vec{k} - 2\alpha xy (\vec{k}) \neq 0 \end{aligned}$$

Hence the force is not a central force.

(b) As  $U = \alpha x^2 + \beta y^2$

So, 
$$F_x = \frac{\partial U}{\partial x} = -2\alpha x \text{ and } F_y = -\frac{\partial U}{\partial y} = -2\beta y.$$

So, 
$$F = \sqrt{F_x^2 + F_y^2} = \sqrt{4\alpha^2 x^2 + 4\beta^2 y^2}$$

According to the problem

$$F = 2\sqrt{\alpha^2 x^2 + \beta^2 y^2} = C \text{ (constant)}$$

or, 
$$\alpha^2 x^2 + \beta^2 y^2 = \frac{C^2}{2}$$

or, 
$$\frac{x^2}{\beta^2} + \frac{y^2}{\alpha^2} = \frac{C^2}{2\alpha^2\beta^2} = k \text{ (say)} \quad (2)$$

Therefore the surfaces for which  $F$  is constant is an ellipse.

For an equipotential surface  $U$  is constant.

So, 
$$\alpha x^2 + \beta y^2 = C_0 \text{ (constant)}$$

or, 
$$\frac{x^2}{\sqrt{\beta^2}} + \frac{y^2}{\sqrt{\alpha^2}} = \frac{C_0}{\alpha\beta} = K_0 \text{ (constant)}$$

Hence the equipotential surface is also an ellipse.

1.133 Let us calculate the work performed by the forces of each field over the path from a certain point 1 ( $x_1, y_1$ ) to another certain point 2 ( $x_2, y_2$ )

(i)  $dA = \vec{F} \cdot d\vec{r} = ay \vec{i} \cdot d\vec{r} = ay dx$  or,  $A = a \int_{x_1}^{x_2} y dx$

(ii)  $dA = \vec{F} \cdot d\vec{r} = (ax\vec{i} + by\vec{j}) \cdot d\vec{r} = ax dx + by dy$

Hence 
$$A = \int_{x_1}^{x_2} a x dx + \int_{y_1}^{y_2} b y dy$$

In the first case, the integral depends on the function of type  $y(x)$ , i.e. on the shape of the path. Consequently, the first field of force is not potential. In the second case, both the integrals do not depend on the shape of the path. They are defined only by the coordinate of the initial and final points of the path, therefore the second field of force is potential.

1.134 Let  $s$  be the sought distance, then from the equation of increment of M.E.

$\Delta T + \Delta U = A_{fr}$

$$\left(0 - \frac{1}{2}mv_0^2\right) + (+mgs \sin \alpha) = -kmg \cos \alpha s$$

or, 
$$s = \frac{v_0^2}{2g} / (\sin \alpha + k \cos \alpha)$$

Hence 
$$A_{fr} = -kmg \cos \alpha s = \frac{-kmv_0^2}{2(k + \tan \alpha)}$$

1.135 Velocity of the body at height  $h$ ,  $v_h = \sqrt{2g(H-h)}$ , horizontally (from the figure given in the problem). Time taken in falling through the distance  $h$ .

$t = \sqrt{\frac{2h}{g}}$  (as initial vertical component of the velocity is zero.)

Now 
$$s = v_h t = \sqrt{2g(H-h)} \times \sqrt{\frac{2h}{g}} = \sqrt{4(Hh-h^2)}$$

For  $s_{\max}$ ,  $\frac{d}{ds} (Hh - h^2) = 0$ , which yields  $h = \frac{H}{2}$

Putting this value of  $h$  in the expression obtained for  $s$ , we get,

$$s_{\max} = H$$

- 1.136 To complete a smooth vertical track of radius  $R$ , the minimum height at which a particle starts, must be equal to  $\frac{5}{2}R$  (one can prove it from energy conservation). Thus in our problem body could not reach the upper most point of the vertical track of radius  $R/2$ . Let the particle  $A$  leave the track at some point  $O$  with speed  $v$  (Fig.). Now from energy conservation for the body  $A$  in the field of gravity :

$$mg \left[ h - \frac{h}{2} (1 + \sin \theta) \right] = \frac{1}{2} mv^2$$

$$\text{or, } v^2 = gh(1 - \sin \theta) \quad (1)$$

From Newton's second law for the particle at the point  $O$ ;  $F_n = mw_n$ ,

$$N + mg \sin \theta = \frac{mv^2}{(h/2)}$$

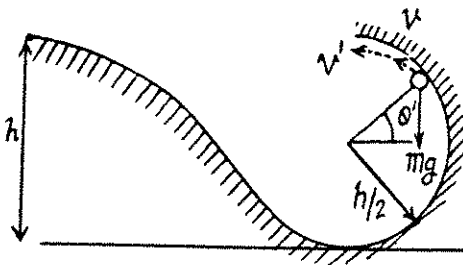
But, at the point  $O$  the normal reaction  $N = 0$

$$\text{So, } v^2 = \frac{gh}{2} \sin \theta \quad (2)$$

$$\text{From (3) and (4), } \sin \theta = \frac{2}{3} \text{ and } v = \sqrt{\frac{gh}{3}}$$

After leaving the track at  $O$ , the particle  $A$  comes in air and further goes up and at maximum height of its trajectory in air, its velocity (say  $v'$ ) becomes horizontal (Fig.). Hence, the sought velocity of  $A$  at this point.

$$v' = v \cos (90 - \theta) = v \sin \theta = \frac{2}{3} \sqrt{\frac{gh}{3}}$$



- 1.137 Let, the point of suspension be shifted with velocity  $v_A$  in the horizontal direction towards left then in the rest frame of point of suspension the ball starts with same velocity horizontally towards right. Let us work in this, frame. From Newton's second law in projection form towards the point of suspension at the upper most point (say  $B$ ) :

$$mg + T = \frac{mv_B^2}{l} \text{ or, } T = \frac{mv_B^2}{l} - mg \quad (1)$$

Condition required, to complete the vertical circle is that  $T \geq 0$ . But  $(2)$

$$\frac{1}{2} mv_A^2 = mg(2l) + \frac{1}{2} mv_B^2 \text{ So, } v_B^2 = v_A^2 - 4gl \quad (3)$$

From (1), (2) and (3)

$$T = \frac{m(v_A^2 - 4gl)}{l} - mg \geq 0 \quad \text{or, } v_A \geq \sqrt{5gl}$$

Thus  $v_{A(\min)} = \sqrt{5gl}$

From the equation  $F_n = mw_n$  at point C

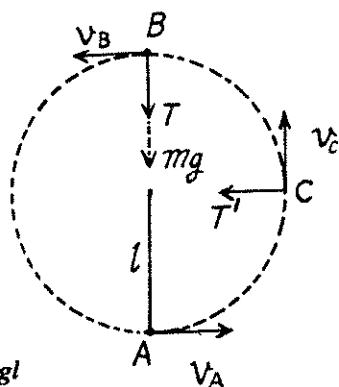
$$T' = \frac{mv_c^2}{l} \quad (4)$$

Again from energy conservation

$$\frac{1}{2}mv_A^2 = \frac{1}{2}mv_c^2 + mgl \quad (5)$$

From (4) and (5)

$$T = 3mg$$



- 1.138 Since the tension is always perpendicular to the velocity vector, the work done by the tension force will be zero. Hence, according to the work energy theorem, the kinetic energy or velocity of the disc will remain constant during its motion. Hence, the sought time  $t = \frac{s}{v_0}$ , where  $s$  is the total distance traversed by the small disc during its motion.

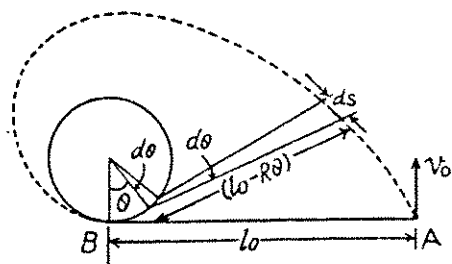
Now, at an arbitrary position (Fig.)

$$ds = (l_0 - R\theta) d\theta,$$

$$\text{so, } s = \int_0^{l_0/R} (l_0 - R\theta) d\theta$$

$$\text{or, } s = \frac{l_0^2}{R} - \frac{R l_0^2}{2R^2} = \frac{l_0^2}{2R}$$

Hence, the required time,  $t = \frac{l_0^2}{2R v_0}$



It should be clearly understood that the only uncompensated force acting on the disc A in this case is the tension  $T$ , of the thread. It is easy to see that there is no point here, relative to which the moment of force  $T$  is invariable in the process of motion. Hence conservation of angular momentum is not applicable here.

- 1.139 Suppose that  $\Delta l$  is the elongation of the rubber cord. Then from energy conservation,

$$\Delta U_g + \Delta U_s = 0 \quad (\text{as } \Delta T = 0)$$

$$\text{or, } -mg(l + \Delta l) + \frac{1}{2}\kappa \Delta l^2 = 0$$

$$\text{or, } \frac{1}{2}\kappa \Delta l^2 - mg \Delta l - mgl = 0$$

$$\text{or, } \Delta l = \frac{mg \pm \sqrt{(mg)^2 + 4 \times \frac{\kappa}{2} mgl}}{2 \times \frac{\kappa}{2}} \times \frac{\kappa}{2} = \frac{mg}{\kappa} \left[ 1 + \sqrt{1 \pm \frac{2\kappa l}{mg}} \right]$$

Since the value of  $\sqrt{1 + \frac{2\kappa l}{mg}}$  is certainly greater than 1, hence negative sign is avoided.

$$\text{So, } \Delta l = \frac{mg}{\kappa} \left( 1 + \sqrt{1 + \frac{2\kappa l}{mg}} \right)$$

- 1.140 When the thread PA is burnt, obviously the speed of the bars will be equal at any instant of time until it breaks off. Let  $v$  be the speed of each block and  $\theta$  be the angle, which the elongated spring makes with the vertical at the moment, when the bar A breaks off the plane. At this stage the elongation in the spring.

$$\Delta l = l_0 \sec \theta - l_0 = l_0 (\sec \theta - 1) \quad (1)$$

Since the problem is concerned with position and there are no forces other than conservative forces, the mechanical energy of the system (both bars + spring) in the field of gravity is conserved, i.e.  $\Delta T + \Delta U = 0$

$$\text{So, } 2 \left( \frac{1}{2} mv^2 \right) + \frac{1}{2} \kappa l_0^2 (\sec \theta - 1)^2 - mgl_0 \tan \theta = 0 \quad (2)$$

From Newton's second law in projection form along vertical direction :

$$mg = N + \kappa l_0 (\sec \theta - 1) \cos \theta$$

But, at the moment of break off,  $N = 0$ .

$$\text{Hence, } \kappa l_0 (\sec \theta - 1) \cos \theta = mg$$

$$\text{or, } \cos \theta = \frac{\kappa l_0 - mg}{\kappa l_0} \quad (3)$$

Taking  $\kappa = \frac{5mg}{l_0}$ , simultaneous solution of (2) and (3) yields :

$$v = \sqrt{\frac{19gl_0}{32}} = 1.7 \text{ m/s.}$$

- 1.141 Obviously the elongation in the cord,  $\Delta l = l_0 (\sec \theta - 1)$ , at the moment the sliding first starts and at the moment horizontal projection of spring force equals the limiting friction.

$$\text{So, } \kappa_1 \Delta l \sin \theta = kN \quad (1)$$

(where  $\kappa_1$  is the elastic constant).  $\kappa \Delta l$

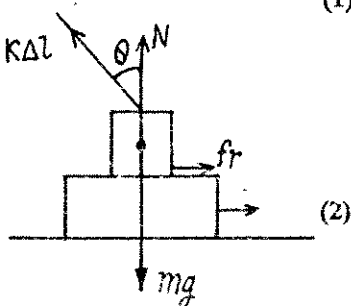
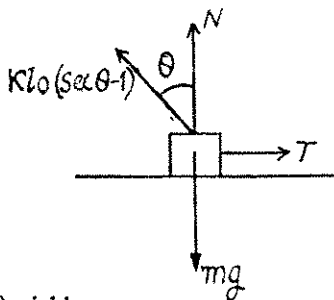
From Newton's law in projection form along vertical direction :

$$\kappa_1 \Delta l \cos \theta + N = mg.$$

$$\text{or, } N = mg - \kappa_1 \Delta l \cos \theta$$

From (1) and (2),

$$\kappa_1 \Delta l \sin \theta = k(mg - \kappa_1 \Delta l \cos \theta)$$



$$\text{or, } \kappa_1 = \frac{kmg}{\Delta l \sin \theta + k \Delta l \cos \theta}$$

From the equation of the increment of mechanical energy :  $\Delta U + \Delta T = A_{fr}$

$$\text{or, } \left( \frac{1}{2} \kappa_1 \Delta l^2 \right) = A_{fr}$$

$$\text{or, } \frac{kmg \Delta l^2}{2 \Delta l (\sin \theta + k \cos \theta)} = A_{fr}$$

$$\text{Thus } A_{fr} = \frac{kmg l_0 (\sec \theta - 1)}{2 (\sin \theta + k \cos \theta)} = 0.09 \text{ J (on substitution)}$$

1.142 Let the deformation in the spring be  $\Delta l$ , when the rod  $AB$  has attained the angular velocity  $\omega$ .

From the second law of motion in projection form  $F_n = m\omega_n^2$ .

$$\kappa \Delta l = m\omega^2 (l_0 + \Delta l) \quad \text{or, } \Delta l = \frac{m\omega^2 l_0}{\kappa - m\omega^2}$$

$$\text{From the energy equation, } A_{ext} = \frac{1}{2} m v^2 + \frac{1}{2} \kappa \Delta l^2$$

$$= \frac{1}{2} m \omega^2 (l_0 + \Delta l)^2 + \frac{1}{2} \kappa \Delta l^2$$

$$= \frac{1}{2} m \omega^2 \left( l_0 + \frac{m\omega^2 l_0}{\kappa - m\omega^2} \right)^2 + \frac{1}{2} \kappa \left( \frac{m\omega^2 l_0^2}{\kappa - m\omega^2} \right)^2$$

$$\text{On solving } A_{ext} = \frac{\kappa l_0^2 \eta (1 + \eta)}{2 (1 - \eta)^2}, \quad \text{where } \eta = \frac{m\omega^2}{\kappa}$$

1.143 We know that acceleration of centre of mass of the system is given by the expression.

$$\vec{w}_c = \frac{m_1 \vec{w}_1 + m_2 \vec{w}_2}{m_1 + m_2}$$

$$\text{Since } \vec{w}_1 = -\vec{w}_2$$

$$\vec{w}_c = \frac{(m_1 - m_2) \vec{w}_1}{m_1 + m_2} \quad (1)$$

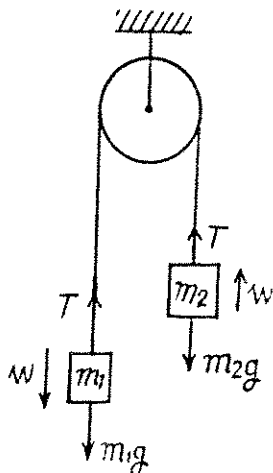
Now from Newton's second law  $\vec{F} = m\vec{w}$ , for the bodies  $m_1$  and  $m_2$  respectively.

$$\vec{T} + m_1 \vec{g} = m_1 \vec{w}_1 \quad (2)$$

$$\text{and } \vec{T} + m_2 \vec{g} = m_2 \vec{w}_2 = -m_2 \vec{w}_1 \quad (3)$$

Solving (2) and (3)

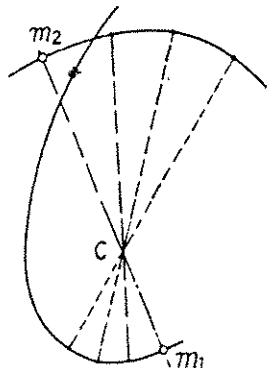
$$\vec{w}_1 = \frac{(m_1 - m_2) \vec{g}}{m_1 + m_2} \quad (4)$$



Thus from (1), (2) and (4),

$$\vec{w}_c = \frac{(m_1 - m_2)^2 \vec{g}}{(m_1 + m_2)^2}$$

- 1.144** As the closed system consisting two particles  $m_1$  and of  $m_2$  is initially at rest the C.M. of the system will remain at rest. Further as  $m_2 = m_1/2$ , the C.M. of the system divides the line joining  $m_1$  and  $m_2$  at all the moments of time in the ratio 1 : 2. In addition to it the total linear momentum of the system at all the times is zero. So,  $\vec{p}_1 = -\vec{p}_2$  and therefore the velocities of  $m_1$  and  $m_2$  are also directed in opposite sense. Bearing in mind all these thing, the sought trajectory is as shown in the figure.

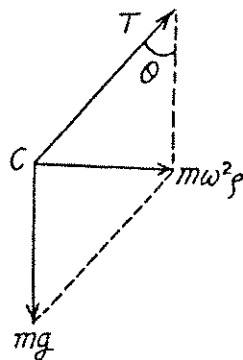


- 1.145** First of all, it is clear that the chain does not move in the vertical direction during the uniform rotation. This means that the vertical component of the tension  $T$  balances gravity. As for the horizontal component of the tension  $T$ , it is constant in magnitude and permanently directed toward the rotation axis. It follows from this that the C.M. of the chain, the point  $C$ , travels along horizontal circle of radius  $\rho$  (say). Therefore we have,

$$T \cos \theta = mg \quad \text{and} \quad T \sin \theta = m\omega^2 \rho$$

$$\text{Thus} \quad \rho = \frac{g \tan \theta}{\omega^2} = 0.8 \text{ cm}$$

$$\text{and} \quad T = \frac{mg}{\cos \theta} = 5 \text{ N}$$



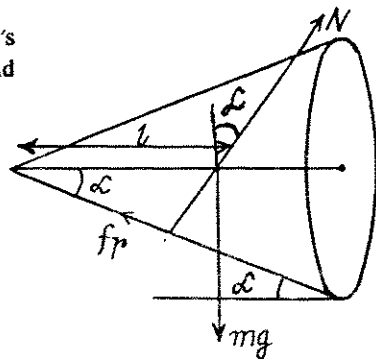
- 1.146** (a) Let us draw free body diagram and write Newton's second law in terms of projection along vertical and horizontal direction respectively.

$$N \cos \alpha - mg + fr \sin \alpha = 0 \quad (1)$$

$$fr \cos \alpha - N \sin \alpha = m\omega^2 l \quad (2)$$

From (1) and (2)

$$fr \cos \alpha - \frac{\sin \alpha}{\cos \alpha} (-fr \sin \alpha + mg) = m\omega^2 l$$



So, 
$$fr = mg \left( \sin \alpha + \frac{\omega^2 l}{g} \cos \alpha \right) = 6N \quad (3)$$

(b) For rolling, without sliding,

$$fr \leq kN$$

but,  $N = mg \cos \alpha - m \omega^2 l \sin \alpha$

$$mg \left( \sin \alpha + \frac{\omega^2 l}{g} \cos \alpha \right) \leq k (mg \cos \alpha - m \omega^2 l \sin \alpha) \quad [\text{Using (3)}]$$

Rearranging, we get,

$$m \omega^2 l (\cos \alpha + k \sin \alpha) \leq (k mg \cos \alpha - mg \sin \alpha)$$

Thus 
$$\omega \leq \sqrt{g(k - \tan \alpha) / (1 + k \tan \alpha)} \quad l = 2 \text{ rad/s}$$

1.147 (a) Total kinetic energy in frame  $K'$  is

$$T = \frac{1}{2} m_1 (\vec{v}_1 - \vec{V})^2 + \frac{1}{2} m_2 (\vec{v}_2 - \vec{V})^2$$

This is minimum with respect to variation in  $\vec{V}$ , when

$$\frac{\delta T'}{\delta \vec{V}} = 0, \text{ i.e. } m_1 (\vec{v}_1 - \vec{V})^2 + m_2 (\vec{v}_2 - \vec{V})^2 = 0$$

or 
$$\vec{V} = \frac{m_1 \vec{v}_1 + m_2 \vec{v}_2}{m_1 + m_2} = \vec{v}_c$$

Hence, it is the frame of C.M. in which kinetic energy of a system is minimum.

(b) Linear momentum of the particle 1 in the  $K'$  or  $C$  frame

$$\vec{p}_1 = m_1 (\vec{v}_1 - \vec{v}_c) = \frac{m_1 m_2}{m_1 + m_2} (\vec{v}_1 - \vec{v}_2)$$

or, 
$$\vec{p}_1 = \mu (\vec{v}_1 - \vec{v}_2), \text{ where, } \mu = \frac{m_1 m_2}{m_1 + m_2} = \text{reduced mass}$$

Similarly, 
$$\vec{p}_2 = \mu (\vec{v}_2 - \vec{v}_1)$$

So, 
$$|\vec{p}_1| = |\vec{p}_2| = \tilde{p} = \mu v_{rel} \text{ where, } v_{rel} = |\vec{v}_1 - \vec{v}_2| \quad (3)$$

Now the total kinetic energy of the system in the  $C$  frame is

$$\tilde{T} = \tilde{T}_1 + \tilde{T}_2 = \frac{\tilde{p}^2}{2m_1} + \frac{\tilde{p}^2}{2m_2} = \frac{\tilde{p}^2}{2\mu}$$

Hence 
$$\tilde{T} = \frac{1}{2} \mu v_{rel}^2 = \frac{1}{2} \mu |\vec{v}_1 - \vec{v}_2|^2$$



**1.148** To find the relationship between the values of the mechanical energy of a system in the  $K$  and  $C$  reference frames, let us begin with the kinetic energy  $T$  of the system. The velocity of the  $i$ -th particle in the  $K$  frame may be represented as  $\vec{v}_i = \vec{v}_i + \vec{v}_C$ . Now we can write

$$\begin{aligned} T &= \sum \frac{1}{2} m_i v_i^2 = \sum \frac{1}{2} m_i (\vec{v}_i + \vec{v}_C) \cdot (\vec{v}_i + \vec{v}_C) \\ &= \sum \frac{1}{2} m_i \vec{v}_i^2 + \vec{v}_C \sum m_i \vec{v}_i + \sum \frac{1}{2} m_i v_C^2 \end{aligned}$$

Since in the  $C$  frame  $\sum m_i \vec{v}_i = 0$ , the previous expression takes the form

$$T = \tilde{T} + \frac{1}{2} m v_C^2 = \tilde{T} + \frac{1}{2} m V^2 \quad (\text{since according to the problem } v_C = V) \quad (1)$$

Since the internal potential energy  $U$  of a system depends only on its configuration, the magnitude  $U$  is the same in all reference frames. Adding  $U$  to the left and right hand sides of Eq. (1), we obtain the sought relationship

$$E = \tilde{E} + \frac{1}{2} m V^2$$

**1.149** As initially  $U = \tilde{U} = 0$ , so,  $\tilde{E} = \tilde{T}$

From the solution of 1.147 (b)

$$\tilde{T} = \frac{1}{2} \mu |\vec{v}_1 - \vec{v}_2|,$$

As

$$\vec{v}_1 \perp \vec{v}_2$$

Thus

$$\tilde{T} = \frac{1}{2} \frac{m_1 m_2}{m_1 + m_2} (v_1^2 + v_2^2)$$

**1.150** Velocity of masses  $m_1$  and  $m_2$ , after  $t$  seconds are respectively.

$$\vec{v}_1' = \vec{v}_1 + \vec{g}t \quad \text{and} \quad \vec{v}_2' = \vec{v}_2 + \vec{g}t$$

Hence the final momentum of the system,

$$\begin{aligned} \vec{p} &= m_1 \vec{v}_1' + m_2 \vec{v}_2' = m_1 \vec{v}_1 + m_2 \vec{v}_2 + (m_1 + m_2) \vec{g}t \\ &= \vec{p}_0 + m \vec{g}t, \quad (\text{where, } \vec{p}_0 = m_2 \vec{v}_1 + m_2 \vec{v}_2 \text{ and } m = m_1 + m_2) \end{aligned}$$

And radius vector,

$$\vec{r}_C = \vec{v}_C t + \frac{1}{2} \vec{w}_C t^2$$

$$\frac{(m_1 \vec{v}_1 + m_2 \vec{v}_2) t}{(m_1 + m_2)} + \frac{1}{2} \vec{g} t^2$$

$$= \vec{v}_0 t + \frac{1}{2} \vec{g} t^2, \quad \text{where } \vec{v}_0 = \frac{m_1 \vec{v}_1 + m_2 \vec{v}_2}{m_1 + m_2}$$

1.151 After releasing the bar 2 acquires the velocity  $v_2$ , obtained by the energy, conservation :

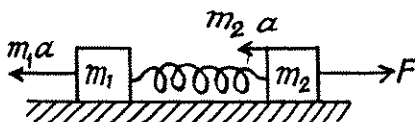
$$\frac{1}{2} m_2 v_2^2 = \frac{1}{2} \kappa x^2 \quad \text{or,} \quad v_2 = x \sqrt{\frac{\kappa}{m_2}} \quad (1)$$

Thus the sought velocity of C.M.

$$v_{cm} = \frac{0 + m_2 x \sqrt{\frac{\kappa}{m_2}}}{m_1 + m_2} = \frac{x \sqrt{m_2 \kappa}}{(m_1 + m_2)}$$

1.152 Let us consider both blocks and spring as the physical system. The centre of mass of the system moves with acceleration  $a = \frac{F}{m_1 + m_2}$  towards right. Let us work in the frame of centre of mass. As this frame is a non-inertial frame (accelerated with respect to the ground) we have to apply a pseudo force  $m_1 a$  towards left on the block  $m_1$  and  $m_2 a$  towards left on the block  $m_2$ .

As the center of mass is at rest in this frame, the blocks move in opposite directions and come to instantaneous rest at some instant. The elongation of the spring will be maximum or minimum at this instant. Assume that the block  $m_1$  is displaced by the distance  $x_1$  and the block  $m_2$  through a distance  $x_2$  from the initial positions.



From the energy equation in the frame of C.M.

$$\Delta \tilde{T} + U = A_{ext},$$

(where  $A_{ext}$  also includes the work done by the pseudo forces)

Here,

$$\Delta \tilde{T} = 0, \quad U = \frac{1}{2} k (x_1 + x_2)^2 \quad \text{and}$$

$$W_{ext} = \left( \frac{F - m_2 F}{m_1 + m_2} \right) x_2 + \frac{m_1 F}{m_1 + m_2} x_1 = \frac{m_1 F (x_1 + x_2)}{m_1 + m_2},$$

$$\text{or,} \quad \frac{1}{2} k (x_1 + x_2)^2 = \frac{m_1 (x_1 + x_2) F}{m_1 + m_2}$$

$$\text{So,} \quad x_1 + x_2 = 0 \quad \text{or,} \quad x_1 + x_2 = \frac{2 m_1 F}{k (m_1 + m_2)}$$

Hence the maximum separation between the blocks equals :  $l_0 + \frac{2 m_1 F}{k (m_1 + m_2)}$

Obviously the minimum separation corresponds to zero elongation and is equal to  $l_0$

1.153 (a) The initial compression in the spring  $\Delta l$  must be such that after burning of the thread, the upper cube rises to a height that produces a tension in the spring that is atleast equal to the weight of the lower cube. Actually, the spring will first go from its compressed

state to its natural length and then get elongated beyond this natural length. Let  $l$  be the maximum elongation produced under these circumstances.

Then

$$\kappa l = mg \quad (1)$$

Now, from energy conservation,

$$\frac{1}{2} \kappa \Delta l^2 = mg(\Delta l + l) + \frac{1}{2} \kappa l^2 \quad (2)$$

(Because at maximum elongation of the spring, the speed of upper cube becomes zero)

From (1) and (2),

$$\Delta l^2 - \frac{2mg \Delta l}{\kappa} - \frac{3m^2 g^2}{\kappa^2} = 0 \quad \text{or,} \quad \Delta l = \frac{3mg}{\kappa}, \quad -\frac{mg}{\kappa}$$

Therefore, acceptable solution of  $\Delta l$  equals  $\frac{3mg}{\kappa}$

(b) Let  $v$  the velocity of upper cube at the position (say, at  $C$ ) when the lower block breaks off the floor, then from energy conservation.

$$\frac{1}{2} mv^2 = \frac{1}{2} \kappa (\Delta l^2 - l^2) - mg(l + \Delta l)$$

$$(\text{where } l = mg/\kappa \text{ and } \Delta l = 7 \frac{mg}{\kappa})$$

$$\text{or,} \quad v^2 = 32 \frac{mg^2}{\kappa} \quad (2)$$

At the position  $C$ , the velocity of C.M.;  $v_C = \frac{mv + 0}{2m} = \frac{v}{2}$  - Let, the C.M. of the system (spring + two cubes) further rises up to  $\Delta y_{C2}$

Now, from energy conservation,

$$\frac{1}{2} (2m) v_C^2 = (2m) g \Delta y_{C2}$$

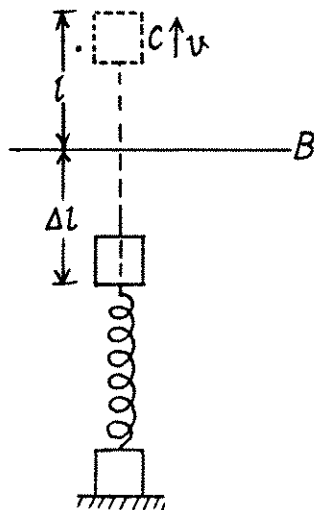
$$\text{or,} \quad \Delta y_{C2} = \frac{v_C^2}{2g} = \frac{v^2}{8g} = \frac{4mg}{\kappa}$$

But, upto position  $C$ , the C.M. of the system has already elevated by,

$$\Delta y_{C1} = \frac{(\Delta l + l)m + 0}{2m} = \frac{4mg}{\kappa}$$

Hence, the net displacement of the C.M. of the system, in upward direction

$$\Delta y_C = \Delta y_{C1} + \Delta y_{C2} = \frac{8mg}{\kappa}$$



**1.154** Due to ejection of mass from a moving system (which moves due to inertia) in a direction perpendicular to it, the velocity of moving system does not change. The momentum change being adjusted by the forces on the rails. Hence in our problem velocities of buggies change only due to the entrance of the man coming from the other buggy. From the

Solving (1) and (2), we get

$$v_1 = \frac{mv}{M-m} \text{ and } v_2 = \frac{Mv}{M-m}$$

As

$$\vec{v}_1 \uparrow \downarrow \vec{v} \text{ and } \vec{v}_2 \uparrow \uparrow \vec{v}$$

So,

$$\vec{v}_1 = \frac{-m\vec{v}}{(M-m)} \text{ and } \vec{v}_2 = \frac{M\vec{v}}{(M-m)}$$

**1.155** From momentum conservation, for the system "rear buggy with man"

$$(M+m)\vec{v}_0 = m(\vec{u} + \vec{v}_R) + M\vec{v}_R \quad (1)$$

From momentum conservation, for the system (front buggy + man coming from rear buggy)

$$M\vec{v}_0 + m(\vec{u} + \vec{v}_R) = (M+m)\vec{v}_F$$

So,

$$\vec{v}_F = \frac{M\vec{v}_0}{M+m} + \frac{m}{M+m}(\vec{u} + \vec{v}_R)$$

Putting the value of  $\vec{v}_R$  from (1), we get

$$\vec{v}_F = \vec{v}_0 + \frac{mM}{(M+m)^2}\vec{u}$$

**1.156** (i) Let  $\vec{v}_1$  be the velocity of the buggy after both man jump off simultaneously. For the closed system (two men + buggy), from the conservation of linear momentum,

$$M\vec{v}_1 + 2m(\vec{u} + \vec{v}_1) = 0$$

or,

$$\vec{v}_1 = \frac{-2m\vec{u}}{M+2m} \quad (1)$$

(ii) Let  $\vec{v}'$  be the velocity of buggy with man, when one man jump off the buggy. For the closed system (buggy with one man + other man) from the conservation of linear momentum :

$$0 = (M+m)\vec{v}' + m(\vec{u} + \vec{v}') \quad (2)$$

Let  $\vec{v}_2$  be the sought velocity of the buggy when the second man jump off the buggy; then from conservation of linear momentum of the system (buggy + one man) :

$$(M+m)\vec{v}' = M\vec{v}_2 + m(\vec{u} + \vec{v}_2) \quad (3)$$

Solving equations (2) and (3) we get

$$\vec{v}_2 = \frac{m(2M+3m)\vec{u}}{(M+m)(M+2m)} \quad (4)$$

From (1) and (4)

$$\frac{v_2}{v_1} = 1 + \frac{m}{2(M+m)} > 1$$

Hence  $v_2 > v_1$

**1.157** The descending part of the chain is in free fall, it has speed  $v = \sqrt{2gh}$  at the instant, all its points have descended a distance  $y$ . The length of the chain which lands on the floor during the differential time interval  $dt$  following this instant is  $vdt$ .

For the incoming chain element on the floor :

From  $dp_y = F_y dt$  (where  $y$ -axis is directed down)

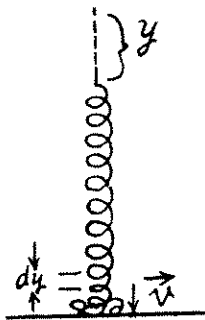
$$0 - (\lambda v dt) v = F_y dt$$

or

$$F_y = -\lambda v^2 = -2\lambda g y$$

Hence, the force exerted on the falling chain equals  $\lambda v^2$  and is directed upward. Therefore from third law the force exerted by the falling chain on the table at the same instant of time becomes  $\lambda v^2$  and is directed downward.

Since a length of chain of weight  $(\lambda y g)$  already lies on the table the total force on the floor is  $(2\lambda y g) + (\lambda y g) = (3\lambda y g)$  or the weight of a length  $3y$  of chain.



1.158 Velocity of the ball, with which it hits the slab,  $v = \sqrt{2gh}$

After first impact,  $v' = ev$  (upward) but according to the problem  $v' = \frac{v}{\eta}$ , so  $e = \frac{1}{\eta}$  (1)

and momentum, imparted to the slab,

$$= mv - (-mv') = mv(1 + e)$$

Similarly, velocity of the ball after second impact,

$$v'' = ev' = e^2 v$$

And momentum imparted  $= m(v' + v'') = m(1 + e)ev$

Again, momentum imparted during third impact,

$$= m(1 + e)e^2 v, \text{ and so on,}$$

Hence, net momentum, imparted  $= mv(1 + e) + mve(1 + e) + mve^2(1 + e) + \dots$

$$= mv(1 + e)(1 + e + e^2 + \dots)$$

$$= mv \frac{(1 + e)}{(1 - e)}, \text{ (from summation of G.P.)}$$

$$= \sqrt{2gh} \left( \frac{1 + \frac{1}{\eta}}{1 - \frac{1}{\eta}} \right) = m \sqrt{2gh} / (\eta + 1) / (\eta - 1) \text{ (Using Eq. 1)}$$

$$= 0.2 \text{ kg m/s. (On substitution)}$$

1.159 (a) Since the resistance of water is negligibly small, the resultant of all external forces acting on the system "a man and a raft" is equal to zero. This means that the position of the C.M. of the given system does not change in the process of motion.

$$\text{i.e. } \vec{r}_C = \text{constant or, } \Delta \vec{r}_C = 0 \text{ i.e. } \sum m_i \Delta \vec{r}_i = 0$$

or,

$$m(\Delta \vec{r}_{mM} + \Delta \vec{r}_M) + M \Delta \vec{r}_M = 0$$

Thus,

$$m(\vec{l}' + \vec{l}) + M \vec{l} = 0, \text{ or, } \vec{l} = -\frac{m \vec{l}'}{m + M}$$

(b) As net external force on "man-raft" system is equal to zero, therefore the momentum of this system does not change,

$$\text{So, } 0 = m[\vec{v}_1'(t) + \vec{v}_2'(t)] + M \vec{v}_2(t)$$

- 1.159 (a) Since the resistance of water is negligibly small, the resultant of all external forces acting on the system "a man and a raft" is equal to zero. This means that the position of the C.M. of the given system does not change in the process of motion.

$$\text{i.e. } \vec{r}_C = \text{constant or, } \Delta \vec{r}_C = 0 \quad \text{i.e. } \sum m_i \Delta \vec{r}_i = 0$$

$$\text{or, } m (\Delta \vec{r}_{mM} + \Delta \vec{r}_M) + M \Delta \vec{r}_M = 0$$

$$\text{Thus, } m (\vec{l}' + \vec{l}) + M \vec{l} = 0, \quad \text{or, } \vec{l} = -\frac{m \vec{l}'}{m+M}$$

- (b) As net external force on "man-raft" system is equal to zero, therefore the momentum of this system does not change,

$$\text{So, } 0 = m [\vec{v}'(t) + \vec{v}_2(t)] + M \vec{v}_2(t)$$

$$\text{or, } \vec{v}_2(t) = -\frac{m \vec{v}'(t)}{m+M} \quad (1)$$

As  $\vec{v}'(t)$  or  $\vec{v}_2(t)$  is along horizontal direction, thus the sought force on the raft

$$= \frac{M d \vec{v}_2(t)}{dt} = -\frac{Mm}{m+M} \frac{d \vec{v}'(t)}{dt}$$

Note : we may get the result of part (a), if we integrate Eq. (1) over the time of motion of man or raft.

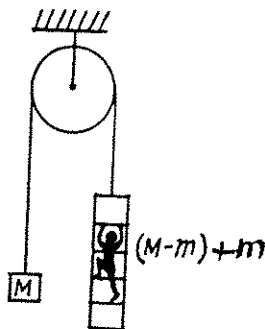
- 1.160 In the reference frame fixed to the pulley axis the location of C.M. of the given system is described by the radius vector

$$\Delta \vec{r}_C = \frac{M \Delta \vec{r}_M + (M-m) \Delta \vec{r}_{(M-m)} + m \Delta \vec{r}_m}{2M}$$

$$\text{But } \Delta \vec{r}_M = -\Delta \vec{r}_{(M-m)}$$

$$\text{and } \Delta \vec{r}_m = \Delta \vec{r}_{m(M-m)} + \Delta \vec{r}_{(M-m)}$$

$$\text{Thus } \Delta \vec{r}_C = \frac{m \vec{l}'}{2M}$$



Note : one may also solve this problem using momentum conservation.

- 1.161 Velocity of cannon as well as that of shell equals  $\sqrt{2gl \sin \alpha}$  down the inclined plane taken as the positive  $x$ -axis. From the linear impulse momentum theorem in projection form along  $x$ -axis for the system (cannon + shell) i.e.  $\Delta p_x = F_x \Delta t$ :

$$p \cos \alpha - M \sqrt{2gl \sin \alpha} = Mg \sin \alpha \Delta t \quad (\text{as mass of the shell is negligible})$$

$$\text{or, } \Delta t = \frac{p \cos \alpha - M \sqrt{2gl \sin \alpha}}{Mg \sin \alpha}$$

- 1.162 From conservation of momentum, for the system (bullet + body) along the initial direction of bullet

$$mv_0 = (m+M)v, \quad \text{or, } v = \frac{mv_0}{m+M}$$

- 1.163** When the disc breaks off the body  $M$ , its velocity towards right (along  $x$ -axis) equals the velocity of the body  $M$ , and let the disc's velocity' in upward direction (along  $y$ -axis) at that moment be  $v'_y$

From conservation of momentum, along  $x$ -axis for the system (disc + body)

$$mv = (m + M) v'_x \quad \text{or} \quad v'_x = \frac{mv}{m + M} \quad (1)$$

And from energy conservation, for the same system in the field of gravity :

$$\frac{1}{2} mv^2 = \frac{1}{2} (m + M) v'^2_x + \frac{1}{2} m v'^2_y + mgh',$$

where  $h'$  is the height of break off point from initial level. So,

$$\frac{1}{2} mv^2 = \frac{1}{2} (m + M) \frac{m^2 v^2}{(M + m)^2} + \frac{1}{2} m v'^2_y + mgh', \quad \text{using (1)}$$

$$\text{or,} \quad v'^2_y = v^2 - \frac{mv^2}{(m + M)} - 2gh'$$

Also, if  $h''$  is the height of the disc, from the break-off point,

$$\text{then,} \quad v'^2_y = 2gh''$$

$$\text{So,} \quad 2g(h'' + h') = v^2 - \frac{mv^2}{(M + m)}$$

Hence, the total height, raised from the initial level

$$= h' + h'' = \frac{Mv^2}{2g(M + m)}$$

- 1.164** (a) When the disc slides and comes to a plank, it has a velocity equal to  $v = \sqrt{2gh}$ . Due to friction between the disc and the plank the disc slows down and after some time the disc moves in one piece with the plank with velocity  $v'$  (say).

From the momentum conservation for the system (disc + plank) along horizontal towards right :

$$mv = (m + M) v' \quad \text{or} \quad v' = \frac{mv}{m + M}$$

Now from the equation of the increment of total mechanical energy of a system :

$$\frac{1}{2} (M + m) v'^2 - \frac{1}{2} mv^2 = A_{fr}$$

$$\text{or,} \quad \frac{1}{2} (M + m) \frac{m^2 v^2}{(m + M)^2} - \frac{1}{2} mv^2 = A_{fr}$$

$$\text{so,} \quad \frac{1}{2} v^2 \left[ \frac{m^2}{M + m} - m \right] = A_{fr}$$

$$\text{Hence,} \quad A_{fr} = - \left( \frac{mM}{m + M} \right) gh = -\mu gh$$

$$\left( \text{where } \mu = \frac{mM}{m + M} = \text{reduced mass} \right)$$

(b) We look at the problem from a frame in which the hill is moving (together with the disc on it) to the right with speed  $u$ . Then in this frame the speed of the disc when it just gets onto the plank is, by the law of addition of velocities,  $\bar{v} = u + \sqrt{2gh}$ . Similarly the common speed of the plank and the disc when they move together is

$$\bar{v} = u + \frac{m}{m+M} \sqrt{2gh}.$$

Then as above  $\bar{A}_p = \frac{1}{2} (m+M) \bar{v}^2 - \frac{1}{2} m \bar{v}^2 - \frac{1}{2} M u^2$

$$= \frac{1}{2} (m+M) \left\{ u^2 + \frac{2m}{m+M} u \sqrt{2gh} + \frac{m^2}{(m+M)^2} 2gh \right\} - \frac{1}{2} (m+M) u^2 - \frac{1}{2} m 2u \sqrt{2gh} - mgh$$

We see that  $\bar{A}_p$  is independent of  $u$  and is in fact just  $- \mu g h$  as in (a). Thus the result obtained does not depend on the choice of reference frame.

Do note however that it will be incorrect to apply "conservation of energy" formula in the frame in which the hill is moving. The energy carried by the hill is not negligible in this frame. See also the next problem.

- 1.165 In a frame moving relative to the earth, one has to include the kinetic energy of the earth as well as earth's acceleration to be able to apply conservation of energy to the problem. In a reference frame falling to the earth with velocity  $v_o$ , the stone is initially going up with velocity  $v_o$  and so is the earth. The final velocity of the stone is  $0 = v_o - gt$  and that of the earth is  $v_o + \frac{m}{M} gt$  ( $M$  is the mass of the earth), from Newton's third law, where  $t$  = time of fall. From conservation of energy

$$\frac{1}{2} m v_o^2 + \frac{1}{2} M v_o^2 + mgh = \frac{1}{2} M \left( v_o + \frac{m}{M} v_o \right)^2$$

Hence 
$$\frac{1}{2} v_o^2 \left( m + \frac{m^2}{M} \right) = mgh$$

Neglecting  $\frac{m}{M}$  in comparison with 1, we get

$$v_o^2 = 2gh \text{ or } v_o = \sqrt{2gh}$$

The point is this in earth's rest frame the effect of earth's acceleration is of order  $\frac{m}{M}$  and can be neglected but in a frame moving with respect to the earth the effect of earth's acceleration must be kept because it is of order one (i.e. large).

- 1.166 From conservation of momentum, for the closed system "both colliding particles"

$$m_1 \vec{v}_1 + m_2 \vec{v}_2 = (m_1 + m_2) \vec{v}$$

or, 
$$\vec{v} = \frac{m_1 \vec{v}_1 + m_2 \vec{v}_2}{m_1 + m_2} = \frac{1(3\vec{i} - 2\vec{j}) + 2(4\vec{j} - 6\vec{k})}{3} = \vec{i} + 2\vec{j} - 4\vec{k}$$

Hence 
$$|\vec{v}| = \sqrt{1 + 4 + 16} \text{ m/s} = 4.6 \text{ m/s}$$



- 1.167** For perfectly inelastic collision, in the C.M. frame, final kinetic energy of the colliding system (both spheres) becomes zero. Hence initial kinetic energy of the system in C.M. frame completely turns into the internal energy ( $Q$ ) of the formed body. Hence

$$Q = \tilde{T}_i = \frac{1}{2} \mu |\vec{v}_1 - \vec{v}_2|^2$$

Now from energy conservation  $\Delta T = -Q = -\frac{1}{2} \mu |\vec{v}_1 - \vec{v}_2|^2$ ,

In lab frame the same result is obtained as

$$\begin{aligned} \Delta T &= \frac{1}{2} \frac{(m_1 \vec{v}_1 + m_2 \vec{v}_2)^2}{m_1 + m_2} - \frac{1}{2} m_1 |\vec{v}_1|^2 + m_2 |\vec{v}_2|^2 \\ &= -\frac{1}{2} \mu |\vec{v}_1 - \vec{v}_2|^2 \end{aligned}$$

- 1.168** (a) Let the initial and final velocities of  $m_1$  and  $m_2$  are  $\vec{u}_1$ ,  $\vec{u}_2$  and  $\vec{v}$ ,  $\vec{v}_2$  respectively. Then from conservation of momentum along horizontal and vertical directions, we get :

$$m_1 u_1 = m_2 v_2 \cos \theta \quad (1)$$

$$\text{and } m_1 v_1 = m_2 v_2 \sin \theta \quad (2)$$

Squaring (1) and (2) and then adding them,

$$m_2^2 v_2^2 = m_1^2 (u_1^2 + v_1^2)$$

Now, from kinetic energy conservation,

$$\frac{1}{2} m_1 u_1^2 = \frac{1}{2} m_2 v_2^2 + \frac{1}{2} m_1 v_1^2 \quad (3)$$

$$\text{or, } m (u_1^2 - v_1^2) = m_2 v_2^2 = m_2 \frac{m_1^2}{m_2^2} (u_1^2 + v_1^2) \quad [\text{Using (3)}]$$

$$\text{or, } u_1^2 \left(1 - \frac{m_1}{m_2}\right) = v_1^2 \left(1 + \frac{m_1}{m_2}\right)$$

$$\text{or, } \left(\frac{v_1}{u_1}\right)^2 = \frac{m_2 - m_1}{m_1 + m_2} \quad (4)$$

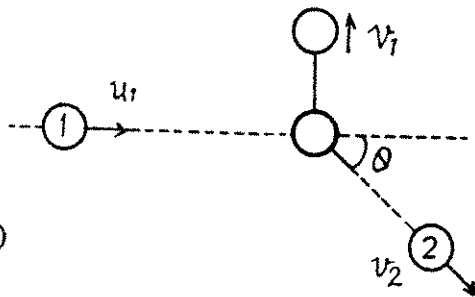
So, fraction of kinetic energy lost by the particle 1,

$$\begin{aligned} &= \frac{\frac{1}{2} m_1 u_1^2 - \frac{1}{2} m_1 v_1^2}{\frac{1}{2} m_1 u_1^2} = 1 - \frac{v_1^2}{u_1^2} \\ &= 1 - \frac{m_2 - m_1}{m_1 + m_2} = \frac{2 m_1}{m_1 + m_2} \quad [\text{Using (4)}] \end{aligned} \quad (5)$$

- (b) When the collision occurs head on,

$$m_1 u_1 = m_1 v_1 + m_2 v_2 \quad (1)$$

and from conservation of kinetic energy,



$$\begin{aligned}\frac{1}{2} m_1 u_1^2 &= \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 \\ &= \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 \left[ \frac{m_1 (u_1 - v_1)^2}{m_2} \right]^2 \quad [\text{Using (5)}]\end{aligned}$$

$$\text{or,} \quad v_1 \left( 1 + \frac{m_1}{m_2} \right) = u_1 \left( \frac{m_1}{m_2} - 1 \right)$$

$$\text{or,} \quad \frac{v_1}{u_1} = \frac{(m_1 / m_2 - 1)}{(1 + m_1 / m_2)} \quad (6)$$

Fraction of kinetic energy, lost

$$= 1 - \frac{v_1^2}{u_1^2} = 1 - \left( \frac{m_1 - m_2}{m_1 + m_2} \right)^2 = \frac{4 m_1 m_2}{(m_1 + m_2)^2} \quad [\text{Using (6)}]$$

**1.169** (a) When the particles fly apart in opposite direction with equal velocities (say  $v$ ), then from conservation of momentum,

$$m_1 u + 0 = (m_2 - m_1) v \quad (1)$$

and from conservation of kinetic energy,

$$\frac{1}{2} m_1 u^2 = \frac{1}{2} m_1 v^2 + \frac{1}{2} m_2 v^2$$

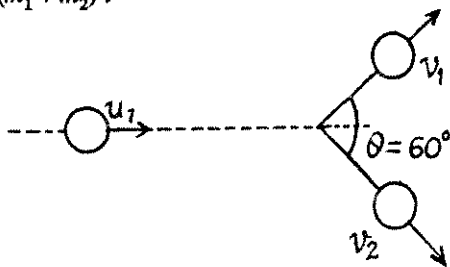
$$\text{or,} \quad m_1 u^2 = (m_1 + m_2) v^2 \quad (2)$$

From Eq. (1) and (2),

$$m_1 u^2 = (m_1 + m_2) \frac{m_1^2 u^2}{(m_2 - m_1)^2}$$

$$\text{or,} \quad m_2^2 - 3 m_1 m_2 = 0$$

$$\text{Hence} \quad \frac{m_1}{m_2} = \frac{1}{3} \quad \text{as } m_2 \neq 0$$



(b) When they fly apart symmetrically relative to the initial motion direction with the angle of divergence  $\theta = 60^\circ$ ,

From conservation of momentum, along horizontal and vertical direction,

$$m_1 u_1 = m_1 v_1 \cos(\theta/2) + m_2 v_2 \cos(\theta/2) \quad (1)$$

$$\text{and} \quad m_1 v_1 \sin(\theta/2) = m_2 v_2 \sin(\theta/2)$$

$$\text{or,} \quad m_1 v_1 = m_2 v_2 \quad (2)$$

Now, from conservation of kinetic energy,

$$\frac{1}{2} m_1 u_1^2 + 0 = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 \quad (3)$$

From (1) and (2),

$$m_1 u_1 = \cos(\theta/2) \left( m_1 v_1 + \frac{m_1 v_1}{m_2} m_2 \right) = 2 m_1 v_1 \cos(\theta/2)$$

So,

$$u_1 = 2 v_1 \cos (\theta/2) \quad (4)$$

From (2), (3), and (4)

$$4 m_1 \cos^2 (\theta/2) v_1^2 = m_1 v_1^2 + \frac{m_2 m_1^2 v_1^2}{m_2^2}$$

$$\text{or, } 4 \cos^2 (\theta/2) = 1 + \frac{m_1}{m_2}$$

$$\text{or, } \frac{m_1}{m_2} = 4 \cos^2 \frac{\theta}{2} - 1$$

and putting the value of  $\theta$ , we get,  $\frac{m_1}{m_2} = 2$

**1.170** If  $(v_{1x}, v_{1y})$  are the instantaneous velocity components of the incident ball and  $(v_{2x}, v_{2y})$  are the velocity components of the struck ball at the same moment, then since there are no external impulsive forces (i.e. other than the mutual interaction of the balls) We have

$$u \sin \alpha = v_{1y}, \quad v_{2y} = 0$$

$$m u \cos \alpha = m v_{1x} + m v_{2x}$$

The impulsive force of mutual interaction satisfies

$$\frac{d}{dt}(v_{1x}) = \frac{F}{m} = - \frac{d}{dt}(v_{2x})$$

( $F$  is along the  $x$  axis as the balls are smooth. Thus  $Y$  component of momentum is not transferred.) Since loss of K.E. is stored as deformation energy  $D$ , we have

$$\begin{aligned} D &= \frac{1}{2} m u^2 - \frac{1}{2} m v_1^2 - \frac{1}{2} m v_2^2 \\ &= \frac{1}{2} m u^2 \cos^2 \alpha - \frac{1}{2} m v_{1x}^2 - \frac{1}{2} m v_{2x}^2 \\ &= \frac{1}{2m} \left[ m^2 u^2 \cos^2 \alpha - m^2 v_{1x}^2 - (m u \cos \alpha - m v_{1x})^2 \right] \\ &= \frac{1}{2m} \left[ 2 m^2 u \cos \alpha v_{1x} - 2 m^2 v_{1x}^2 \right] = m (v_{1x} u \cos \alpha - v_{1x}^2) \\ &= m \left[ \frac{u^2 \cos^2 \alpha}{4} - \left( \frac{u \cos \alpha}{2} - v_{1x} \right)^2 \right] \end{aligned}$$

We see that  $D$  is maximum when

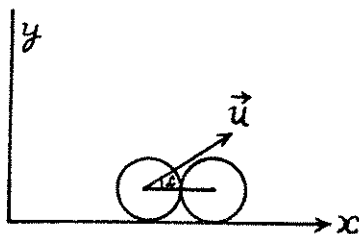
$$\frac{u \cos \alpha}{2} = v_{1x}$$

and

$$D_{\max} = \frac{m u^2 \cos^2 \alpha}{4}$$

$$\text{Then } \eta = \frac{D_{\max}}{\frac{1}{2} m u^2} = \frac{1}{2} \cos^2 \alpha = \frac{1}{4}$$

On substituting  $\alpha = 45^\circ$



1.171 From the conservation of linear momentum of the shell just before and after its fragmentation

$$3\vec{v} = \vec{v}_1 + \vec{v}_2 + \vec{v}_3 \quad (1)$$

where  $\vec{v}_1$ ,  $\vec{v}_2$  and  $\vec{v}_3$  are the velocities of its fragments.

$$\text{From the energy conservation } 3\eta v^2 = v_1^2 + v_2^2 + v_3^2 \quad (2)$$

$$\text{Now } \vec{v}_i \text{ or } \vec{v}_{ic} = \vec{v}_i - \vec{v}_c = \vec{v}_i - \vec{v} \quad (3)$$

where  $\vec{v}_c = \vec{v}$  = velocity of the C.M. of the fragments the velocity of the shell. Obviously in the C.M. frame the linear momentum of a system is equal to zero, so

$$\vec{v}_1 + \vec{v}_2 + \vec{v}_3 = 0 \quad (4)$$

Using (3) and (4) in (2), we get

$$3\eta v^2 = (\vec{v} + \vec{v}_1)^2 + (\vec{v} + \vec{v}_2)^2 + (\vec{v} + \vec{v}_1 - \vec{v}_2)^2 = 3v^2 + 2\tilde{v}_1^2 + 2\tilde{v}_2^2 + 2\tilde{v}_1 \cdot \tilde{v}_2$$

$$\text{or, } 2\tilde{v}_1^2 + 2\tilde{v}_1 \tilde{v}_2 \cos\theta + 2\tilde{v}_2^2 + 3(1-\eta)v^2 = 0 \quad (5)$$

If we have had used  $\vec{v}_2 = -\vec{v}_1 - \vec{v}_3$ , then Eq. 5 would contain  $\tilde{v}_3$  instead of  $\tilde{v}_2$  and so on.

The problem being symmetrical we can look for the maximum of any one. Obviously it will be the same for each.

For  $\tilde{v}_1$  to be real in Eq. (5)

$$4\tilde{v}_2^2 \cos^2\theta \geq 8(2\tilde{v}_2^2 + 3(1-\eta)v^2) \text{ or } 6(\eta-1)v^2 \geq (4-\cos^2\theta)\tilde{v}_2^2$$

$$\text{So, } \tilde{v}_2 \leq v \sqrt{\frac{6(\eta-1)}{4-\cos^2\theta}} \text{ or } \tilde{v}_{2(\max)} = \sqrt{2(\eta-1)} v$$

$$\text{Hence } v_{2(\max)} = |\vec{v} + \vec{v}_2|_{\max} = v + \sqrt{2(\eta-1)} v = v(1 + \sqrt{2(\eta-1)}) = 1 \text{ km/s}$$

Thus owing to the symmetry

$$v_{1(\max)} = v_{2(\max)} = v_{3(\max)} = v(1 + \sqrt{2(\eta-1)}) = 1 \text{ km/s}$$

1.172 Since, the collision is head on, the particle 1 will continue moving along the same line as before the collision, but there will be a change in the magnitude of its velocity vector. Let it start moving with velocity  $v_1$  and particle 2 with  $v_2$  after collision, then from the conservation of momentum

$$mu = mv_1 + mv_2 \text{ or, } u = v_1 + v_2 \quad (1)$$

And from the condition, given,

$$\eta = \frac{\frac{1}{2}mu^2 - \left(\frac{1}{2}mv_1^2 + \frac{1}{2}mv_2^2\right)}{\frac{1}{2}mu^2} = 1 - \frac{v_1^2 + v_2^2}{u^2}$$

$$\text{or, } v_1^2 + v_2^2 = (1-\eta)u^2 \quad (2)$$

From (1) and (2),

$$v_1^2 + (u - v_1)^2 = (1-\eta)u^2$$

$$\text{or, } v_1^2 + u^2 - 2uv_1 + v_1^2 = (1-\eta)u^2$$

$$\text{or,} \quad 2v_1^2 - 2v_1 u + \eta u^2 = 0$$

$$\begin{aligned} \text{So,} \quad v_1 &= 2u \pm \frac{\sqrt{4u^2 - 8\eta u^2}}{4} \\ &= \frac{1}{2} \left[ u \pm \sqrt{u^2 - 2\eta u^2} \right] = \frac{1}{2} u (1 \pm \sqrt{1 - 2\eta}) \end{aligned}$$

Positive sign gives the velocity of the 2nd particle which lies ahead. The negative sign is correct for  $v_1$ .

So,  $v_1 = \frac{1}{2} u (1 - \sqrt{1 - 2\eta}) = 5 \text{ m/s}$  will continue moving in the same direction.

Note that  $v_1 = 0$  if  $\eta = 0$  as it must.

**1.173** Since, no external impulsive force is effective on the system " $M + m$ ", its total momentum along any direction will remain conserved.

So from  $p_x = \text{const.}$

$$mu = Mv_1 \cos \theta \quad \text{or,} \quad v_1 = \frac{m}{M} \frac{u}{\cos \theta} \quad (1)$$

and from  $p_y = \text{const}$

$$mv_2 = Mv_1 \sin \theta \quad \text{or,} \quad v_2 = \frac{M}{m} v_1 \sin \theta = u \tan \theta, \quad [\text{using (1)}]$$

Final kinetic energy of the system

$$T_f = \frac{1}{2} mv_2^2 + \frac{1}{2} Mv_1^2$$

And initial kinetic energy of the system =  $\frac{1}{2} mu^2$

$$\text{So,} \quad \% \text{ change} = \frac{T_f - T_i}{T_i} \times 100$$

$$= \frac{\frac{1}{2} m u^2 \tan^2 \theta + \frac{1}{2} M \frac{m^2}{M^2} \frac{u^2}{\cos^2 \theta} - \frac{1}{2} mu^2}{\frac{1}{2} mu^2} \times 100$$

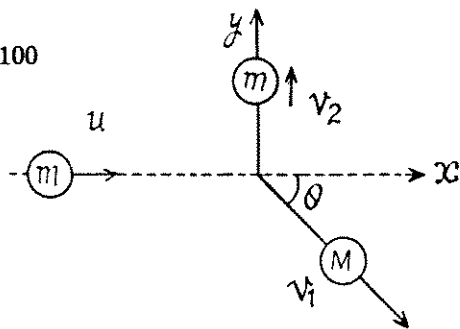
$$= \frac{\frac{1}{2} u^2 \tan^2 \theta + \frac{1}{2} \frac{m}{M} u^2 \sec^2 \theta - \frac{1}{2} u^2}{\frac{1}{2} u^2} \times 100$$

$$= \left( \tan^2 \theta + \frac{m}{M} \sec^2 \theta - 1 \right) \times 100$$

and putting the values of  $\theta$  and  $\frac{m}{M}$ , we get % of change in kinetic energy = -40 %

**1.174** (a) Let the particles  $m_1$  and  $m_2$  move with velocities  $\vec{v}_1$  and  $\vec{v}_2$  respectively. On the basis of solution of problem 1.147 (b)

$$\tilde{P} = \mu v_{rel} = \mu \left| \vec{v}_1 - \vec{v}_2 \right|$$



As

$$\vec{v}_1 \perp \vec{v}_2$$

So,

$$\tilde{p} = \mu \sqrt{v_1^2 + v_2^2} \quad \text{where } \mu = \frac{m_1 m_2}{m_1 + m_2}$$

(b) Again from 1.147 (b)

$$\tilde{T} = \frac{1}{2} \mu v_{rel}^2 = \frac{1}{2} \mu |\vec{v}_1 - \vec{v}_2|^2$$

So,

$$\tilde{T} = \frac{1}{2} \mu (v_1^2 + v_2^2)$$

**1.175** From conservation of momentum

$$\vec{p}_1 = \vec{p}_1' + \vec{p}_2'$$

so

$$(\vec{p}_1 - \vec{p}_1')^2 = p_1^2 - 2 p_1 p_1' \cos \theta_1 + p_1'^2 = p_2'^2$$

From conservation of energy

$$\frac{p_1^2}{2m_1} = \frac{p_1'^2}{2m_1} + \frac{p_2'^2}{2m_2}$$

Eliminating  $p_2'$  we get

$$0 = p_1'^2 \left( 1 + \frac{m_2}{m_1} \right) - 2 p_1' p_1 \cos \theta_1 + p_1^2 \left( 1 - \frac{m_2}{m_1} \right)$$

This quadratic equation for  $p_1'$  has a real solution in terms of  $p_1$  and  $\cos \theta_1$  only if

$$4 \cos^2 \theta_1 \geq 4 \left( 1 - \frac{m_2^2}{m_1^2} \right)$$

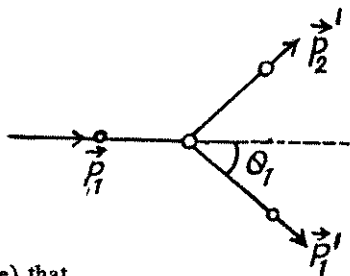
or

$$\sin^2 \theta_1 \leq \frac{m_2^2}{m_1^2}$$

$$\text{or } \sin \theta_1 \leq + \frac{m_2}{m_1} \quad \text{or } \sin \theta_1 \geq - \frac{m_2}{m_1}$$

This clearly implies (since only + sign makes sense) that

$$\sin \theta_{1 \max} = \frac{m_2}{m_1}$$



**1.176** From the symmetry of the problem, the velocity of the disc A will be directed either in the initial direction or opposite to it just after the impact. Let the velocity of the disc A after the collision be  $v'$  and be directed towards right after the collision. It is also clear from the symmetry of problem that the discs B and C have equal speed (say  $v''$ ) in the directions, shown. From the condition of the problem,

$$\cos \theta = \frac{\eta \frac{d}{2}}{d} = \frac{\eta}{2} \quad \text{so, } \sin \theta = \sqrt{4 - \eta^2} / 2 \quad (1)$$

For the three discs, system, from the conservation of linear momentum in the symmetry direction (towards right)

$$mv = 2m v'' \sin \theta + m v' \quad \text{or, } v = 2 v'' \sin \theta + v' \quad (2)$$

From the definition of the coefficient of restitution, we have for the discs A and B (or C)

$$e = \frac{v'' - v' \sin \theta}{v \sin \theta - 0}$$

But  $e = 1$ , for perfectly elastic collision,

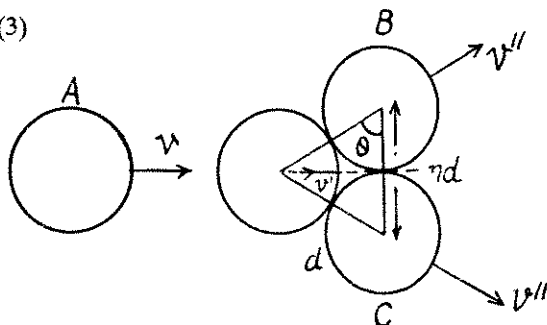
$$\text{So, } v \sin \theta = v'' - v' \sin \theta \quad (3)$$

From (2) and (3),

$$\begin{aligned} v' &= \frac{v(1 - 2 \sin^2 \theta)}{(1 + 2 \sin^2 \theta)} \\ &= \frac{v(\eta^2 - 2)}{6 - \eta^2} \quad \{\text{using (1)}\} \end{aligned}$$

Hence we have,

$$v' = \frac{v(\eta^2 - 2)}{6 - \eta^2}$$



Therefore, the disc A will recoil if  $\eta < \sqrt{2}$  and stop if  $\eta = \sqrt{2}$ .

**Note :** One can write the equations of momentum conservation along the direction perpendicular to the initial direction of disc A and the conservation of kinetic energy instead of the equation of restitution.

- 1.177 (a) Let a molecule comes with velocity  $\vec{v}_1$  to strike another stationary molecule and just after collision their velocities become  $\vec{v}_1'$  and  $\vec{v}_2'$  respectively. As the mass of the each molecule is same, conservation of linear momentum and conservation of kinetic energy for the system (both molecules) respectively gives :

$$\vec{v}_1 = \vec{v}_1' + \vec{v}_2'$$

and

$$v_1^2 = v_1'^2 + v_2'^2$$

From the property of vector addition it is obvious from the obtained Eqs. that

$$\vec{v}_1' \perp \vec{v}_2' \quad \text{or} \quad \vec{v}_1' \cdot \vec{v}_2' = 0$$

- (b) Due to the loss of kinetic energy in inelastic collision  $v_1^2 > v_1'^2 + v_2'^2$

so,  $\vec{v}_1' \cdot \vec{v}_2' > 0$  and therefore angle of divergence  $< 90^\circ$ .

- 1.178 Suppose that at time  $t$ , the rocket has the mass  $m$  and the velocity  $\vec{v}$ , relative to the reference frame, employed. Now consider the inertial frame moving with the velocity that the rocket has at the given moment. In this reference frame, the momentum increment that the rocket & ejected gas system acquires during time  $dt$  is,

$$d\vec{p} = m d\vec{v} + \mu dt \vec{u} = \vec{F} dt$$

$$\text{or, } m \frac{d\vec{v}}{dt} = \vec{F} - \mu \vec{u}$$

$$\text{or, } m \vec{w} = \vec{F} - \mu \vec{u}$$

1.179 According to the question,  $\vec{F} = 0$  and  $\mu = -dm/dt$  so the equation for this system becomes,

$$m \frac{d\vec{v}}{dt} = \frac{dm}{dt} \vec{u}$$

As  $d\vec{v} \uparrow \downarrow \vec{u}$  so,  $m dv = -u dm$ .

Integrating within the limits :

$$\frac{1}{u} \int_0^v dv = - \int_{m_0}^m \frac{dm}{m} \quad \text{or} \quad \frac{v}{u} = \ln \frac{m_0}{m}$$

Thus,  $v = u \ln \frac{m_0}{m}$

As  $d\vec{v} \uparrow \downarrow \vec{u}$ , so in vector form  $\vec{v} = -\vec{u} \ln \frac{m_0}{m}$

1.180 According to the question,  $\vec{F}$  (external force) = 0

So,

$$m \frac{d\vec{v}}{dt} = \frac{dm}{dt} \vec{u}$$

As

$$d\vec{v} \uparrow \downarrow \vec{u},$$

so, in scalar form,

$$m dv = -u dm$$

or,

$$\frac{wdt}{u} = - \frac{dm}{m}$$

Integrating within the limits for  $m(t)$

$$\frac{wt}{u} = - \int_{m_0}^m \frac{dm}{m} \quad \text{or} \quad \frac{v}{u} = - \ln \frac{m}{m_0}$$

Hence,

$$m = m_0 e^{-(wt/u)}$$

1.181 As  $\vec{F} = 0$ , from the equation of dynamics of a body with variable mass;

$$m \frac{d\vec{v}}{dt} = \vec{u} \frac{dm}{dt} \quad \text{or} \quad d\vec{v} = \vec{u} \frac{dm}{m} \quad (1)$$

Now  $d\vec{v} \uparrow \downarrow \vec{u}$  and since  $\vec{u} \perp \vec{v}$ , we must have  $|d\vec{v}| = v_0 d\alpha$  (because  $v_0$  is constant) where  $d\alpha$  is the angle by which the spaceship turns in time  $dt$ .

So,

$$-u \frac{dm}{m} = v_0 d\alpha \quad \text{or} \quad d\alpha = -\frac{u}{v_0} \frac{dm}{m}$$

or,

$$\alpha = -\frac{u}{v_0} \int_{m_0}^m \frac{dm}{m} = \frac{u}{v_0} \ln \left( \frac{m_0}{m} \right)$$



1.182 We have  $\frac{dm}{dt} = -\mu$  or,  $dm = -\mu dt$

Integrating 
$$\int_{m_0}^m dm = -\mu \int_0^t dt \text{ or, } m = m_0 - \mu t$$

As  $\vec{u} = 0$  so, from the equation of variable mass system :

$$(m_0 - \mu t) \frac{d\vec{v}}{dt} = \vec{F} \text{ or, } \frac{d\vec{v}}{dt} = \vec{w} = \vec{F}/(m_0 - \mu t)$$

or, 
$$\int_0^{\vec{v}} d\vec{v} = \vec{F} \int_0^t \frac{dt}{(m_0 - \mu t)}$$

Hence 
$$\vec{v} = \frac{\vec{F}}{\mu} \ln \left( \frac{m_0}{m_0 - \mu t} \right)$$

1.183 Let the car be moving in a reference frame to which the hopper is fixed and at any instant of time, let its mass be  $m$  and velocity  $\vec{v}$ .

Then from the general equation, for variable mass system.

$$m \frac{d\vec{v}}{dt} = \vec{F} + \vec{u} \frac{dm}{dt}$$

We write the equation, for our system as,

$$m \frac{d\vec{v}}{dt} = \vec{F} - \vec{v} \frac{dm}{dt} \text{ as, } \vec{u} = -\vec{v} \quad (1)$$

So 
$$\frac{d}{dt} (\vec{mv}) = \vec{F}$$

and 
$$\vec{v} = \frac{\vec{F}t}{m} \text{ on integration.}$$

But 
$$m = m_0 + \mu t$$

so, 
$$\vec{v} = \frac{\vec{F}t}{m_0 \left( 1 + \frac{\mu t}{m_0} \right)}$$

Thus the sought acceleration, 
$$\vec{w} = \frac{d\vec{v}}{dt} = \frac{\vec{F}}{m_0 \left( 1 + \frac{\mu t}{m_0} \right)^2}$$

1.184 Let the length of the chain inside the smooth horizontal tube at an arbitrary instant is  $x$ .  
From the equation,

$$m\vec{w} = \vec{F} + \vec{u} \frac{dm}{dt}$$

as  $\vec{u} = 0$ ,  $\vec{F} \uparrow \vec{w}$ , for the chain inside the tube

$$\lambda x w = T \text{ where } \lambda = \frac{m}{l} \quad (1)$$

Similarly for the overhanging part,

$$\vec{u} = 0$$

$$\text{Thus } mw = F$$

$$\text{or } \lambda h w = \lambda h g - T \quad (2)$$

From (1) and (2),

$$\lambda(x+h)w = \lambda h g \text{ or, } (x+h)v \frac{dv}{ds} = hg$$

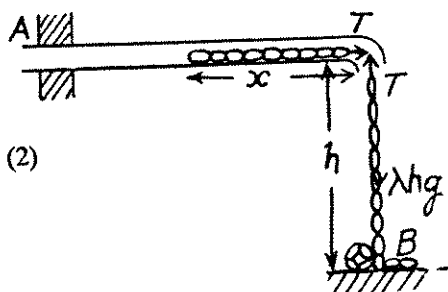
$$\text{or, } (x+h)v \frac{dv}{(-dx)} = gh,$$

[As the length of the chain inside the tube decreases with time,  $ds = -dx$ .]

$$\text{or, } v dv = -gh \frac{dx}{x+h}$$

$$\text{Integrating, } \int_0^v v dv = -gh \int_{(l-h)}^0 \frac{dx}{x+h}$$

$$\text{or, } \frac{v^2}{2} = gh \ln \left( \frac{l}{h} \right) \text{ or } v = \sqrt{2gh \ln \left( \frac{l}{h} \right)}$$



**1.185** Force moment relative to point  $O$  ;

$$\vec{N} = \frac{d\vec{M}}{dt} = 2b\vec{t}$$

Let the angle between  $\vec{M}$  and  $\vec{N}$ ,

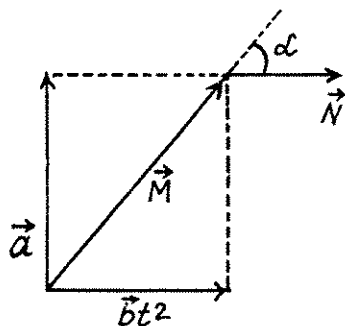
$$\alpha = 45^\circ \text{ at } t = t_0,$$

$$\begin{aligned} \text{Then } \frac{1}{\sqrt{2}} &= \frac{\vec{M} \cdot \vec{N}}{|\vec{M}| |\vec{N}|} = \frac{(\vec{a} + b\vec{t}_0^2) \cdot (2b\vec{t}_0)}{\sqrt{a^2 + b^2 t_0^4} 2bt_0} \\ &= \frac{2b^2 t_0^3}{\sqrt{a^2 + b^2 t_0^4} 2bt_0} = \frac{bt_0^2}{\sqrt{a^2 + b^2 t_0^4}} \end{aligned}$$

$$\text{So, } 2b^2 t_0^4 = a^2 + b^2 t_0^4 \text{ or, } t_0 = \sqrt{\frac{a}{b}} \text{ (as } t_0 \text{ cannot be negative)}$$

It is also obvious from the figure that the angle  $\alpha$  is equal to  $45^\circ$  at the moment  $t_0$ ,

$$\text{when } a = b t_0^2, \text{ i.e. } t_0 = \sqrt{a/b} \text{ and } \vec{N} = 2\sqrt{\frac{a}{b}} b.$$



$$\begin{aligned}
 1.186 \quad \vec{M}(t) &= \vec{r} \times \vec{p} = \left( \vec{v}_0 t + \frac{1}{2} \vec{g} t^2 \right) \times m (\vec{v}_0 + \vec{g} t) \\
 &= m v_0 g t^2 \sin \left( \frac{\pi}{2} + \alpha \right) (-\vec{k}) + \frac{1}{2} m v_0 g t^2 \sin \left( \frac{\pi}{2} + \alpha \right) (\vec{k}) \\
 &= \frac{1}{2} m v_0 g t^2 \cos \alpha (-\vec{k}) :
 \end{aligned}$$

$$\text{Thus } M(t) = \frac{m v_0 g t^2 \cos \alpha}{2}$$

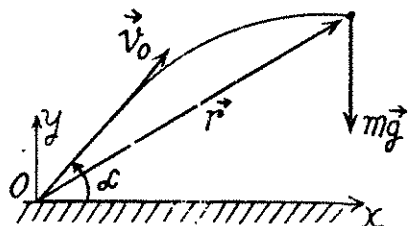
Thus angular momentum at maximum height

$$\text{i.e. at } t = \frac{\tau}{2} = \frac{v_0 \sin \alpha}{g},$$

$$M\left(\frac{\tau}{2}\right) = \left( \frac{m v_0^3}{2g} \right) \sin^2 \alpha \cos \alpha = 37 \text{ kg} \cdot \text{m}^2/\text{s}$$

Alternate :

$$\begin{aligned}
 \vec{M}(0) &= 0 \text{ so, } \vec{M}(t) = \int_0^t \vec{N} dt = \int_0^t (\vec{r} \times m \vec{g}) \\
 &= \int_0^t \left[ \left( \vec{v}_0 t + \frac{1}{2} \vec{g} t^2 \right) \times m \vec{g} \right] dt = \left( \vec{v}_0 \times m \vec{g} \right) \frac{t^2}{2}
 \end{aligned}$$

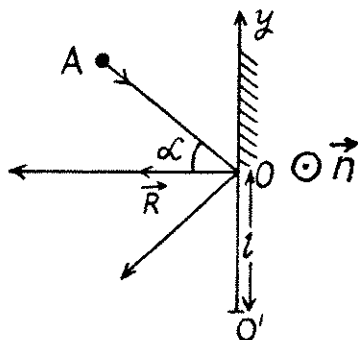


- 1.187 (a) The disc experiences gravity, the force of reaction of the horizontal surface, and the force  $\vec{R}$  of reaction of the wall at the moment of the impact against it. The first two forces counter-balance each other, leaving only the force  $\vec{R}$ . It's moment relative to any point of the line along which the vector  $\vec{R}$  acts or along normal to the wall is equal to zero and therefore the angular momentum of the disc relative to any of these points does not change in the given process.

(b) During the course of collision with wall the position of disc is same and is equal to  $\vec{r}_{oo'}$ . Obviously the increment in linear momentum of the ball  $\Delta \vec{p} = 2mv \cos \alpha \hat{n}$

Here,  $\Delta \vec{M} = \vec{r}_{oo'} \times \Delta \vec{p} = 2mv l \cos \alpha \hat{n}$  and directed normally emerging from the plane of figure

$$\text{Thus } |\Delta \vec{M}| = 2mv l \cos \alpha$$



- 1.188 (a) The ball is under the influence of forces  $\vec{T}$  and  $m\vec{g}$  at all the moments of time, while moving along a horizontal circle. Obviously the vertical component of  $\vec{T}$  balance  $m\vec{g}$  and

so the net moment of these two about any point becomes zero. The horizontal component of  $\vec{T}$ , which provides the centripetal acceleration to ball is already directed toward the centre ( $C$ ) of the horizontal circle, thus its moment about the point  $C$  equals zero at all the moments of time. Hence the net moment of the force acting on the ball about point  $C$  equals zero and that's why the angular momentum of the ball is conserved about the horizontal circle.

(b) Let  $\alpha$  be the angle which the thread forms with the vertical.

Now from equation of particle dynamics :

$$T \cos \alpha = mg \text{ and } T \sin \alpha = m\omega^2 l \sin \alpha$$

$$\text{Hence on solving } \cos \alpha = \frac{g}{\omega^2 l} \quad (1)$$

As  $|\vec{M}|$  is constant in magnitude so from figure.

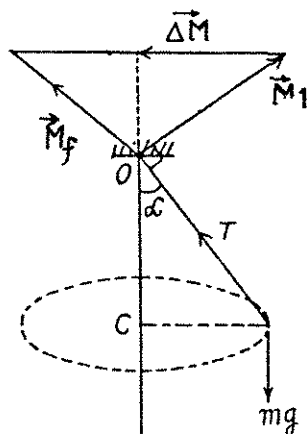
$$|\Delta \vec{M}| = 2M \cos \alpha \text{ where}$$

$$M = |\vec{M}_i| = |\vec{M}_f|$$

$$= |\vec{r}_{bo} \times m \vec{v}| = mvl \left( \text{as } \vec{r}_{bo} \perp \vec{v} \right)$$

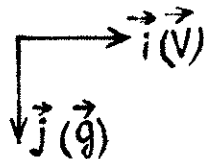
$$\text{Thus } |\Delta \vec{M}| = 2mvl \cos \alpha = 2m\omega l^2 \sin \alpha \cos \alpha$$

$$= \frac{2mgl}{\omega} \sqrt{1 - \left( \frac{g}{\omega^2 l} \right)^2} \text{ (using 1).}$$



- 1.189 During the free fall time  $t = \tau = \sqrt{\frac{2h}{g}}$ , the reference point  $O$  moves in horizontal direction (say towards right) by the distance  $V\tau$ . In the translating frame as  $\vec{M}(O) = 0$ , so

$$\begin{aligned} \Delta \vec{M} &= \vec{M}_f = \vec{r} \\ &= (-V\tau \vec{i} + h\vec{j}) \times m [g\tau \vec{j} - V\vec{i}] \\ &= -mVg\tau^2 h \vec{k} + mVh(\vec{k}) \\ &= -mVg \left( \frac{2h}{g} \right) \vec{k} + mVh(\vec{k}) = -mVh\vec{k} \end{aligned}$$



$$\text{Hence } |\Delta \vec{M}| = mVh$$

- 1.190 The Coriolis force is  $(2m \vec{v}' \times \vec{\omega})$ .

Here  $\vec{\omega}$  is along the  $z$ -axis (vertical). The moving disc is moving with velocity  $v_0$  which is constant. The motion is along the  $x$ -axis say. Then the Coriolis force is along  $y$ -axis and has the magnitude  $2m v_0 \omega$ . At time  $t$ , the distance of the centre of moving disc from  $O$  is  $v_0 t$  (along  $x$ -axis). Thus the torque  $N$  due to the coriolis force is

$$N = 2m v_0 \omega v_0 t \text{ along the } z\text{-axis.}$$

Hence equating this to  $\frac{dM}{dt}$

$$\frac{dM}{dt} = 2m v_0^2 \omega t \quad \text{or} \quad M = m v_0^2 \omega t^2 + \text{constant.}$$

The constant is irrelevant and may be put equal to zero if the disc is originally set in motion from the point  $O$ .

This discussion is approximate. The Coriolis force will cause the disc to swerve from straight line motion and thus cause deviation from the above formula which will be substantial for large  $t$ .

**1.191** If  $\dot{r}$  = radial velocity of the particle then the total energy of the particle at any instant is

$$\frac{1}{2} m \dot{r}^2 + \frac{M^2}{2mr^2} + k r^2 = E \quad (1)$$

where the second term is the kinetic energy of angular motion about the centre  $O$ . Then the extreme values of  $r$  are determined by  $\dot{r} = 0$  and solving the resulting quadratic equation

$$k(r^2)^2 - E r^2 + \frac{M^2}{2m} = 0$$

we get

$$r^2 = \frac{E \pm \sqrt{E^2 - \frac{2M^2 k}{m}}}{2k}$$

From this we see that

$$E = k(r_1^2 + r_2^2) \quad (2)$$

where  $r_1$  is the minimum distance from  $O$  and  $r_2$  is the maximum distance. Then

$$\frac{1}{2} m v_2^2 + 2k r_2^2 = k(r_1^2 + r_2^2)$$

Hence,

$$m = \frac{2k r_2^2}{v_2^2}$$

**Note :** Eq. (1) can be derived from the standard expression for kinetic energy and angular momentum in plane polar coordinates :

$$T = \frac{1}{2} m \dot{r}^2 + \frac{1}{2} m r^2 \dot{\theta}^2$$

$M$  = angular momentum =  $m r^2 \dot{\theta}$

**1.192** The swinging sphere experiences two forces : The gravitational force and the tension of the thread. Now, it is clear from the condition, given in the problem, that the moment of these forces about the vertical axis, passing through the point of suspension  $N_z = 0$ . Consequently, the angular momentum  $M_z$  of the sphere relative to the given axis ( $z$ ) is constant.

Thus

$$m v_0 (l \sin \theta) = m v l \quad (1)$$

where  $m$  is the mass of the sphere and  $v$  is its velocity in the position, when the thread forms an angle  $\frac{\pi}{2}$  with the vertical. Mechanical energy is also conserved, as the sphere is

under the influence of only one other force, i.e. tension, which does not perform any work, as it is always perpendicular to the velocity.

$$\text{So,} \quad \frac{1}{2}mv_0^2 + mgl \cos \theta = \frac{1}{2}mv^2 \quad (2)$$

From (1) and (2), we get,

$$v_0 = \sqrt{2gl/\cos \theta}$$

- 1.193 Forces, acting on the mass  $m$  are shown in the figure. As  $\vec{N} = m\vec{g}$ , the net torque of these two forces about any fixed point must be equal to zero. Tension  $T$ , acting on the mass  $m$  is a central force, which is always directed towards the centre  $O$ . Hence the moment of force  $T$  is also zero about the point  $O$  and therefore the angular momentum of the particle  $m$  is conserved about  $O$ .

Let, the angular velocity of the particle be  $\omega$ , when the separation between hole and particle  $m$  is  $r$ , then from the conservation of momentum about the point  $O$ ,

$$m(\omega_0 r_0) r_0 = m(\omega r) r,$$

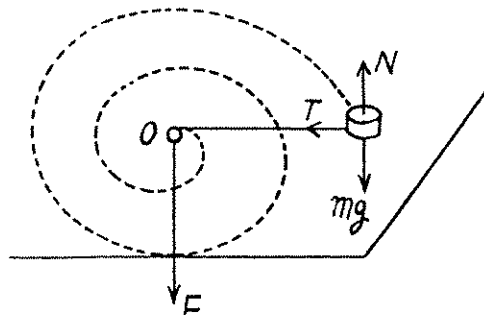
$$\text{or} \quad \omega = \frac{\omega_0 r_0^2}{r^2}$$

Now, from the second law of motion for  $m$ ,

$$T = F = m\omega^2 r$$

Hence the sought tension;

$$F = \frac{m\omega_0^2 r_0^4 r}{r^4} = \frac{m\omega_0^2 r_0^4}{r^3}$$



- 1.194 On the given system the weight of the body  $m$  is the only force whose moment is effective about the axis of pulley. Let us take the sense of  $\vec{\omega}$  of the pulley at an arbitrary instant as the positive sense of axis of rotation (z-axis)

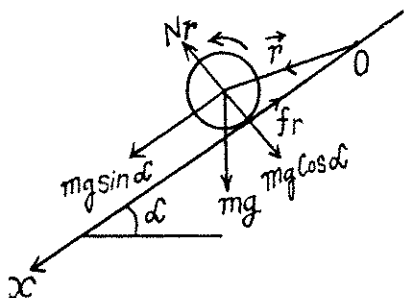
$$\text{As} \quad M_z(0) = 0, \text{ so, } \Delta M_z = M_z(t) = \int N_z dt$$

$$\text{So,} \quad M_z(t) = \int_0^t mg R dt = mg R t$$

- 1.195 Let the point of contact of sphere at initial moment ( $t = 0$ ) be at  $O$ . At an arbitrary moment, the forces acting on the sphere are shown in the figure. We have normal reaction  $N_r = mg \sin \alpha$  and both pass through same line and the force of static friction passes through the point  $O$ , thus the moment about point  $O$  becomes zero. Hence  $mg \sin \alpha$  is the only force which has effective torque about point  $O$ , and is given by  $|\vec{N}| = mg R \sin \alpha$  normally emerging from the plane of figure.

$$\text{As } \vec{M}(t=0) = 0, \text{ so, } \Delta \vec{M} = \vec{M}(t) = \int \vec{N} dt$$

$$\text{Hence,} \quad M(t) = Nt = mg R \sin \alpha t$$



- 1.196 Let position vectors of the particles of the system be  $\vec{r}_i$  and  $\vec{r}_i'$  with respect to the points  $O$  and  $O'$  respectively. Then we have,

$$\vec{r}_i = \vec{r}_i' + \vec{r}_0 \quad (1)$$

where  $\vec{r}_0$  is the radius vector of  $O'$  with respect to  $O$ .

Now, the angular momentum of the system relative to the point  $O$  can be written as follows;

$$\vec{M} = \sum (\vec{r}_i \times \vec{p}_i) = \sum (\vec{r}_i' \times \vec{p}_i) + \sum (\vec{r}_0 \times \vec{p}_i) \quad [\text{using (1)}]$$

or, 
$$\vec{M} = \vec{M}' + (\vec{r}_0 \times \vec{p}), \text{ where, } \vec{p} = \sum \vec{p}_i \quad (2)$$

From (2), if the total linear momentum of the system,  $\vec{p} = 0$ , then its angular momentum does not depend on the choice of the point  $O$ .

*Note that in the C.M. frame, the system of particles, as a whole is at rest.*

- 1.197 On the basis of solution of problem 1.196, we have concluded that; "in the C.M. frame, the angular momentum of system of particles is independent of the choice of the point, relative to which it is determined" and in accordance with the problem, this is denoted by  $\vec{M}$ .

We denote the angular momentum of the system of particles, relative to the point  $O$ , by  $\vec{M}$ . Since the internal and proper angular momentum  $\vec{M}$ , in the C.M. frame, does not depend on the choice of the point  $O'$ , this point may be taken coincident with the point  $O$  of the  $K$ -frame, at a given moment of time. Then at that moment, the radius vectors of all the particles, in both reference frames, are equal ( $\vec{r}_i' = \vec{r}_i$ ) and the velocities are related by the equation,

$$\vec{v}_i = \vec{v}_i' + \vec{v}_c, \quad (1)$$

where  $\vec{v}_c$  is the velocity of C.M. frame, relative to the  $K$ -frame. Consequently, we may write,

$$\vec{M} = \sum m_i (\vec{r}_i \times \vec{v}_i) = \sum m_i (\vec{r}_i' \times \vec{v}_i') + \sum m_i (\vec{r}_i' \times \vec{v}_c)$$

or, 
$$\vec{M} = \vec{M} + m (\vec{r}_c \times \vec{v}_c), \text{ as } \sum m_i \vec{r}_i = m \vec{r}_c, \text{ where } m = \sum m_i.$$

or, 
$$\vec{M} = \vec{M} + (\vec{r}_c \times m \vec{v}_c) = \vec{M} + (\vec{r}_c \times \vec{p})$$

- 1.198 From conservation of linear momentum along the direction of incident ball for the system consists with colliding ball and sphere

$$mv_0 = mv' + \frac{m}{2} v_1 \quad (1)$$

where  $v'$  and  $v_1$  are the velocities of ball and sphere 1 respectively after collision. (Remember that the collision is head on).

As the collision is perfectly elastic, from the definition of co-efficient of restitution,

$$1 = \frac{v' - v_1}{0 - v_0} \text{ or, } v' - v_1 = -v_0 \quad (2)$$

Solving (1) and (2), we get,

$$v_1 = \frac{4}{3} v_0, \text{ directed towards right.}$$

In the C.M. frame of spheres 1 and 2 (Fig.)

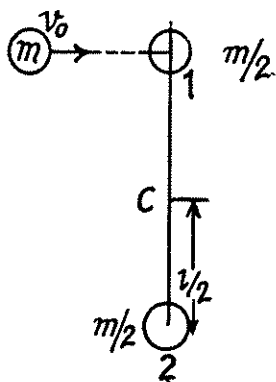
$$\vec{p}_1 = -\vec{p}_2 \text{ and } |\vec{p}_1| = |\vec{p}_2| = \mu |\vec{v}_1 - \vec{v}_2|$$

$$\text{Also, } \vec{r}_{1C} = -\vec{r}_{2C}, \text{ thus } \vec{M} = 2 [\vec{r}_{1C} \times \vec{p}_1]$$

$$\text{As } \vec{r}_{1C} \perp \vec{p}_1, \text{ so, } \vec{M} = 2 \left[ \frac{l}{2} \frac{m/2}{2} \frac{4 v_0}{3} \hat{n} \right]$$

(where  $\hat{n}$  is the unit vector in the sense of  $\vec{r}_{1C} \times \vec{p}_1$ )

$$\text{Hence } \vec{M} = \frac{m v_0 l}{3}$$



1.199 In the C.M. frame of the system (both the discs + spring), the linear momentum of the discs are related by the relation,  $\vec{p}_1 = -\vec{p}_2$  at all the moments of time.

$$\text{where, } \vec{p}_1 = \vec{p}_2 = \vec{p} = \mu v_{rel}$$

And the total kinetic energy of the system,

$$T = \frac{1}{2} \mu v_{rel}^2 \text{ [See solution of 1.147 (b)]}$$

Bearing in mind that at the moment of maximum deformation of the spring, the projection of  $\vec{v}_{rel}$  along the length of the spring becomes zero, i.e.  $v_{rel}(x) = 0$ .

The conservation of mechanical energy of the considered system in the C.M. frame gives.

$$\frac{1}{2} \left( \frac{m}{2} \right) v_0^2 = \frac{1}{2} \kappa x^2 + \frac{1}{2} \left( \frac{m}{2} \right) v_{rel}^2(y) \quad (1)$$

Now from the conservation of angular momentum of the system about the C.M.,

$$\frac{1}{2} \left( \frac{l_0}{2} \right) \left( \frac{m}{2} v_0 \right) = 2 \left( \frac{l_0 + x}{2} \right) \frac{m}{2} v_{rel}(y)$$

$$\text{or, } v_{rel}(y) = \frac{v_0 l_0}{(l_0 + x)} = v_0 \left( 1 + \frac{x}{l_0} \right)^{-1} \approx v_0 \left( 1 - \frac{x}{l_0} \right), \text{ as } x \ll l_0 \quad (2)$$

$$\text{Using (2) in (1), } \frac{1}{2} m v_0^2 \left[ 1 - \left( 1 - \frac{x}{l_0} \right)^2 \right] = \kappa x^2$$

$$\text{or, } \frac{1}{2} m v_0^2 \left[ 1 - \left( 1 - \frac{2x}{l_0} + \frac{x^2}{l_0^2} \right) \right] = \kappa x^2$$

$$\text{or, } \frac{m v_0^2 x}{l_0} \approx \kappa x^2, \text{ [neglecting } x^2/l_0^2]$$

$$\text{As } x \neq 0, \text{ thus } x = \frac{m v_0^2}{\kappa l_0}$$



## 1.4 UNIVERSAL GRAVITATION

1.200 We have

$$\frac{Mv^2}{r} = \frac{\gamma M m_s}{r^2} \quad \text{or} \quad r = \frac{\gamma m_s}{v^2}$$

Thus 
$$\omega = \frac{v}{r} = \frac{v}{\gamma m_s / v^2} = \frac{v^3}{\gamma m_s}$$

(Here  $m_s$  is the mass of the Sun.)

So 
$$T = \frac{2\pi \gamma m_s}{v^3} = \frac{2\pi \times 6.67 \times 10^{-11} \times 1.97 \times 10^{30}}{(34.9 \times 10^3)^3} = 1.94 \times 10^7 \text{ sec} = 225 \text{ days.}$$

(The answer is incorrectly written in terms of the planetary mass  $M$ )

1.201 For any planet

$$MR\omega^2 = \frac{\gamma M m_s}{R^2} \quad \text{or} \quad \omega = \sqrt{\frac{\gamma m_s}{R^3}}$$

So, 
$$T = \frac{2\pi}{\omega} = 2\pi R^{3/2} / \sqrt{\gamma m_s}$$

(a) Thus 
$$\frac{T_J}{T_E} = \left(\frac{R_J}{R_E}\right)^{3/2}$$

So 
$$\frac{R_J}{R_E} = (T_J / T_E)^{2/3} = (12)^{2/3} = 5.24.$$

(b) 
$$V_J^2 = \frac{\gamma m_s}{R_J}, \quad \text{and} \quad R_J = \left(T \frac{\sqrt{\gamma m_s}}{2\pi}\right)^{2/3}$$

So 
$$V_J^2 = \frac{(\gamma m_s)^{2/3} (2\pi)^{2/3}}{T^{2/3}} \quad \text{or,} \quad V_J = \left(\frac{2\pi \gamma m_s}{T}\right)^{2/3}$$

where  $T = 12$  years.  $m_s =$  mass of the Sun.

Putting the values we get  $V_J = 12.97 \text{ km/s}$

$$\text{Acceleration} = \frac{v_J^2}{R_J} = \left(\frac{2\pi \gamma m_s}{T}\right)^{2/3} \times \left(\frac{2\pi}{T \sqrt{\gamma m_s}}\right)^{2/3}$$

$$= \left(\frac{2\pi}{T}\right)^{4/3} (\gamma m_s)^{1/3}$$

$$= 2.15 \times 10^{-4} \text{ km/s}^2$$

1.202 Semi-major axis =  $(r + R)/2$ 

It is sufficient to consider the motion be along a circle of semi-major axis  $\frac{r+R}{2}$  for  $T$  does not depend on eccentricity.

$$\text{Hence } T = \frac{2\pi \left( \frac{r+R}{2} \right)^{3/2}}{\sqrt{\gamma m_s}} = \pi \sqrt{(r+R)^3 / 2 \gamma m_s}$$

(again  $m_s$  is the mass of the Sun)

1.203 We can think of the body as moving in a very elongated orbit of maximum distance  $R$  and minimum distance 0 so semi major axis =  $R/2$ . Hence if  $\tau$  is the time of fall then

$$\left( \frac{2\tau}{T} \right)^2 = \left( \frac{R/2}{R} \right)^3 \quad \text{or} \quad \tau^2 = T^2/32$$

$$\text{or} \quad \tau = T / 4\sqrt{2} = 365 / 4\sqrt{2} = 64.5 \text{ days.}$$

1.204  $T = 2\pi R^{3/2} / \sqrt{\gamma m_s}$ 

If the distances are scaled down,  $R^{3/2}$  decreases by a factor  $\eta^{3/2}$  and so does  $m_s$ . Hence  $T$  does not change.

1.205 The double star can be replaced by a single star of mass  $\frac{m_1 m_2}{m_1 + m_2}$  moving about the centre of mass subjected to the force  $\gamma m_1 m_2 / r^2$ . Then

$$T = \frac{2\pi r^{3/2}}{\sqrt{\gamma m_1 m_2 / \frac{m_1 m_2}{m_1 + m_2}}} = \frac{2\pi r^{3/2}}{\sqrt{\gamma M}}$$

$$\text{So} \quad r^{3/2} = \frac{T}{2\pi} \sqrt{\gamma M}$$

$$\text{or,} \quad r = \left( \frac{T}{2\pi} \right)^{2/3} (\gamma M)^{1/3} = \sqrt[3]{\gamma M (T/2\pi)^2}$$

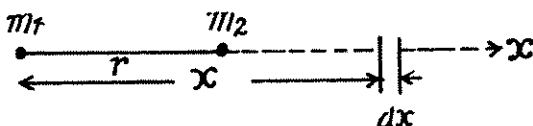
1.206 (a) The gravitational potential due to  $m_1$  at the point of location of  $m_2$  :

$$V_2 = \int_r^\infty \vec{G} \cdot d\vec{r} = \int_r^\infty -\frac{\gamma m_1}{x^2} dx = -\frac{\gamma m_1}{r}$$

$$\text{So,} \quad U_{21} = m_2 V_2 = -\frac{\gamma m_1 m_2}{r}$$

$$\text{Similarly} \quad U_{12} = -\frac{\gamma m_1 m_2}{r}$$

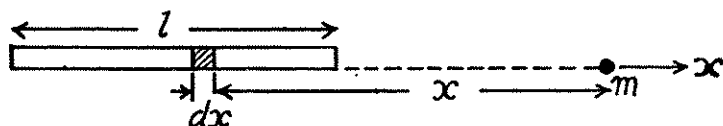
Hence

$$U_{12} = U_{21} = U = -\frac{\gamma m_1 m_2}{r}$$


(b) Choose the location of the point mass as the origin. Then the potential energy  $dU$  of an element of mass  $dM = \frac{M}{l}dx$  of the rod in the field of the point mass is

$$dU = -\gamma m \frac{M}{l} dx \frac{1}{x}$$

where  $x$  is the distance between the element and the point. (Note that the rod and the point mass are on a straight line.) If then  $a$  is the distance of the nearer end of the rod from the point mass.



$$U = -\gamma \frac{mM}{l} \int_a^{a+l} \frac{dx}{x} = -\gamma \frac{mM}{l} \ln \left( 1 + \frac{l}{a} \right)$$

The force of interaction is

$$\begin{aligned} F &= -\frac{\partial U}{\partial a} \\ &= -\gamma \frac{mM}{l} \times \frac{1}{1 + \frac{l}{a}} \left( -\frac{l}{a^2} \right) = -\frac{\gamma mM}{a(a+l)} \end{aligned}$$

Minus sign means attraction.

**1.207** As the planet is under central force (gravitational interaction), its angular momentum is conserved about the Sun (which is situated at one of the foci of the ellipse)

$$\text{So, } m v_1 r_1 = m v_2 r_2 \quad \text{or, } v_1^2 = \frac{v_2^2 r_2^2}{r_1^2} \quad (1)$$

From the conservation of mechanical energy of the system (Sun + planet),

$$-\frac{\gamma m_s m}{r_1} + \frac{1}{2} m v_1^2 = -\frac{\gamma m_s m}{r_2} + \frac{1}{2} m v_2^2$$

$$\text{or, } -\frac{\gamma m_s}{r_1} + \frac{1}{2} v_2^2 \frac{r_2^2}{r_1^2} = -\left( \frac{\gamma m_s}{r_2} \right) + \frac{1}{2} v_2^2 \quad [\text{Using (1)}]$$

$$\text{Thus, } v_2 = \sqrt{2 \gamma m_s r_1 / r_2 (r_1 + r_2)} \quad (2)$$

$$\text{Hence } M = m v_2 r_2 = m \sqrt{2 \gamma m_s r_1 r_2 / (r_1 + r_2)}$$

- 1.208 From the previous problem, if  $r_1$ ,  $r_2$  are the maximum and minimum distances from the sun to the planet and  $v_1$ ,  $v_2$  are the corresponding velocities, then, say,

$$E = \frac{1}{2}mv_2^2 - \frac{\gamma mm_s}{r_2}$$

$$= \frac{\gamma mm_s}{r_1 + r_2} \cdot \frac{r_1}{r_2} - \frac{\gamma mm_s}{r_2} = -\frac{\gamma mm_s}{r_1 + r_2} = -\frac{\gamma mm_s}{2a} \quad [\text{Using Eq. (2) of 1.207}]$$

where  $2a = \text{major axis} = r_1 + r_2$ . The same result can also be obtained directly by writing an equation analogous to Eq (1) of problem 1.191.

$$E = \frac{1}{2}m\dot{r}^2 + \frac{M^2}{2mr^2} - \frac{\gamma mm_s}{r}$$

(Here  $M$  is angular momentum of the planet and  $m$  is its mass). For extreme position  $\dot{r} = 0$  and we get the quadratic

$$Er^2 + \gamma mm_s r - \frac{M^2}{2m} = 0$$

The sum of the two roots of this equation are

$$r_1 + r_2 = -\frac{\gamma mm_s}{E} = 2a$$

Thus

$$E = -\frac{\gamma mm_s}{2a} = \text{constant}$$

- 1.209 From the conservation of angular momentum about the Sun.

$$m v_0 r_0 \sin \alpha = m v_1 r_1 = m v_2 r_2 \quad \text{or,} \quad v_1 r_1 = v_2 r_2 = v_0 r_0 \sin \alpha \quad (1)$$

From conservation of mechanical energy,

$$\frac{1}{2}m v_0^2 - \frac{\gamma m_s m}{r_0} = \frac{1}{2}m v_1^2 - \frac{\gamma m_s m}{r_1}$$

$$\text{or,} \quad \frac{v_0^2}{2} - \frac{\gamma m_s}{r_0} = \frac{v_0^2 r_0^2 \sin^2 \alpha}{2 r_1^2} - \frac{\gamma m_s}{r_1} \quad (\text{Using 1})$$

$$\text{or,} \quad \left( v_0^2 - \frac{2 \gamma m_s}{r_0} \right) r_1^2 + 2 \gamma m_s r_1 - v_0^2 r_0^2 \sin^2 \alpha = 0$$

$$\text{So,} \quad r_1 = \frac{-2 \gamma m_s \pm \sqrt{4 \gamma^2 m_s^2 + 4 \left( v_0^2 r_0^2 \sin^2 \alpha \right) \left( v_0^2 - \frac{2 \gamma m_s}{r_0} \right)}}{2 \left( v_0^2 - \frac{2 \gamma m_s}{r_0} \right)}$$

$$= \frac{1 \pm \sqrt{1 - \frac{v_0^2 r_0^2 \sin^2 \alpha}{\gamma m_s} \left( \frac{2}{r_0} - \frac{v_0^2}{\gamma m_s} \right)}}{\left( \frac{2}{r_0} - \frac{v_0^2}{\gamma m_s} \right)} = \frac{r_0 \left[ 1 \pm \sqrt{1 - (2 - \eta) \eta \sin^2 \alpha} \right]}{(2 - \eta)}$$

where  $\eta = v_0^2 r_0 / \gamma m_s$  ( $m_s$  is the mass of the Sun).

**1.210** At the minimum separation with the Sun, the cosmic body's velocity is perpendicular to its position vector relative to the Sun. If  $r_{\min}$  be the sought minimum distance, from conservation of angular momentum about the Sun (C).

$$mv_0 l = mvr_{\min} \text{ or, } v = \frac{v_0 l}{r_{\min}} \quad (1)$$

From conservation of mechanical energy of the system (sun + cosmic body),

$$\frac{1}{2}mv_0^2 = -\frac{\gamma m_s m}{r_{\min}} + \frac{1}{2}mv^2$$

$$\text{So, } \frac{v_0^2}{2} = -\frac{\gamma m_s}{r_{\min}} + \frac{v_0^2}{2r_{\min}^2} \quad (\text{using 1})$$

$$\text{or, } v_0^2 r_{\min}^2 + 2\gamma m_s r_{\min} - v_0^2 l^2 = 0$$

$$\text{So, } r_{\min} = \frac{-2\gamma m_s \pm \sqrt{4\gamma^2 m_s^2 + 4v_0^2 v_0^2 l^2}}{2v_0^2} = \frac{-\gamma m_s \pm \sqrt{\gamma^2 m_s^2 + v_0^4 l^2}}{v_0^2}$$

Hence, taking positive root

$$r_{\min} = (\gamma m_s / v_0^2) \left[ \sqrt{1 + (l v_0^2 / \gamma m_s)^2} - 1 \right]$$

**1.211** Suppose that the sphere has a radius equal to  $a$ . We may imagine that the sphere is made up of concentric thin spherical shells (layers) with radii ranging from 0 to  $a$ , and each spherical layer is made up of elementary bands (rings). Let us first calculate potential due to an elementary band of a spherical layer at the point of location of the point mass  $m$  (say point  $P$ ) (Fig.). As all the points of the band are located at the distance  $l$  from the point  $P$ , so,

$$\partial \varphi = -\frac{\gamma \partial M}{l} \quad (\text{where mass of the band}) \quad (1)$$

$$\begin{aligned} \partial M &= \left( \frac{dM}{4\pi a^2} \right) (2\pi a \sin \theta) (a d\theta) \\ &= \left( \frac{dM}{2} \right) \sin \theta d\theta \end{aligned} \quad (2)$$

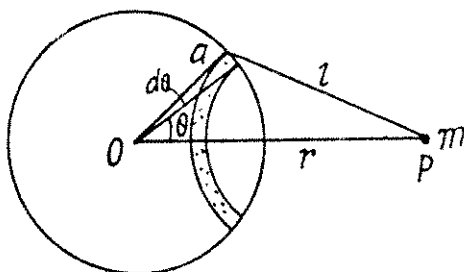
$$\text{And } l^2 = a^2 + r^2 - 2ar \cos \theta \quad (3)$$

Differentiating Eq. (3), we get

$$l dl = ar \sin \theta d\theta \quad (4)$$

Hence using above equations

$$\partial \varphi = -\left( \frac{\gamma dM}{2ar} \right) dl \quad (5)$$



Now integrating this Eq. over the whole spherical layer

$$d\varphi = \int \partial\varphi = -\frac{\gamma dM}{2ar} \int_{r-a}^{r+a}$$

So 
$$d\varphi = -\frac{\gamma dM}{r} \quad (6)$$

Equation (6) demonstrates that the potential produced by a thin uniform spherical layer outside the layer is such as if the whole mass of the layer were concentrated at its centre; Hence the potential due to the sphere at point  $P$ ;

$$\varphi = \int d\varphi = -\frac{\gamma}{r} \int dM = -\frac{\gamma M}{r} \quad (7)$$

This expression is similar to that of Eq. (6)

Hence the sought potential energy of gravitational interaction of the particle  $m$  and the sphere,

$$U = m\varphi = -\frac{\gamma Mm}{r}$$

(b) Using the Eq., 
$$G_r = -\frac{\partial\varphi}{\partial r}$$

$$G_r = -\frac{\gamma M}{r^2} \quad (\text{using Eq. 7})$$

So 
$$\vec{G} = -\frac{\gamma M}{r^3} \vec{r} \text{ and } \vec{F} = m\vec{G} = -\frac{\gamma mM}{r^3} \vec{r} \quad (8)$$

1.212 (The problem has already a clear hint in the answer sheet of the problem book). Here we adopt a different method.

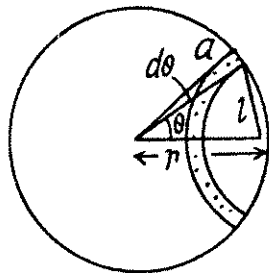
Let  $m$  be the mass of the spherical layer, which is imagined to be made up of rings. At a point inside the spherical layer at distance  $r$  from the centre, the gravitational potential due to a ring element of radius  $a$  equals,

$$d\varphi = -\frac{\gamma m}{2ar} dl \quad (\text{see Eq. (5) of solution of 1.211})$$

$$\text{So, } \varphi = \int d\varphi = -\frac{\gamma m}{2ar} \int_{a-r}^{a+r} dl = -\frac{\gamma m}{a} \quad (1)$$

Hence 
$$G_r = -\frac{\partial\varphi}{\partial r} = 0.$$

Hence gravitational field strength as well as field force becomes zero, inside a thin spherical layer.



1.213 One can imagine that the uniform hemisphere is made up of thin hemispherical layers of radii ranging from 0 to  $R$ . Let us consider such a layer (Fig.). Potential at point  $O$ , due to this layer is,

$$d\varphi = -\frac{\gamma dm}{r} = -\frac{3\gamma M}{R^3} r dr, \text{ where } dm = \frac{M}{(2/3)\pi R^3} \left( \frac{4\pi r^2}{2} \right) dr$$

(This is because all points of each hemispherical shell are equidistant from  $O$ .)

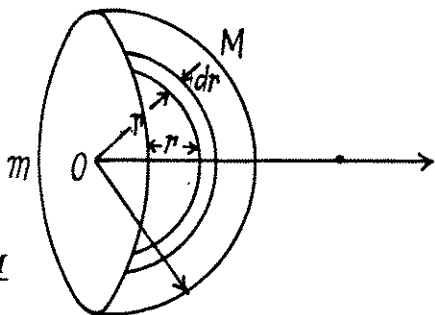
$$\text{Hence, } \varphi = \int d\varphi = -\frac{3\gamma M}{R^3} \int_0^R r dr = -\frac{3\gamma M}{2R}$$

Hence, the work done by the gravitational field force on the particle of mass  $m$ , to remove it to infinity is given by the formula

$$A = m\varphi, \text{ since } \varphi = 0 \text{ at infinity.}$$

Hence the sought work,

$$A_{0 \rightarrow \infty} = -\frac{3\gamma mM}{2R}$$



(The work done by the external agent is  $-A$ .)

**1.214** In the solution of problem 1.211, we have obtained  $\varphi$  and  $G$  due to a uniform sphere, at a distance  $r$  from its centre outside it. We have from Eqs. (7) and (8) of 1.211,

$$\varphi = -\frac{\gamma M}{r} \text{ and } \vec{G} = -\frac{\gamma M}{r^3} \vec{r} \quad (\text{A})$$

According with the Eq. (1) of the solution of 1.212, potential due to a spherical shell of radius  $a$ , at any point, inside it becomes

$$\varphi = \frac{\gamma M}{a} = \text{Const. and } G_r = -\frac{\partial \varphi}{\partial r} = 0 \quad (\text{B})$$

For a point (say  $P$ ) which lies inside the uniform solid sphere, the potential  $\varphi$  at that point may be represented as a sum.

$$\varphi_{\text{inside}} = \varphi_1 + \varphi_2$$

where  $\varphi_1$  is the potential of a solid sphere having radius  $r$  and  $\varphi_2$  is the potential of the layer of radii  $r$  and  $R$ . In accordance with equation (A)

$$\varphi_1 = -\frac{\gamma}{r} \left( \frac{M}{(4/3)\pi R^3} \frac{4}{3}\pi r^3 \right) = -\frac{\gamma M}{R^3} r^2$$

The potential  $\varphi_2$  produced by the layer (thick shell) is the same at all points inside it. The potential  $\varphi_2$  is easiest to calculate, for the point positioned at the layer's centre. Using Eq. (B)

$$\varphi_2 = -\gamma \int_r^R \frac{dM}{r} = -\frac{3}{2} \frac{\gamma M}{R^3} (R^2 - r^2)$$

$$\text{where } dM = \frac{M}{(4/3)\pi R^3} 4\pi r^2 dr = \left( \frac{3M}{R^3} \right) r^2 dr$$

is the mass of a thin layer between the radii  $r$  and  $r + dr$ .

$$\text{Thus } \varphi_{\text{inside}} = \varphi_1 + \varphi_2 = \left( \frac{\gamma M}{2R} \right) \left( 3 - \frac{r^2}{R^2} \right) \quad (\text{C})$$

From the Eq.

$$G_r = -\frac{\partial \varphi}{\partial r}$$

$$G_r = \frac{\gamma M r}{R^3}$$

or

$$\vec{G} = -\frac{\gamma M}{R^3} \vec{r} = -\gamma \frac{4}{3} \pi \rho \vec{r}$$

(where  $\rho = \frac{M}{\frac{4}{3} \pi R^3}$ , is the density of the sphere)

(D)

The plots  $\varphi(r)$  and  $G(r)$  for a uniform sphere of radius  $R$  are shown in figure of answersheet.

**Alternate :** Like Gauss's theorem of electrostatics, one can derive Gauss's theorem for

gravitation in the form  $\oint \vec{G} \cdot d\vec{S} = -4\pi\gamma m_{\text{enclosed}}$ . For calculation of  $\vec{G}$  at a point inside the sphere at a distance  $r$  from its centre, let us consider a Gaussian surface of radius  $r$ . Then,

$$G_r 4\pi r^2 = -4\pi\gamma \left(\frac{M}{R^3}\right) r^3 \quad \text{or,} \quad G_r = -\frac{\gamma M}{R^3} r$$

Hence, 
$$\vec{G} = -\frac{\gamma M}{R^3} \vec{r} = -\gamma \frac{4}{3} \pi \rho \vec{r} \quad \left( \text{as } \rho = \frac{M}{(4/3) \pi R^3} \right)$$

So, 
$$\varphi = \int_r^\infty G_r dr = \int_r^\infty -\frac{\gamma M}{R^3} r dr + \int_R^\infty -\frac{\gamma M}{r^2} dr$$

Integrating and summing up, we get,

$$\varphi = -\frac{\gamma M}{2R} \left( 3 - \frac{r^2}{R^2} \right)$$

And from Gauss's theorem for outside it :

$$G_r 4\pi r^2 = -4\pi\gamma M \quad \text{or} \quad G_r = -\frac{\gamma M}{r^2}$$

Thus 
$$\varphi(r) = \int_r^\infty G_r dr = -\frac{\gamma M}{r}$$

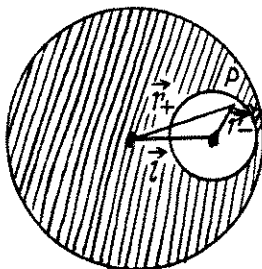
**1.215** Treating the cavity as negative mass of density  $-\rho$  in a uniform sphere density  $+\rho$  and using the superposition principle, the sought field strength is :

$$\vec{G} = \vec{G}_1 + \vec{G}_2$$

or 
$$\vec{G} = -\frac{4}{3} \pi \gamma \rho \vec{r}_+ + -\frac{4}{3} \pi \gamma (-\rho) \vec{r}_-$$

(where  $\vec{r}_+$  and  $\vec{r}_-$  are the position vectors of an arbitrary point  $P$  inside the cavity with respect to centre of sphere and cavity respectively.)

Thus 
$$\vec{G} = -\frac{4}{3} \pi \gamma \rho (\vec{r}_+ - \vec{r}_-) = -\frac{4}{3} \pi \gamma \rho \vec{l}$$





- 1.216 We partition the solid sphere into thin spherical layers and consider a layer of thickness  $dr$  lying at a distance  $r$  from the centre of the ball. Each spherical layer presses on the layers within it. The considered layer is attracted to the part of the sphere lying within it (the outer part does not act on the layer). Hence for the considered layer

$$dp \, 4\pi r^2 = dF$$

$$\text{or, } dp \, 4\pi r^2 = \frac{\gamma \left( \frac{4}{3} \pi r^3 \rho \right) (4\pi r^2 dr \rho)}{r^2}$$

(where  $\rho$  is the mean density of sphere)

$$\text{or, } dp = \frac{4}{3} \pi \gamma \rho^2 r \, dr$$

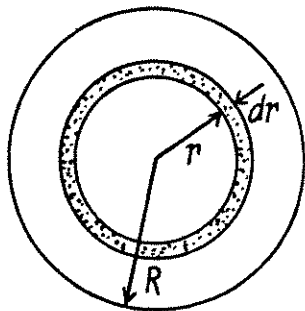
$$\text{Thus } p = \int_r^R dp = \frac{2\pi}{3} \gamma \rho^2 (R^2 - r^2)$$

(The pressure must vanish at  $r = R$ .)

$$\text{or, } p = \frac{3}{8} \left( 1 - (r^2/R^2) \right) \gamma M^2 / \pi R^4, \text{ Putting } \rho = M / \left( \frac{4}{3} \right) \pi R^3$$

Putting  $r = 0$ , we have the pressure at sphere's centre, and treating it as the Earth where mean density is equal to  $\rho = 5.5 \times 10^3 \text{ kg/m}^3$  and  $R = 64 \times 10^2 \text{ km}$

we have,  $p = 1.73 \times 10^{11} \text{ Pa}$  or  $1.72 \times 10^6 \text{ atms.}$



- 1.217 (a) Since the potential at each point of a spherical surface (shell) is constant and is equal to  $\varphi = -\frac{\gamma m}{R}$ , [as we have in Eq. (1) of solution of problem 1.212]

We obtain in accordance with the equation

$$\begin{aligned} U &= \frac{1}{2} \int dm \, \varphi = \frac{1}{2} \varphi \int dm \\ &= \frac{1}{2} \left( -\frac{\gamma m}{R} \right) m = -\frac{\gamma m^2}{2R} \end{aligned}$$

(The factor  $\frac{1}{2}$  is needed otherwise contribution of different mass elements is counted twice.)

(b) In this case the potential inside the sphere depends only on  $r$  (see Eq. (C) of the solution of problem 1.214)

$$\varphi = -\frac{3\gamma m}{2R} \left( 1 - \frac{r^2}{3R^2} \right)$$

Here  $dm$  is the mass of an elementary spherical layer confined between the radii  $r$  and  $r + dr$ :

$$dm = (4\pi r^2 dr \rho) = \left( \frac{3m}{R^3} \right) r^2 dr$$

$$U = \frac{1}{2} \int dm \varphi$$

$$= \frac{1}{2} \int_0^R \left( \frac{3m}{R^3} \right) r^2 dr \left\{ -\frac{3\gamma m}{2R} \left( 1 - \frac{r^2}{3R^2} \right) \right\}$$

After integrating, we get

$$U = -\frac{3}{5} \frac{\gamma m^2}{R}$$

1.218 Let  $\omega = \sqrt{\frac{\gamma M_E}{r^3}}$  = circular frequency of the satellite in the outer orbit,

$\omega_0 = \sqrt{\frac{\gamma M_E}{(r - \Delta r)^3}}$  = circular frequency of the satellite in the inner orbit.

So, relative angular velocity =  $\omega_0 \pm \omega$  where - sign is to be taken when the satellites are moving in the same sense and + sign if they are moving in opposite sense.

Hence, time between closest approaches

$$= \frac{2\pi}{\omega_0 \pm \omega} = \frac{2\pi}{\sqrt{\gamma M_E} / r^{3/2} \frac{3\Delta r}{2r} + \delta} = \begin{cases} 4.5 \text{ days } (\delta = 0) \\ 0.80 \text{ hour } (\delta = 2) \end{cases}$$

where  $\delta$  is 0 in the first case and 2 in the second case.

$$1.219 \quad \omega_1 = \frac{\gamma M}{R^2} = \frac{6.67 \times 10^{-11} \times 5.96 \times 10^{24}}{(6.37 \times 10^6)^2} = 9.8 \text{ m/s}^2$$

$$\omega_2 = \omega^2 R = \left( \frac{2\pi}{T} \right)^2 R = \left( \frac{2 \times 22}{24 \times 3600 \times 7} \right)^2 6.37 \times 10^6 = 0.034 \text{ m/s}^2$$

$$\text{and } \omega_3 = \frac{\gamma M_S}{R_{\text{mean}}^2} = \frac{6.67 \times 10^{-11} \times 1.97 \times 10^{30}}{(149.50 \times 10^6 \times 10^3)^2} = 5.9 \times 10^{-3} \text{ m/s}^2$$

Then

$$\omega_1 : \omega_2 : \omega_3 = 1 : 0.0034 : 0.0006$$

1.220 Let  $h$  be the sought height in the first case. so

$$\frac{99}{100} g = \frac{\gamma M}{(R+h)^2}$$

$$= \frac{\gamma M}{R^2 \left( 1 + \frac{h}{R} \right)^2} = \frac{g}{\left( 1 + \frac{h}{R} \right)^2}$$

or 
$$\frac{99}{100} = \left(1 + \frac{h}{R}\right)^{-2}$$

From the statement of the problem, it is obvious that in this case  $h \ll R$

Thus 
$$\frac{99}{100} = \left(1 - \frac{2h}{R}\right) \text{ or } h = \frac{R}{200} = \left(\frac{6400}{200}\right) \text{ km} = 32 \text{ km}$$

In the other case if  $h'$  be the sought height, then

$$\frac{g}{2} = g \left(1 + \frac{h'}{R}\right)^{-2} \text{ or } \frac{1}{2} = \left(1 + \frac{h'}{R}\right)^{-2}$$

From the language of the problem, in this case  $h'$  is not very small in comparison with  $R$ . Therefore in this case we cannot use the approximation adopted in the previous case.

Here,  $\left(1 + \frac{h'}{R}\right)^2 = 2$  So,  $\frac{h'}{R} = \pm \sqrt{2} - 1$

As -ve sign is not acceptable

$$h' = (\sqrt{2} - 1)R = (\sqrt{2} - 1) 6400 \text{ km} = 2650 \text{ km}$$

**1.221** Let the mass of the body be  $m$  and let it go upto a height  $h$ .

From conservation of mechanical energy of the system

$$-\frac{\gamma M m}{R} + \frac{1}{2} m v_0^2 = -\frac{\gamma M m}{(R+h)} + 0$$

Using  $\frac{\gamma M}{R^2} = g$ , in above equation and on solving we get,

$$h = \frac{R v_0^2}{2 g R - v_0^2}$$

**1.222** Gravitational pull provides the required centripetal acceleration to the satellite. Thus if  $h$  be the sought distance, we have

so, 
$$\frac{m v^2}{(R+h)} = \frac{\gamma m M}{(R+h)^2} \text{ or, } (R+h) v^2 = \gamma M$$

or, 
$$R v^2 + h v^2 = g R^2, \text{ as } g = \frac{\gamma M}{R^2}$$

Hence 
$$h = \frac{g R^2 - R v^2}{v^2} = R \left[ \frac{g R}{v^2} - 1 \right]$$

**1.223** A satellite that hovers above the earth's equator and corotates with it moving from the west to east with the diurnal angular velocity of the earth appears stationary to an observer on the earth. It is called geostationary. For this calculation we may neglect the annual motion of the earth as well as all other influences. Then, by Newton's law,

$$\frac{\gamma M m}{r^2} = m \left( \frac{2\pi}{T} \right)^2 r$$

where  $M$  = mass of the earth,  $T$  = 86400 seconds = period of daily rotation of the earth and  $r$  = distance of the satellite from the centre of the earth. Then

$$r = \sqrt[3]{\gamma M \left( \frac{T}{2\pi} \right)^2}$$

Substitution of  $M = 5.96 \times 10^{24}$  kg gives

$$r = 4.220 \times 10^4 \text{ km}$$

The instantaneous velocity with respect to an inertial frame fixed to the centre of the earth at that moment will be

$$\left( \frac{2\pi}{T} \right) r = 3.07 \text{ km/s}$$

and the acceleration will be the centripetal acceleration.

$$\left( \frac{2\pi}{T} \right)^2 r = 0.223 \text{ m/s}^2$$

- 1.224 We know from the previous problem that a satellite moving west to east at a distance  $R = 2.00 \times 10^4$  km from the centre of the earth will be revolving round the earth with an angular velocity faster than the earth's diurnal angular velocity. Let

$\omega$  = angular velocity of the satellite

$\omega_0 = \frac{2\pi}{T}$  = angular velocity of the earth. Then

$$\omega - \omega_0 = \frac{2\pi}{\tau}$$

as the relative angular velocity with respect to earth. Now by Newton's law

$$\frac{\gamma M}{R^2} = \omega^2 R$$

So,

$$\begin{aligned} M &= \frac{R^3}{\gamma} \left( \frac{2\pi}{\tau} + \frac{2\pi}{T} \right)^2 \\ &= \frac{4\pi^2 R^3}{\gamma T^2} \left( 1 + \frac{T}{\tau} \right)^2 \end{aligned}$$

Substitution gives

$$M = 6.27 \times 10^{24} \text{ kg}$$

- 1.225 The velocity of the satellite in the inertial space fixed frame is  $\sqrt{\frac{\gamma M}{R}}$  east to west. With respect to the Earth fixed frame, from the  $\vec{v}_1' = \vec{v} - (\vec{\omega} \times \vec{r})$  the velocity is

$$v' = \frac{2\pi R}{T} + \sqrt{\frac{\gamma M}{R}} = 7.03 \text{ km/s}$$

Here  $M$  is the mass of the earth and  $T$  is its period of rotation about its own axis.

It would be  $-\frac{2\pi R}{T} + \sqrt{\frac{\gamma M}{R}}$ , if the satellite were moving from west to east.

To find the acceleration we note the formula

$$m \vec{\omega}' = \vec{F} + 2m(\vec{v}' \times \vec{\omega}) + m\omega^2 \vec{R}$$

Here  $\vec{F} = -\frac{\gamma M m}{R^3} \vec{R}$  and  $\vec{v}' \perp \vec{\omega}$  and  $\vec{v}' \times \vec{\omega}$  is directed towards the centre of the Earth.

$$\text{Thus } \omega' = \frac{\gamma M}{R^2} + 2 \left( \frac{2\pi R}{T} + \sqrt{\frac{\gamma M}{R}} \right) \frac{2\pi}{T} - \left( \frac{2\pi}{T} \right)^2 R$$

toward the earth's rotation axis

$$= \frac{\gamma M}{R^2} + \frac{2\pi}{T} \left[ \frac{2\pi R}{T} + 2 \sqrt{\frac{\gamma M}{R}} \right] = 4.94 \text{ m/s}^2 \text{ on substitution.}$$

**1.226** From the well known relationship between the velocities of a particle w.r.t a space fixed frame (K) rotating frame (K')  $\vec{v} = \vec{v}' + (\vec{\omega} \times \vec{r})$

$$v_1 = v - \left( \frac{2\pi}{T} \right) R$$

Thus kinetic energy of the satellite in the earth's frame

$$T_1' = \frac{1}{2} m v_1'^2 = \frac{1}{2} m \left( v - \frac{2\pi R}{T} \right)^2$$

Obviously when the satellite moves in opposite sense compared to the rotation of the Earth its velocity relative to the same frame would be

$$v_2' = v + \left( \frac{2\pi}{T} \right) R$$

And kinetic energy

$$T_2' = \frac{1}{2} m v_2'^2 = \frac{1}{2} m \left( v + \frac{2\pi R}{T} \right)^2 \quad (2)$$

From (1) and (2)

$$T' = \frac{\left( v + \frac{2\pi R}{T} \right)^2}{\left( v - \frac{2\pi R}{T} \right)^2} \quad (3)$$

Now from Newton's second law

$$\frac{\gamma M m}{R^2} = \frac{m v^2}{R} \quad \text{or } v = \sqrt{\frac{\gamma M}{R}} = \sqrt{gR} \quad (4)$$

Using (4) and (3)

$$\frac{T_2'}{T_1'} = \frac{\left( \sqrt{gR} + \frac{2\pi R}{T} \right)^2}{\left( \sqrt{gR} - \frac{2\pi R}{T} \right)^2} = 1.27 \text{ nearly (Using Appendices)}$$

**1.227** For a satellite in a circular orbit about any massive body, the following relation holds between kinetic, potential & total energy :

$$T = -E, U = 2E \quad (1)$$

Thus since total mechanical energy must decrease due to resistance of the cosmic dust, the kinetic energy will increase and the satellite will 'fall'. We see then, by work energy theorem

$$dT = -dE = -dA_f$$

So,  $mv dv = \alpha v^2 v dt$  or,  $\frac{\alpha dt}{m} = \frac{dv}{v^2}$

Now from Newton's law at an arbitrary radius  $r$  from the moon's centre.

$$\frac{v^2}{r} = \frac{\gamma M}{r^2} \quad \text{or} \quad v = \sqrt{\frac{\gamma M}{r}}$$

( $M$  is the mass of the moon.) Then

$$v_i = \sqrt{\frac{\gamma M}{r_i R}}, \quad v_f = \sqrt{\frac{\gamma M}{R}}$$

where  $R$  = moon's radius. So

$$\int_{v_i}^{v_f} \frac{dv}{v^2} = \frac{\alpha}{m} \int_0^{\tau} dt = \frac{\alpha \tau}{m}$$

or,  $\tau = \frac{m}{\alpha} \left( \frac{1}{v_i} - \frac{1}{v_f} \right) = \frac{m}{\alpha \sqrt{\frac{\gamma M}{R}}} (\sqrt{r_i} - 1) = \frac{m}{\alpha \sqrt{gR}} (\sqrt{r_i} - 1)$

where  $g$  is moon's gravity. The averaging implied by Eq. (1) (for noncircular orbits) makes the result approximate.

**1.228** From Newton's second law

$$\frac{\gamma M m}{R^2} = \frac{mv_0^2}{R} \quad \text{or} \quad v_0 = \sqrt{\frac{\gamma M}{R}} = 1.67 \text{ km/s} \quad (1)$$

From conservation of mechanical energy

$$\frac{1}{2}mv_e^2 - \frac{\gamma M m}{R} = 0 \quad \text{or} \quad v_e = \sqrt{\frac{2\gamma M}{R}} = 2.37 \text{ km/s} \quad (2)$$

In Eq. (1) and (2),  $M$  and  $R$  are the mass of the moon and its radius. In Eq. (1) if  $M$  and  $R$  represent the mass of the earth and its radius, then, using appendices, we can easily get

$$v_0 = 7.9 \text{ km/s and } v_e = 11.2 \text{ km/s.}$$

**1.229** In a parabolic orbit,  $E = 0$

$$\text{So } \frac{1}{2}mv_i^2 - \frac{\gamma Mm}{R} = 0 \text{ or, } v_i = \sqrt{2} \sqrt{\frac{\gamma M}{R}}$$

where  $M$  = mass of the Moon,  $R$  = its radius. (This is just the escape velocity.)

On the other hand in orbit

$$mv_f^2 R = \frac{\gamma Mm}{R^2} \text{ or } v_f = \sqrt{\frac{\gamma M}{R}}$$

$$\text{Thus } \Delta v = (1 - \sqrt{2}) \sqrt{\frac{\gamma M}{R}} = -0.70 \text{ km/s.}$$

**1.230** From 1.228 for the Earth surface

$$v_0 = \sqrt{\frac{\gamma M}{R}} \text{ and } v_e = \sqrt{\frac{2\gamma M}{R}}$$

Thus the sought additional velocity

$$\Delta v = v_e - v_0 = \sqrt{\frac{\gamma M}{R}} (\sqrt{2} - 1) = gR (\sqrt{2} - 1)$$

This 'kick' in velocity must be given along the direction of motion of the satellite in its orbit.

**1.231** Let  $r$  be the sought distance, then

$$\frac{\gamma \eta M}{(nR - r)^2} = \frac{\gamma M}{r^2} \text{ or } \eta r^2 = (nR - r)^2$$

$$\text{or } \sqrt{\eta} r = (nR - r) \text{ or } r = \frac{nR}{\sqrt{\eta} + 1} = 3.8 \times 10^4 \text{ km.}$$

**1.232** Between the earth and the moon, the potential energy of the spaceship will have a maximum at the point where the attractions of the earth and the moon balance each other. This maximum P.E. is approximately zero. We can also neglect the contribution of either body to the p.E. of the spaceship sufficiently near the other body. Then the minimum energy that must be imparted to the spaceship to cross the maximum of the P.E. is clearly (using  $E$  to denote the earth)

$$\frac{\gamma M_E m}{R_E}$$

With this energy the spaceship will cross over the hump in the P.E. and coast down the hill of p.E. towards the moon and crashland on it. What the problem seeks is the minimum energy required for softlanding. That requires the use of rockets to bring about the braking of the spaceship and since the kinetic energy of the gases ejected from the rocket will always be positive, the total energy required for softlanding is greater than that required for crashlanding. To calculate this energy we assume that the rockets are used fairly close to the moon when the spaceship has nearly attained its terminal velocity on the moon

$\sqrt{\frac{2\gamma M_O}{R_0}}$  where  $M_0$  is the mass of the moon and  $R_0$  is its radius. In general

$dE = v dp$  and since the speed of the ejected gases is not less than the speed of the rocket, and momentum transferred to the ejected gases must equal the momentum of the spaceship the energy  $E$  of the gas ejected is not less than the kinetic energy of spaceship

$$\frac{\gamma M_0 m}{R_0}$$

Adding the two we get the minimum work done on the ejected gases to bring about the softlanding.

$$A_{\min} = \gamma m \left( \frac{M_E}{R_E} + \frac{M_0}{R_0} \right)$$

On substitution we get  $1.3 \times 10^8$  kJ.

- 1.233 Assume first that the attraction of the earth can be neglected. Then the minimum velocity, that must be imparted to the body to escape from the Sun's pull, is, as in 1.230, equal to

$$(\sqrt{2} - 1) v_1$$

where  $v_1^2 = \gamma M_s / r$ ,  $r$  = radius of the earth's orbit,  $M_s$  = mass of the Sun.

In the actual case near the earth, the pull of the Sun is small and does not change much over distances, which are several times the radius of the Earth. The velocity  $v_3$  in question is that which overcomes the earth's pull with sufficient velocity to escape the Sun's pull. Thus

$$\frac{1}{2} m v_3^2 - \frac{\gamma M_E}{R} = \frac{1}{2} m (\sqrt{2} - 1)^2 v_1^2$$

where  $R$  = radius of the earth,  $M_E$  = mass of the earth.

Writing  $v_1^2 = \gamma M_E / R$ , we get

$$v_3 = \sqrt{2 v_1^2 + (\sqrt{2} - 1)^2 v_1^2} = 16.6 \text{ km/s}$$



## 1.5 DYNAMICS OF A SOLID BODY

1.234 Since, motion of the rod is purely translational, net torque about the C.M. of the rod should be equal to zero.

$$\text{Thus } F_1 \frac{l}{2} = F_2 \left( \frac{l}{2} - a \right) \text{ or, } \frac{F_1}{F_2} = 1 - \frac{a}{l/2} \quad (1)$$

For the translational motion of rod.

$$F_2 - F_1 = mw_c \text{ or } 1 - \frac{F_1}{F_2} = \frac{mw_c}{F_2} \quad (2)$$

From (1) and (2)

$$\frac{a}{l/2} = \frac{mw_c}{F_2} \text{ or, } l = \frac{2aF_2}{mw_c} = 1 \text{ m}$$

$$\begin{aligned} 1.235 \text{ Sought moment } \vec{N} &= \vec{r} \times \vec{F} = (a\vec{i} + b\vec{j}) \times (A\vec{i} + B\vec{j}) \\ &= aB\vec{k} + Ab(-\vec{k}) = (aB - Ab)\vec{k} \end{aligned}$$

$$\text{and arm of the force } l = \frac{N}{F} = \frac{aB - Ab}{\sqrt{A^2 + B^2}}$$

1.236 Relative to point  $O$ , the net moment of force :

$$\begin{aligned} \vec{N} &= \vec{r}_1 \times \vec{F}_1 + \vec{r}_2 \times \vec{F}_2 = (a\vec{i} \times A\vec{j}) + (B\vec{j} \times B\vec{i}) \\ &= ab\vec{k} + AB(-\vec{k}) = (ab - AB)\vec{k} \end{aligned} \quad (1)$$

Resultant of the external force

$$\vec{F} = \vec{F}_1 + \vec{F}_2 = A\vec{j} + B\vec{i} \quad (2)$$

As  $\vec{N} \cdot \vec{F} = 0$  (as  $\vec{N} \perp \vec{F}$ ) so the sought arm  $l$  of the force  $\vec{F}$

$$l = N/F = \frac{ab - AB}{\sqrt{A^2 + B^2}}$$

1.237 For coplanar forces, about any point in the same plane,  $\sum \vec{r}_i \times \vec{F}_i = \vec{r} \times \vec{F}_{net}$

(where  $\vec{F}_{net} = \sum \vec{F}_i$  = resultant force) or,  $\vec{N}_{net} = \vec{r} \times \vec{F}_{net}$

Thus length of the arm,  $l = \frac{N_{net}}{F_{net}}$

Here obviously  $|\vec{F}_{net}| = 2F$  and it is directed toward right along  $AC$ . Take the origin at  $C$ . Then about  $C$ ,

$$\vec{N} = \left( \sqrt{2} a F + \frac{a}{\sqrt{2}} F - \sqrt{2} a F \right) \text{ directed normally into the plane of figure.}$$

(Here  $a$  = side of the square.)

Thus  $\vec{N} = F \frac{a}{\sqrt{2}}$  directed into the plane of the figure.

$$\text{Hence } l = \frac{F(a/\sqrt{2})}{2F} = \frac{a}{2\sqrt{2}} = \frac{a}{2} \sin 45^\circ$$

Thus the point of application of force is at the mid point of the side  $BC$ .

- 1.238 (a) Consider a strip of length  $dx$  at a perpendicular distance  $x$  from the axis about which we have to find the moment of inertia of the rod. The elemental mass of the rod equals

$$dm = \frac{m}{l} dx$$

Moment of inertia of this element about the axis

$$dI = dm x^2 = \frac{m}{l} dx x^2$$

Thus, moment of inertia of the rod, as a whole about the given axis

$$I = \int_0^l \frac{m}{l} x^2 dx = \frac{m l^2}{3}$$

(b) Let us imagine the plane of plate as  $xy$  plane taking the origin at the intersection point of the sides of the plate (Fig.).

Obviously

$$\begin{aligned} I_x &= \int dm y^2 \\ &= \int_0^a \left( \frac{m}{ab} b dy \right) y^2 \\ &= \frac{m a^2}{3} \end{aligned}$$

Similarly

$$I_y = \frac{m b^2}{3}$$

Hence from perpendicular axis theorem

$$I_z = I_x + I_y = \frac{m}{3} (a^2 + b^2),$$

which is the sought moment of inertia.

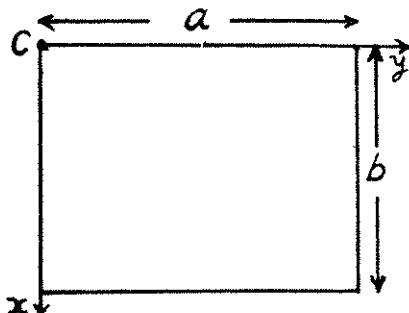
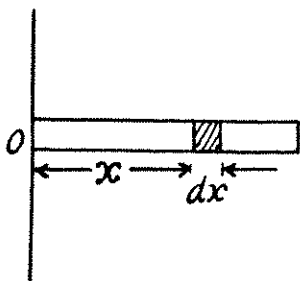
- 1.239 (a) Consider an elementary disc of thickness  $dx$ . Moment of inertia of this element about the  $z$ -axis, passing through its C.M.

$$dI_z = \frac{(dm) R^2}{2} = \rho S dx \frac{R^2}{2}$$

where  $\rho$  = density of the material of the plate and  $S$  = area of cross section of the plate.

Thus the sought moment of inertia

$$\begin{aligned} I_z &= \frac{\rho S R^2}{2} \int_0^b dx = \frac{R^2}{2} \rho S b \\ &= \frac{\pi}{2} \rho b R^4 \quad (\text{as } S = \pi R^2) \end{aligned}$$



putting all the values we get,  $I_z = 2 \cdot \text{gm} \cdot \text{m}^2$

(b) Consider an element disc of radius  $r$  and thickness  $dx$  at a distance  $x$  from the point  $O$ . Then  $r = x \tan \alpha$  and volume of the disc

$$= \pi x^2 \tan^2 \alpha dx$$

Hence, its mass  $dm = \pi x^2 \tan \alpha dx \cdot \rho$  (where  $\rho = \text{density of the cone} = m / \frac{1}{3} \pi R^2 h$ )

Moment of inertia of this element, about the axis  $OA$ ,

$$dI = dm \frac{r^2}{2}$$

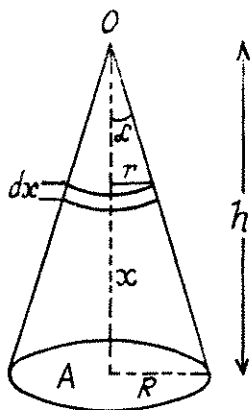
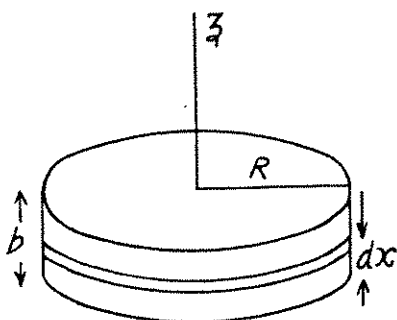
$$= (\pi x^2 \tan^2 \alpha dx) \frac{x^2 \tan^2 \alpha}{2}$$

$$= \frac{\pi \rho}{2} x^4 \tan^4 \alpha dx$$

Thus the sought moment of inertia  $I = \frac{\pi \rho}{2} \tan^4 \alpha \int_0^h x^4 dx$

$$= \frac{\pi \rho R^4 \cdot h^5}{10 h^4} \left( \text{as } \tan \alpha = \frac{R}{h} \right)$$

Hence  $I = \frac{3m R^2}{10} \left( \text{putting } \rho = \frac{3m}{\pi R^2 h} \right)$



- 1.240 (a) Let us consider a lamina of an arbitrary shape and indicate by 1, 2 and 3, three axes coinciding with  $x$ ,  $y$  and  $z$  - axes and the plane of lamina as  $x - y$  plane.

Now, moment of inertia of a point mass about

$x$  - axis,  $dl_x = dm y^2$

Thus moment of inertia of the lamina about

this axis,  $I_x = \int dm y^2$

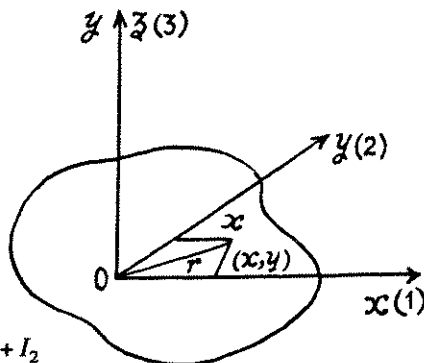
Similarly,  $I_y = \int dm x^2$

and  $I_z = \int dm r^2$

$= \int dm (x^2 + y^2)$  as  $r = \sqrt{x^2 + y^2}$

Thus,

$$I_z = I_x + I_y \text{ or, } I_3 = I_1 + I_2$$



(b) Let us take the plane of the disc as  $x - y$  plane and origin to the centre of the disc (Fig.) From the symmetry  $I_x = I_y$ . Let us consider a ring element of radius  $r$  and thickness  $dr$ , then the moment of inertia of the ring element about the  $y$  - axis.

$$dI_z = dm r^2 = \frac{m}{\pi R^2} (2\pi r dr) r^2$$

Thus the moment of inertia of the disc about  $z$ -axis

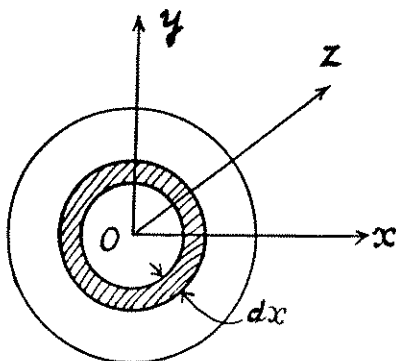
$$I_z = \frac{2m}{R^2} \int_0^R r^3 dr = \frac{mR^2}{2}$$

But we have

$$I_z = I_x + I_y = 2I_x$$

Thus

$$I_x = \frac{I_z}{2} = \frac{mR^2}{4}$$



- 1.241 For simplicity let us use a mathematical trick. We consider the portion of the given disc as the superposition of two complete discs (without holes), one of positive density and radius  $R$  and other of negative density but of same magnitude and radius  $R/2$ .

As (area)  $\propto$  (mass), the respective masses of the considered discs are  $(4m/3)$  and  $(-m/3)$  respectively, and these masses can be imagined to be situated at their respective centers (C.M). Let us take point  $O$  as origin and point  $x$ -axis towards right. Obviously the C.M. of the shaded position of given shape lies on the  $x$ -axis. Hence the C.M. (C) of the shaded portion is given by

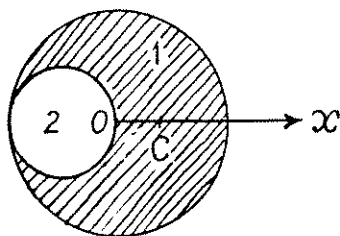
$$x_c = \frac{(-m/3)(-R/2) + (4m/3)0}{(-m/3) + 4m/3} = \frac{R}{6}$$

Thus C.M. of the shape is at a distance  $R/6$  from point  $O$  toward  $x$ -axis

Using parallel axis theorem and bearing in mind that the moment of inertia of a complete homogeneous disc of radius  $m_0$  and radius  $r_0$

equals  $\frac{1}{2} m_0 r_0^2$ . The moment of inertia of the

small disc of mass  $(-m/3)$  and radius  $R/2$  about the axis passing through point  $C$  and perpendicular to the plane of the disc



$$I_{2C} = \frac{1}{2} \left( -\frac{m}{3} \right) \left( \frac{R}{2} \right)^2 + \left( -\frac{m}{3} \right) \left( \frac{R}{2} + \frac{R}{6} \right)^2$$

$$= -\frac{mR^2}{24} - \frac{4}{27} mR^2$$

Similarly

$$I_{1C} = \frac{1}{2} \left( \frac{4m}{3} \right) R^2 + \left( \frac{4m}{3} \right) \left( \frac{R}{6} \right)^2$$

$$= \frac{2}{3} mR^2 + \frac{mR^2}{27}$$

Thus the sought moment of inertia,

$$I_C = I_{1C} + I_{2C} = \frac{15}{24} mR^2 - \frac{3}{27} mR^2 = \frac{37}{72} mR^2$$

1.242 Moment of inertia of the shaded portion, about the axis passing through its centre,

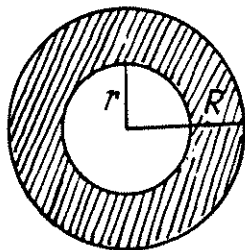
$$I = \frac{2}{5} \left( \frac{4}{3} \pi R^3 \rho \right) R^2 - \frac{2}{5} \left( \frac{4}{3} \pi r^3 \rho \right) r^2$$

$$= \frac{2}{5} \frac{4}{3} \pi \rho (R^5 - r^5)$$

Now, if  $R = r + dr$ , the shaded portion becomes a shell, which is the required shape to calculate the moment of inertia.

$$\text{Now, } I = \frac{2}{5} - \frac{4}{3} \pi \rho \{ (r + dr)^5 - r^5 \}$$

$$= \frac{2}{5} \frac{4}{3} \pi \rho (r^5 + 5r^4 dr + \dots - r^5)$$



Neglecting higher terms.

$$= \frac{2}{5} \left( 4\pi r^4 dr \rho \right) r^2 = \frac{2}{5} m r^2$$

1.243 (a) Net force which is effective on the system (cylinder  $M$  + body  $m$ ) is the weight of the body  $m$  in a uniform gravitational field, which is a constant. Thus the initial acceleration of the body  $m$  is also constant.

From the conservation of mechanical energy of the said system in the uniform field of gravity at time  $t = \Delta t$ :  $\Delta T + \Delta U = 0$

$$\text{or } \frac{1}{2} m v^2 + \frac{1}{2} \frac{M R^2}{2} \omega^2 - m g \Delta h = 0$$

$$\text{or, } \frac{1}{4} (2m + M) v^2 - m g \Delta h = 0 \quad [\text{as } v = \omega R \text{ at all times}] \quad (1)$$

$$\text{But } v^2 = 2w \Delta h$$

Hence using it in Eq. (1), we get

$$\frac{1}{4} (2m + M) 2w \Delta h - m g \Delta h = 0 \quad \text{or } w = \frac{2mg}{(2m + M)}$$

$$\text{From the kinematical relationship, } \beta = \frac{w}{R} = \frac{2mg}{(2m + M) R}$$

Thus the sought angular velocity of the cylinder

$$\omega(t) = \beta t = \frac{2mg}{(2m + M) R} t = \frac{gt}{(1 + M/2m) R}$$

(b) Sought kinetic energy.

$$T(t) = \frac{1}{2} m v^2 + \frac{1}{2} \frac{M R^2}{2} \omega^2 = \frac{1}{4} (2m + M) R^2 \omega^2$$

1.244 For equilibrium of the disc and axle

$$2T = mg \text{ or } T = mg/2$$

As the disc unwinds, it has an angular acceleration  $\beta$  given by

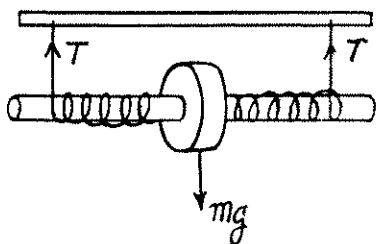
$$I\beta = 2Tr \text{ or } \beta = \frac{2Tr}{I} = \frac{mgr}{I}$$

The corresponding linear acceleration is

$$r\beta = w = \frac{mgr^2}{I}$$

Since the disc remains stationary under the combined action of this acceleration and the acceleration  $(-w)$  of the bar which is transmitted to the axle, we must have

$$w = \frac{mgr^2}{I}$$



1.245 Let the rod be deviated through an angle  $\varphi$  from its initial position at an arbitrary instant of time, measured relative to the initial position in the positive direction. From the equation of the increment of the mechanical energy of the system.

$$\Delta T = A_{ext}$$

$$\text{or, } \frac{1}{2} I \omega^2 = \int N_z d\varphi$$

$$\text{or, } \frac{1}{2} \frac{MI^2}{3} \omega^2 = \int_0^\varphi Fl \cos\varphi d\varphi = Fl \sin\varphi$$

$$\text{Thus, } \omega = \sqrt{\frac{6Fl \sin\varphi}{MI}}$$

1.246 First of all, let us sketch free body diagram of each body. Since the cylinder is rotating and massive, the tension will be different in both the sections of threads. From Newton's law in projection form for the bodies  $m_1$  and  $m_2$  and noting that  $w_1 = w_2 = w = \beta R$ , (as no thread slipping), we have ( $m_1 > m_2$ )

$$m_1 g - T_1 = m_1 w = m_1 \beta R$$

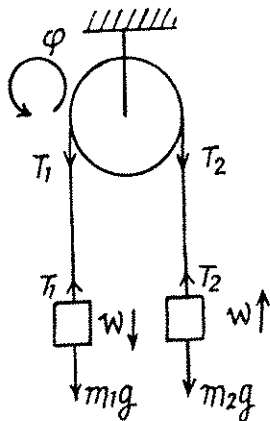
$$\text{and } T_2 - m_2 g = m_2 w \quad (1)$$

Now from the equation of rotational dynamics of a solid about stationary axis of rotation. i.e.  $N_z = I\beta$ , for the cylinder.

$$\text{or, } (T_1 - T_2)R = I\beta = mR^2 \beta/2 \quad (2)$$

Simultaneous solution of the above equations yields :

$$\beta = \frac{(m_1 - m_2)g}{R \left( m_1 + m_2 + \frac{m}{2} \right)} \text{ and } \frac{T_1}{T_2} = \frac{m_1(m + 4m_2)}{m_2(m + 4m_1)}$$



- 1.247 As the system  $(m + m_1 + m_2)$  is under constant forces, the acceleration of body  $m_1$  and  $m_2$  is constant. In addition to it the velocities and accelerations of bodies  $m_1$  and  $m_2$  are equal in magnitude (say  $v$  and  $w$ ) because the length of the thread is constant. From the equation of increment of mechanical energy i.e.  $\Delta T + \Delta U = A_{fr}$ , at time  $t$  when block  $m_1$  is distance  $h$  below from initial position corresponding to  $t = 0$ ,

$$\frac{1}{2} (m_1 + m_2) v^2 + \frac{1}{2} \left( \frac{mR^2}{2} \right) \frac{v^2}{R^2} - m_2 gh = -km_1 gh \quad (1)$$

(as angular velocity  $\omega = v/R$  for no slipping of thread.)

But 
$$v^2 = 2wh$$

So using it in (1), we get

$$w = \frac{2(m_2 - km_1)g}{m + 2(m_1 + m_2)} \quad (2)$$

Thus the work done by the friction force on  $m_1$

$$\begin{aligned} A_{fr} &= -km_1 gh = -km_1 g \left( \frac{1}{2} wt^2 \right) \\ &= -\frac{km_1 (m_2 - km_1) g^2 t^2}{m + 2(m_1 + m_2)} \quad (\text{using 2}). \end{aligned}$$

- 1.248 In the problem, the rigid body is in translation equilibrium but there is an angular retardation. We first sketch the free body diagram of the cylinder. Obviously the friction forces, acting on the cylinder, are kinetic. From the condition of translational equilibrium for the cylinder,

$$mg = N_1 + kN_2; \quad N_2 = kN_1$$

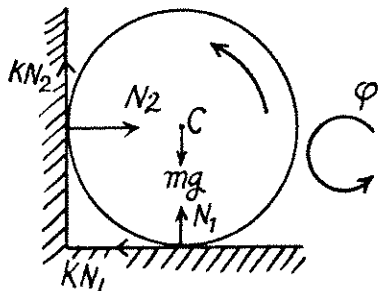
Hence, 
$$N_1 = \frac{mg}{1 + k^2}; \quad N_2 = k \frac{mg}{1 + k^2}$$

For pure rotation of the cylinder about its rotation axis,  $N_z = I\beta_z$

$$\text{or, } -kN_1 R - kN_2 R = \frac{mR^2}{2} \beta_z$$

$$\text{or, } -\frac{kmgR(1+k)}{1+k^2} = \frac{mR^2}{2} \beta_z$$

$$\text{or, } \beta_z = -\frac{2k(1+k)g}{(1+k^2)R}$$



Now, from the kinematical equation,

$$\omega^2 = \omega_0^2 + 2\beta_z \Delta \varphi \text{ we have,}$$

$$\Delta \varphi = \frac{\omega_0^2 (1 + k^2) R}{4k(1 + k)g}, \quad \text{because } \omega = 0$$

Hence, the sought number of turns,

$$n = \frac{\Delta\varphi}{2\pi} = \frac{\omega_0^2 (1+k^2) R}{8\pi k (1+k) g}$$

**1.249** It is the moment of friction force which brings the disc to rest. The force of friction is applied to each section of the disc, and since these sections lie at different distances from the axis, the moments of the forces of friction differ from section to section.

To find  $N_z$ , where  $z$  is the axis of rotation of the disc let us partition the disc into thin rings (Fig.). The force of friction acting on the considered element

$dfr = k(2\pi r dr \sigma)g$ , (where  $\sigma$  is the density of the disc)

The moment of this force of friction is

$$dN_z = -r dfr = -2\pi k \sigma g r^2 dr$$

Integrating with respect to  $r$  from zero to  $R$ , we get

$$N_z = -2\pi k \sigma g \int_0^R r^2 dr = -\frac{2}{3} \pi k \sigma g R^3.$$

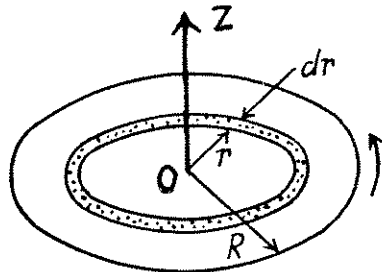
For the rotation of the disc about the stationary axis  $z$ , from the equation  $N_z = I\beta_z$

$$-\frac{2}{3} \pi k \sigma g R^3 = \frac{(\pi R^2 \sigma) R^2}{2} \beta_z \text{ or } \beta_z = -\frac{4kg}{3R}$$

Thus from the angular kinematical equation

$$\omega_z = \omega_{0z} + \beta_z t$$

$$0 = \omega_0 + \left(-\frac{4kg}{3R}\right)t \text{ or } t = \frac{3R\omega_0}{4kg}$$



**1.250** According to the question,

$$I \frac{d\omega}{dt} = -k\sqrt{\omega} \text{ or, } I = \frac{d\omega}{\sqrt{\omega}} = -k dt$$

$$\text{Integrating, } \sqrt{\omega} = -\frac{kt}{2I} + \sqrt{\omega_0}$$

$$\text{or, } \omega = \frac{k^2 t^2}{4I^2} - \frac{\sqrt{\omega_0} kt}{I} + \omega_0, \text{ (Noting that at } t = 0, \omega = \omega_0\text{)}$$

$$\text{Let the flywheel stops at } t = t_0 \text{ then from Eq. (1), } t_0 = \frac{2I\sqrt{\omega_0}}{k}$$

Hence sought average angular velocity

$$\begin{aligned} \langle \omega \rangle &= \frac{\frac{2I\sqrt{\omega_0}}{k}}{\frac{2I\sqrt{\omega_0}}{k}} = \frac{\omega_0}{3} \\ &= \frac{\int_0^{\frac{2I\sqrt{\omega_0}}{k}} \left( \frac{k^2 t^2}{4I^2} - \frac{\sqrt{\omega_0} kt}{I} + \omega_0 \right) dt}{\int_0^{\frac{2I\sqrt{\omega_0}}{k}} dt} \end{aligned}$$



- 1.251 Let us use the equation  $\frac{dM_z}{dt} = N_z$  relative to the axis through  $O$  (1)

For this purpose, let us find the angular momentum of the system  $M_z$  about the given rotation axis and the corresponding torque  $N_z$ . The angular momentum is

$$M_z = I\omega + m v R = \left( \frac{m_0}{2} + m \right) R^2 \omega$$

[where  $I = \frac{m_0}{2} R^2$  and  $v = \omega R$  (no cord slipping)]

So, 
$$\frac{dM_z}{dt} = \left( \frac{M R^2}{2} + m R^2 \right) \beta_z \quad (2)$$

The downward pull of gravity on the overhanging part is the only external force, which exerts a torque about the  $z$ -axis, passing through  $O$  and is given by,

$$N_z = \left( \frac{m}{l} \right) x g R$$

Hence from the equation 
$$\frac{dM_z}{dt} = N_z$$

$$\left( \frac{M R^2}{2} + m R^2 \right) \beta_z = \frac{m}{l} x g R$$

Thus, 
$$\beta_z = \frac{2mgx}{lR(M+2m)} > 0$$

*Note : We may solve this problem using conservation of mechanical energy of the system (cylinder + thread) in the uniform field of gravity.*

- 1.252 (a) Let us indicate the forces acting on the sphere and their points of application. Choose positive direction of  $x$  and  $\varphi$  (rotation angle) along the incline in downward direction and in the sense of  $\vec{\omega}$  (for unidirectional rotation) respectively. Now from equations of dynamics of rigid body i.e.  $F_x = m w_{cx}$  and  $N_{cz} = I_c \beta_z$  we get :

$$mg \sin \alpha - f_r = m w \quad (1)$$

and 
$$f_r R = \frac{2}{5} m R^2 \beta \quad (2)$$

But 
$$f_r \leq k m g \cos \alpha$$

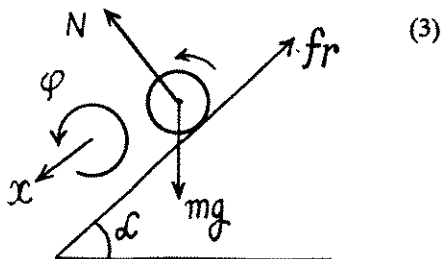
In addition, the absence of slipping provides the kinematical relationship between the accelerations :

$$w = \beta R \quad (4)$$

The simultaneous solution of all the four equations yields :

$$k \cos \alpha \geq \frac{2}{7} \sin \alpha, \text{ or } k \geq \frac{2}{7} \tan \alpha$$

- (b) Solving Eqs. (1) and (2) [of part (a)], we get :



$$w_c = \frac{5}{7} g \sin \alpha.$$

As the sphere starts at  $t = 0$  along positive  $x$  axis, for pure rolling

$$v_c(t) = w_c t = \frac{5}{7} g \sin \alpha t \quad (5)$$

Hence the sought kinetic energy

$$\begin{aligned} T &= \frac{1}{2} m v_c^2 + \frac{1}{2} \frac{2}{5} m R^2 \omega^2 = \frac{7}{10} m v_c^2 \text{ (as } \omega = v_c/R \text{)} \\ &= \frac{7}{10} m \left( \frac{5}{7} g \sin \alpha t \right)^2 = \frac{5}{14} m g^2 \sin^2 \alpha t^2 \end{aligned}$$

- 1.253 (a) Let us indicate the forces and their points of application for the cylinder. Choosing the positive direction for  $x$  and  $\varphi$  as shown in the figure, we write the equation of motion of the cylinder axis and the equation of moments in the C.M. frame relative to that axis i.e. from equation  $F_x = m w_c$  and  $N_z = I_c \beta_z$

$$mg - 2T = m w_c; \quad 2TR = \frac{m R^2}{2} \beta$$

As there is no slipping of thread on the cylinder

$$w_c = \beta R$$

From these three equations

$$T = \frac{mg}{6} = 13 \text{ N}, \quad \beta = \frac{2}{5} \frac{g}{R} = 5 \times 10^2 \text{ rad/s}^2$$

(b) we have  $\beta = \frac{2}{3} \frac{g}{R}$

So,  $w_c = \frac{2}{3} g > 0$  or, in vector form  $\vec{w}_c = \frac{2}{3} \vec{g}$

$$P = \vec{F} \cdot \vec{v} = \vec{F} \cdot (\vec{w}_c t)$$

$$= m \vec{g} \cdot \left( \frac{2}{3} \vec{g} t \right) = \frac{2}{3} m g^2 t$$

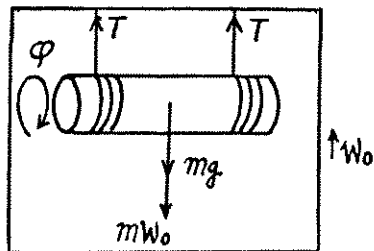
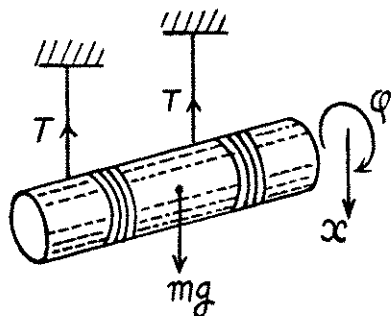
- 1.254 Let us depict the forces and their points of application corresponding to the cylinder attached with the elevator. Newton's second law for solid in vector form in the frame of elevator, gives :

$$2\vec{T} + m\vec{g} + m(-\vec{w}_0) = m\vec{w}' \quad (1)$$

The equation of moment in the C.M. frame relative to the cylinder axis i.e. from  $N_z = I_c \beta_z$  -

$$2TR = \frac{m R^2}{2} \beta = \frac{m R^2}{2} \frac{w'}{R}$$

[as thread does not slip on the cylinder,  $w' = \beta R$ ]



or,

$$T = \frac{mw'}{4}$$

As (1)  $\vec{T} \uparrow \downarrow \vec{w}$ 

so in vector form

$$\vec{T} = -\frac{m\vec{w}}{4} \quad (2)$$

Solving Eqs. (1) and (2),  $\vec{w}' = \frac{2}{3}(\vec{g} - \vec{w}_0)$  and sought force

$$\vec{F} = 2\vec{T} = \frac{1}{3}m(\vec{g} - \vec{w}_0).$$

- 1.255** Let us depict the forces and their points of application for the spool. Choosing the positive direction for  $x$  and  $\varphi$  as shown in the fig., we apply  $F_x = mw_{cx}$  and  $N_{cz} = I_c \beta_z$  and get

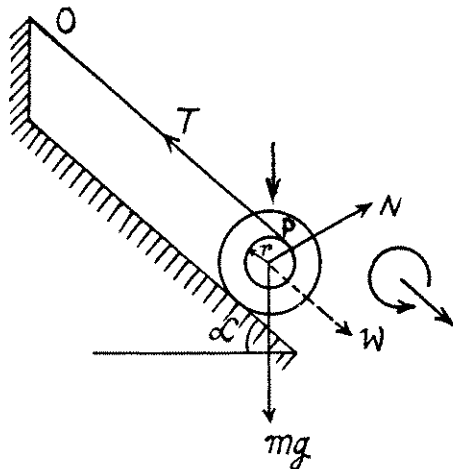
$$mg \sin \alpha - T = mw; Tr = I\beta$$

"Notice that if a point of a solid in plane motion is connected with a thread, the projection of velocity vector of the solid's point of contact along the length of the thread equals the velocity of the other end of the thread (if it is not slacked)"

Thus in our problem,  $v_p = v_0$  but  $v_0 = 0$ , hence point  $P$  is the instantaneous centre of rotation of zero velocity for the spool. Therefore  $v_c = \omega r$  and subsequently  $w_c = \beta r$ .

Solving the equations simultaneously, we get

$$\omega = \frac{g \sin \alpha}{1 + \frac{I}{mr^2}} = 1.6 \text{ m/s}^2$$



- 1.256** Let us sketch the force diagram for solid cylinder and apply Newton's second law in projection form along  $x$  and  $y$  axes (Fig.) :

$$fr_1 + fr_2 = mw_c \quad (1)$$

$$\text{and } N_1 + N_2 - mg - F = 0$$

$$\text{or } N_1 + N_2 = mg + F \quad (2)$$

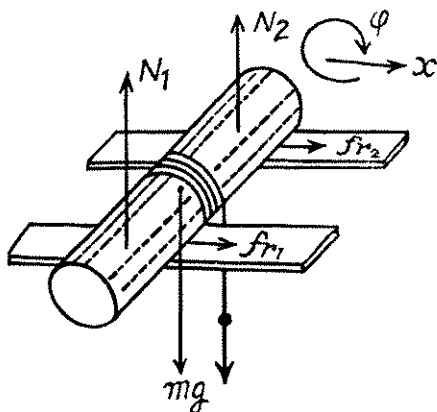
Now choosing positive direction of  $\varphi$  as shown in the figure and using  $N_{cz} = I_c \beta_z$

we get

$$FR - (fr_1 + fr_2)R = \frac{mR^2}{2}\beta = \frac{mR^2}{2}\frac{w_c}{R} \quad (3)$$

[as for pure rolling  $w_c = \beta R$ ]. In addition to,

$$fr_1 + fr_2 \leq k(N_1 + N_2) \quad (4)$$



Solving the Eqs., we get

$$F \leq \frac{3 k m g}{(2 - 3k)}, \text{ or } F_{\max} = \frac{3 k m g}{2 - 3k}$$

and

$$\begin{aligned} \omega_c(\max) &= \frac{k(N_1 + N_2)}{m} \\ &= \frac{k}{m} [mg + F_{\max}] = \frac{k}{m} \left[ mg + \frac{3 k m g}{2 - 3k} \right] = \frac{2 k g}{2 - 3k} \end{aligned}$$

- 1.257 (a) Let us choose the positive direction of the rotation angle  $\varphi$ , such that  $\omega_\alpha$  and  $\beta_z$  have identical signs (Fig.). Equation of motion,  $F_x = m\omega_\alpha$  and  $N_{cz} = I_c \beta_z$  gives :

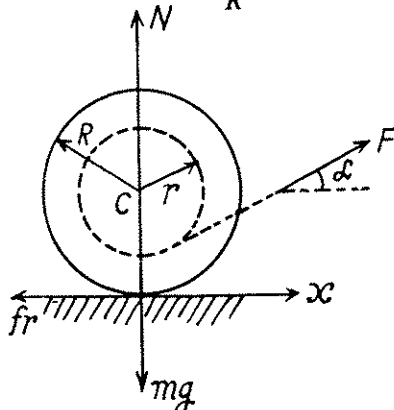
$$F \cos \alpha - fr = m\omega_\alpha : frR - Fr = I_c \beta_z = \gamma m R^2 \beta_z$$

In the absence of the slipping of the spool  $\omega_\alpha = \beta_z R$

$$\text{From the three equations } \omega_{cx} = \omega_c = \frac{F [\cos \alpha - (r/R)]}{m(1 + \gamma)}, \text{ where } \cos \alpha > \frac{r}{R} \quad (1)$$

(b) As static friction ( $fr$ ) does not work on the spool, from the equation of the increment of mechanical energy  $A_{ext} = \Delta T$ .

$$\begin{aligned} A_{ext} &= \frac{1}{2} m v_c^2 + \frac{1}{2} \gamma m R^2 \frac{v_c^2}{R^2} = \frac{1}{2} m (1 + \gamma) v_c^2 \\ &= \frac{1}{2} m (1 + \gamma) 2 \omega_c x = \frac{1}{2} m (1 + \gamma) 2 \omega_c \left( \frac{1}{2} \omega_c t^2 \right) \\ &= \frac{F^2 \left( \cos \alpha - \frac{r}{R} \right)^2 t^2}{2 m (1 + \gamma)} \end{aligned}$$



Note that at  $\cos \alpha = r/R$ , there is no rolling and for  $\cos \alpha < r/R$ ,  $\omega_{cx} < 0$ , i.e. the spool will move towards negative x-axis and rotate in anticlockwise sense.

- 1.258 For the cylinder from the equation  $N_z = I \beta_z$  about its stationary axis of rotation.

$$2Tr = \frac{mr^2}{2} \beta \text{ or } \beta = \frac{4T}{mr} \quad (1)$$

For the rotation of the lower cylinder from the equation  $N_{cz} = I_c \beta_z$

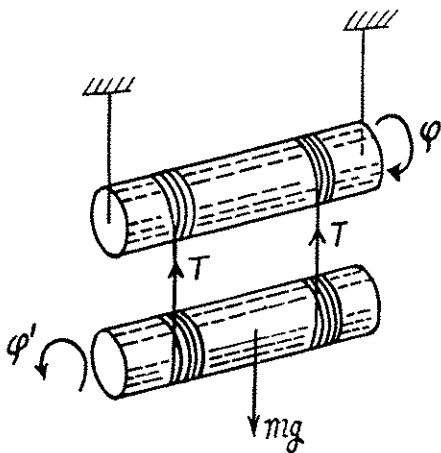
$$2Tr = \frac{mr^2}{2} \beta' \text{ or } \beta' = \frac{4T}{mr} = \beta$$

Now for the translational motion of lower cylinder from the Eq.  $F_x = m\omega_{cx}$  :

$$mg - 2T = m\omega_c \quad (2)$$

As there is no slipping of threads on the cylinders :

$$\omega_c = \beta' r + \beta r = 2\beta r \quad (3)$$



Simultaneous solution of (1), (2) and (3) yields

$$T = \frac{mg}{10}.$$

- 1.259 Let us depict the forces acting on the pulley and weight A, and indicate positive direction for  $x$  and  $\varphi$  as shown in the figure. For the cylinder from the equation  $F_x = m \ddot{x}$  and  $N_{cz} = I_c \beta_z$  we get

$$Mg + T_A - 2T = M \ddot{w}_c \quad (1)$$

$$\text{and } 2TR + T_A(2R) = I \beta = \frac{I \ddot{w}_c}{R} \quad (2)$$

For the weight A from the equation

$$F_x = m \ddot{w}_x$$

$$mg - T_A = m \ddot{w}_A \quad (3)$$

As there is no slipping of the threads on the pulleys.

$$\ddot{w}_A = \ddot{w}_c + 2\beta R = \ddot{w}_c + 2\ddot{w}_c = 3\ddot{w}_c \quad (4)$$

Simultaneous solutions of above four equations gives :

$$\ddot{w}_A = \frac{3(M+3m)g}{\left(M+9m+\frac{I}{R^2}\right)}$$

- 1.260 (a) For the translational motion of the system  $(m_1 + m_2)$ , from the equation :  $F_x = m \ddot{w}_{cx}$

$$F = (m_1 + m_2) \ddot{w}_c \quad \text{or} \quad \ddot{w}_c = F/(m_1 + m_2) \quad (1)$$

Now for the rotational motion of cylinder from the equation :  $N_{cz} = I_c \beta_z$

$$Fr = \frac{m_1 r^2}{2} \beta \quad \text{or} \quad \beta r = \frac{2F}{m_1} \quad (2)$$

But  $\ddot{w}_K = \ddot{w}_c + \beta r$ , So

$$\ddot{w}_K = \frac{F}{m_1 + m_2} + \frac{2F}{m_1} = \frac{F(3m_1 + 2m_2)}{m_1(m_1 + m_2)} \quad (3)$$

- (b) From the equation of increment of mechanical energy :  $\Delta T = A_{ex}$

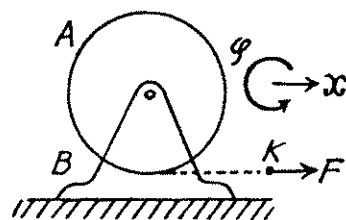
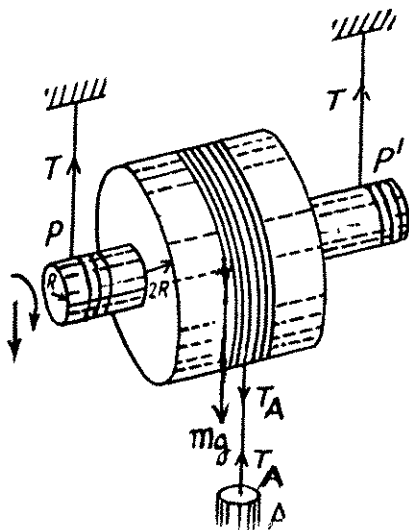
Here

$$\Delta T = T(t), \quad \text{so,} \quad T(t) = A_{ex}$$

As force  $F$  is constant and is directed along  $x$ -axis the sought work done.

$$A_{ex} = Fx$$

(where  $x$  is the displacement of the point of application of the force  $F$  during time interval  $t$ )



$$= F \left( \frac{1}{2} \omega_K t^2 \right) = \frac{F^2 t^2 (3m_1 + 2m_2)}{2m_1(m_1 + m_2)} = T(t)$$

(using Eq. (3))

Alternate :  $T(t) = T_{\text{translation}}(t) + T_{\text{rotation}}(t)$

$$= \frac{1}{2} (m_1 + m_2) \left( \frac{Ft}{(m_1 + m_2)} \right)^2 + \frac{1}{2} \frac{m_1 r^2}{2} \left( \frac{2Ft}{m_1 r} \right)^2 = \frac{F^2 t^2 (3m_1 + 2m_2)}{2m_1(m_1 + m_2)}$$

- 1.261 Choosing the positive direction for  $x$  and  $\varphi$  as shown in Fig, let us we write the equation of motion for the sphere  $F_x = m\omega_{cx}$  and  $N_{cz} = I_c \beta_z$

$$fr = m_2 \omega_2; \quad fr = \frac{2}{5} m_2 r^2 \beta$$

( $\omega_2$  is the acceleration of the C.M. of sphere.)

For the plank from the Eq.  $F_x = m\omega_x$

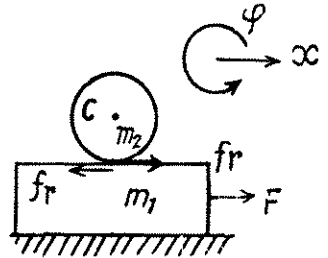
$$F - f_r = m_1 \omega_1$$

In addition, the condition for the absence of slipping of the sphere yields the kinematical relation between the accelerations :

$$\omega_1 = \omega_2 + \beta r$$

Simultaneous solution of the four equations yields :

$$\omega_1 = \frac{F}{\left( m_1 + \frac{2}{7} m_2 \right)} \quad \text{and} \quad \omega_2 = \frac{2}{7} \omega_1$$



- 1.262 (a) Let us depict the forces acting on the cylinder and their point of applications for the cylinder and indicate positive direction of  $x$  and  $\varphi$  as shown in the figure. From the equations for the plane motion of a solid  $F_x = m\omega_{cx}$  and  $N_{cz} = I_c \beta_z$  :

$$kmg = m\omega_{cx} \quad \text{or} \quad \omega_{cx} = kg \quad (1)$$

$$-kmgR = \frac{mR^2}{2} \beta_z \quad \text{or} \quad \beta_z = -2 \frac{kg}{R} \quad (2)$$

Let the cylinder starts pure rolling at  $t = t_0$  after releasing on the horizontal floor at  $t = 0$ .

From the angular kinematical equation

$$\omega_z = \omega_{0z} + \beta_z t,$$

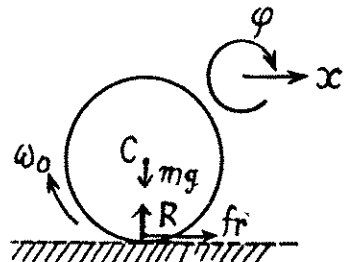
$$\text{or} \quad \omega = \omega_0 - 2 \frac{kg}{R} t \quad (3)$$

From the equation of the linear kinematics,

$$v_{cx} = v_{0cx} + \omega_{cx} t$$

or

$$v_c = 0 + kg t_0 \quad (4)$$



But at the moment  $t = t_0$ , when pure rolling starts  $v_c = \omega R$

so,

$$kg t_0 = \left( \omega_0 - 2 \frac{kg}{R} t_0 \right) R$$

Thus

$$t_0 = \frac{\omega_0 R}{3 kg}$$

(b) As the cylinder picks up speed till it starts rolling, the point of contact has a purely translatory movement equal to  $\frac{1}{2} \omega_c t_0^2$  in the forward directions but there is also a backward movement of the point of contact of magnitude  $(\omega_0 t_0 - \frac{1}{2} \beta t_0^2) R$ . Because of slipping the net displacement is backwards. The total work done is then,

$$\begin{aligned} A_{fr} &= kmg \left[ \frac{1}{2} \omega_c t_0^2 - (\omega_0 t_0 + \frac{1}{2} \beta t_0^2) R \right] \\ &= kmg \left[ \frac{1}{2} kg t_0^2 - \frac{1}{2} \left( -\frac{2kg}{R} \right) t_0^2 R - \omega_0 t_0 R \right] \\ &= kmg \frac{\omega_0 R}{3kg} \left[ \frac{\omega_0 R}{6} + \frac{\omega_0 R}{3} - \omega_0 R \right] = -\frac{m\omega_0^2 R^2}{6} \end{aligned}$$

The same result can also be obtained by the work-energy theorem,  $A_{fr} = \Delta T$ .

**1.263** Let us write the equation of motion for the centre of the sphere at the moment of breaking-off:

$$mv^2/(R+r) = mg \cos \theta,$$

where  $v$  is the velocity of the centre of the sphere at that moment, and  $\theta$  is the corresponding angle (Fig.). The velocity  $v$  can be found from the energy conservation law :

$$mgh = \frac{1}{2} mv^2 + \frac{1}{2} I \omega^2,$$

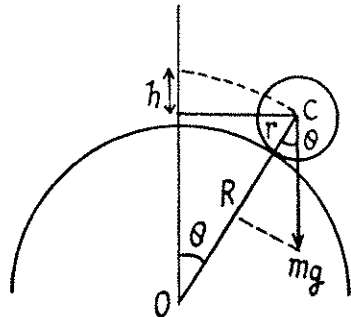
where  $I$  is the moment of inertia of the sphere relative to the axis passing through the sphere's

centre. i.e.  $I = \frac{2}{5} mr^2$ . In addition,

$$v = \omega r; h = (R+r)(1 - \cos \theta).$$

From these four equations we obtain

$$\omega = \sqrt{10 g (R+r) / 17 r^2}.$$



**1.264** Since the cylinder moves without sliding, the centre of the cylinder rotates about the point  $O$ , while passing through the common edge of the planes. In other words, the point  $O$  becomes the foot of the instantaneous axis of rotation of the cylinder.

It at any instant during this motion the velocity of the C.M. is  $v_1$  when the angle (shown in the figure) is  $\beta$ , we have

$$\frac{m v_1^2}{R} = mg \cos \beta - N,$$

where  $N$  is the normal reaction of the edge

$$\text{or, } v_1^2 = gR \cos \beta - \frac{NR}{m} \quad (1)$$

From the energy conservation law,

$$\frac{1}{2} I_0 \frac{v_1^2}{R^2} - \frac{1}{2} I_0 \frac{v_0^2}{R^2} = mgR(1 - \cos \beta)$$

$$\text{But } I_0 = \frac{mR^2}{2} + mR^2 = \frac{3}{2} mR^2,$$

(from the parallel axis theorem)

$$\text{Thus, } v_1^2 = v_0^2 + \frac{4}{3} gR(1 - \cos \beta) \quad (2)$$

From (1) and (2)

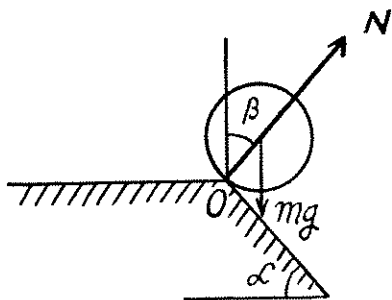
$$v_0^2 = \frac{gR}{3} (7 \cos \beta - 4) - \frac{NR}{m}$$

The angle  $\beta$  in this equation is clearly smaller than or equal to  $\alpha$  so putting  $\beta = \alpha$  we get

$$v_0^2 = \frac{gR}{3} (7 \cos \alpha - 4) - \frac{N_0 R}{M}$$

where  $N_0$  is the corresponding reaction. Note that  $N \geq N_0$ . No jumping occurs during this turning if  $N_0 > 0$ . Hence,  $v_0$  must be less than

$$v_{\max} = \sqrt{\frac{gR}{3} (7 \cos \alpha - 4)}$$



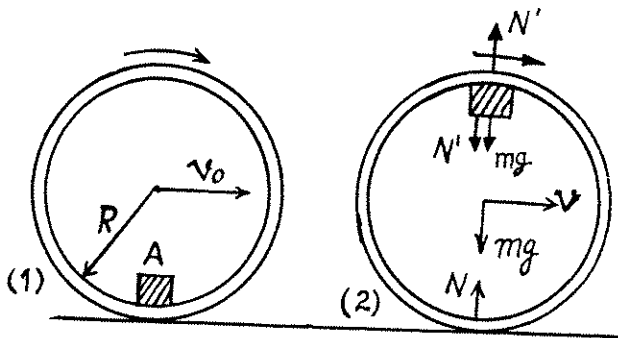
- 1.265 Clearly the tendency of bouncing of the hoop will be maximum when the small body A, will be at the highest point of the hoop during its rolling motion. Let the velocity of C.M. of the hoop equal  $v$  at this position. The static friction does no work on the hoop, so from conservation of mechanical energy;  $E_1 = E_2$

$$\text{or, } 0 + \frac{1}{2} m v_0^2 + \frac{1}{2} m R^2 \left( \frac{v_0}{R} \right)^2 - mgR = \frac{1}{2} m (2v)^2 + \frac{1}{2} m v^2 + \frac{1}{2} m R^2 \left( \frac{v}{R} \right)^2 + mgR$$

$$\text{or, } 3v^2 = v_0^2 - 2gR \quad (1)$$

From the equation  $F_n = m\omega_n$  for body A at final position 2 :

$$mg + N' = m \omega^2 R = m \left( \frac{v}{R} \right)^2 R \quad (2)$$





As the hoop has no acceleration in vertical direction, so for the hoop,

$$N + N' = mg \quad (3)$$

From Eqs. (2) and (3),

$$N = 2mg - \frac{mv^2}{R} \quad (4)$$

As the hoop does not bounce,  $N \geq 0$

So from Eqs. (1), (4) and (5),

$$\frac{8gR - v_0^2}{3R} \geq 0 \quad \text{or} \quad 8gR \geq v_0^2$$

Hence

$$v_0 \leq \sqrt{8gR}$$

- 1.266** Since the lower part of the belt is in contact with the rigid floor, velocity of this part becomes zero. The crawler moves with velocity  $v$ , hence the velocity of upper part of the belt becomes  $2v$  by the rolling condition and kinetic energy of upper part  $= \frac{1}{2} \left( \frac{m}{2} \right) (2v)^2 = mv^2$ , which is also the sought kinetic energy, assuming that the length of the belt is much larger than the radius of the wheels.

- 1.267** The sphere has two types of motion, one is the rotation about its own axis and the other is motion in a circle of radius  $R$ . Hence the sought kinetic energy

$$T = \frac{1}{2} I_1 \omega_1^2 + \frac{1}{2} I_2 \omega_2^2 \quad (1)$$

where  $I_1$  is the moment of inertia about its own axis, and  $I_2$  is the moment of inertia about the vertical axis, passing through  $O$ ,

$$\text{But, } I_1 = \frac{2}{5} mr^2 \text{ and } I_2 = \frac{2}{5} mr^2 + mR^2 \text{ (using parallel axis theorem,)} \quad (2)$$

In addition to

$$\omega_1 = \frac{v}{r} \text{ and } \omega_2 = \frac{v}{R} \quad (3)$$

$$\text{Using (2) and (3) in (1), we get } T' = \frac{7}{10} mv^2 \left( 1 + \frac{2r^2}{7R^2} \right)$$

- 1.268** For a point mass of mass  $dm$ , looked at from  $C$  rotating frame, the equation is

$$dm \vec{w}' = \vec{f} + dm \omega^2 \vec{r}' + 2 dm (\vec{v}' \times \vec{\omega})$$

where  $\vec{r}'$  = radius vector in the rotating frame with respect to rotation axis and  $\vec{v}'$  = velocity in the same frame. The total centrifugal force is clearly

$$\vec{F}_{cf} = \sum dm \omega^2 \vec{r}' = m \omega^2 \vec{R}_c$$

$\vec{R}_c$  is the radius vector of the C.M. of the body with respect to rotation axis, also

$$\vec{F}_{cor} = 2m \vec{v}_c' \times \vec{\omega}$$

where we have used the definitions

$$m \vec{R}_c = \sum dm \vec{r}' \text{ and } m \vec{v}_c' = \sum dm \vec{v}'$$

- 1.269 Consider a small element of length  $dx$  at a distance  $x$  from the point  $C$ , which is rotating in a circle of radius  $r = x \sin \theta$

Now, mass of the element  $= \left(\frac{m}{l}\right) dx$

So, centrifugal force acting on this element

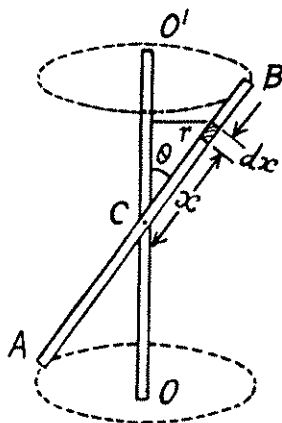
$= \left(\frac{m}{l}\right) dx \omega^2 x \sin \theta$  and moment of this force about  $C$ ,

$$|dN| = \left(\frac{m}{l}\right) dx \omega^2 x \sin \theta \cdot x \cos \theta$$

$$= \frac{m \omega^2}{2l} \sin 2\theta x^2 dx$$

and hence, total moment

$$N = 2 \int_0^{l/2} \frac{m \omega^2}{2l} \sin 2\theta x^2 dx = \frac{1}{24} m \omega^2 l^2 \sin 2\theta,$$



- 1.270 Let us consider the system in a frame rotating with the rod. In this frame, the rod is at rest and experiences not only the gravitational force  $m\vec{g}$  and the reaction force  $\vec{R}$ , but also the centrifugal force  $\vec{F}_{cf}$ .

In the considered frame, from the condition of equilibrium i.e.  $N_{Ox} = 0$

or, 
$$N_{cf} = mg \frac{l}{2} \sin \theta \quad (1)$$

where  $N_{cf}$  is the moment of centrifugal force about  $O$ . To calculate  $N_{cf}$ , let us consider an element of length  $dx$ , situated at a distance  $x$  from the point  $O$ . This element is subjected to a horizontal pseudo force  $\left(\frac{m}{l}\right) dx \omega^2 x \sin \theta$ .

The moment of this pseudo force about the axis of rotation through the point  $O$  is

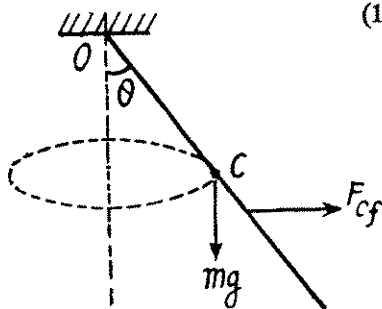
$$dN_{cf} = \left(\frac{m}{l}\right) dx \omega^2 x \sin \theta x \cos \theta$$

$$= \frac{m \omega^2}{l} \sin \theta \cos \theta x^2 dx$$

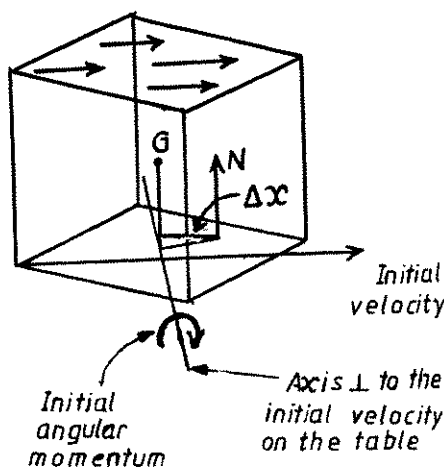
So 
$$N_{cf} = \int_0^l \frac{m \omega^2}{l} \sin \theta \cos \theta x^2 dx = \frac{m \omega^2 l^2}{3} \sin \theta \cos \theta \quad (2)$$

It follows from Eqs. (1) and (2) that,

$$\cos \theta = \left( \frac{3g}{2\omega^2 l} \right) \quad \text{or} \quad \theta = \cos^{-1} \left( \frac{3g}{2\omega^2 l} \right) \quad (3)$$



- 1.271 When the cube is given an initial velocity on the table in some direction (as shown) it acquires an angular momentum about an axis on the table perpendicular to the initial velocity and (say) just below the C.G.. This angular momentum will disappear when the cube stops and this can only be due to a torque. Frictional forces cannot do this by themselves because they act in the plane containing the axis. But if the force of normal reaction act eccentrically (as shown), their torque can bring about the vanishing of the angular momentum. We can calculate the distance  $\Delta x$  between the point of application of the normal reaction and the C.G. of the cube as follows. Take the moment about C.G. of all the forces. This must vanish because the cube does not turn or turnable on the table. Then if the force of friction is  $fr$



$$fr \frac{a}{2} = N \Delta x$$

But  $N = mg$  and  $fr = kmg$ , so

$$\Delta x = ka/2$$

- 1.272 In the process of motion of the given system the kinetic energy and the angular momentum relative to rotation axis do not vary. Hence, it follows that

$$\frac{1}{2} \frac{Ml^2}{3} \omega_0^2 = \frac{1}{2} m(\omega^2 l^2 + v^2) + \frac{1}{2} \frac{Ml^2}{3} \omega^2$$

( $\omega$  is the final angular velocity of the rod)

$$\text{and} \quad \frac{Ml^2}{3} \omega_0 = \frac{Ml^2}{3} \omega + ml^2 \omega$$

From these equations we obtain

$$\omega = \omega_0 / \left(1 + \frac{3M}{M}\right) \text{ and}$$

$$v = \omega_0 l / \sqrt{1 + 3m/M}$$

- 1.273 Due to hitting of the ball, the angular impulse received by the rod about the C.M. is equal to  $p \frac{1}{2}$ . If  $\omega$  is the angular velocity acquired by the rod, we have

$$\frac{ml^2}{12} \omega = \frac{pl}{2} \text{ or } \omega = \frac{6p}{ml} \quad (1)$$

In the frame of C.M., the rod is rotating about an axis passing through its mid point with the angular velocity  $\omega$ . Hence the force exerted by one half on the other = mass of one half  $\times$  acceleration of C.M. of that part, in the frame of C.M.

$$= \frac{m}{2} \left( \omega^2 \frac{l}{4} \right) = m \frac{\omega^2 l}{8} = \frac{9p^2}{2ml} = 9 \text{ N}$$

- 1.274 (a) In the process of motion of the given system the kinetic energy and the angular momentum relative to rotation axis do not vary. Hence it follows that

$$\frac{1}{2}mv^2 = \frac{1}{2}mv'^2 + \frac{1}{2}\left(\frac{Ml^2}{3}\right)\omega^2$$

and

$$mv\frac{l}{2} = mv'\frac{l}{2} + \frac{Ml^2}{3}\omega$$

From these equations we obtain

$$v' = \left(\frac{3m - 4M}{3m + 4M}\right)v, \quad \text{and} \quad \omega = \frac{4v}{l(1 + 4m/3M)}$$

As  $\vec{v}' \uparrow \uparrow \vec{v}$ , so in vector form  $\vec{v}' = \left(\frac{3m - 4M}{3m + 4M}\right)\vec{v}$

- (b) Obviously the sought force provides the centripetal acceleration to the C.M. of the rod and is

$$\begin{aligned} F_n &= mw_{cn} \\ &= M\omega^2 \frac{l}{2} = \frac{8Mv^2}{l(1 + 4M/3m)^2} \end{aligned}$$

- 1.275 (a) About the axis of rotation of the rod, the angular momentum of the system is conserved. Thus if the velocity of the flying bullet is  $v$ ,

$$mvl = \left(ml^2 + \frac{Ml^2}{3}\right)\omega$$

$$\omega = \frac{mv}{\left(m + \frac{M}{3}\right)l} \approx \frac{3mv}{Ml} \quad \text{as } m \ll M \quad (1)$$

Now from the conservation of mechanical energy of the system (rod with bullet) in the uniform field of gravity

$$\frac{1}{2}\left(ml^2 + \frac{Ml^2}{3}\right)\omega^2 = (M + m)g\frac{l}{2}(1 - \cos\alpha) \quad (2)$$

[because C.M. of rod raises by the height  $\frac{l}{2}(1 - \cos\alpha)$ ]

Solving (1) and (2), we get

$$v = \left(\frac{M}{m}\right)\sqrt{\frac{2}{3}gl} \sin \frac{\alpha}{2} \quad \text{and} \quad \omega = \sqrt{\frac{6g}{l}} \sin \frac{\alpha}{2}$$

- (b) Sought  $\Delta p = \left[m(\omega l) + M\left(\omega \frac{l}{2}\right)\right] - mv$

where  $\omega l$  is the velocity of the bullet and  $\omega \frac{l}{2}$  equals the velocity of C.M. of the rod after the impact. Putting the value of  $v$  and  $\omega$  we get

$$\Delta p = \frac{1}{2}mv = M\sqrt{\frac{gl}{6}} \sin \frac{\alpha}{2}$$

This is caused by the reaction at the hinge on the upper end.

- (c) Let the rod starts swinging with angular velocity  $\omega'$ , in this case. Then, like part (a)

$$mvx = \left( \frac{Ml^2}{3} + mx^2 \right) \omega' \quad \text{or} \quad \omega' = \frac{3mvx}{Ml^2}$$

Final momentum is

$$p_f = mx\omega' + \int_0^l y \omega' \frac{M}{l} dy = \frac{M}{2} \omega' l = \frac{3}{2} m v \frac{x}{l}$$

So, 
$$\Delta p = p_f - p_i = mv \left( \frac{3x}{2l} - 1 \right)$$

This vanishes for 
$$x = \frac{2}{3} l$$

- 1.276** (a) As force  $F$  on the body is radial so its angular momentum about the axis becomes zero and the angular momentum of the system about the given axis is conserved. Thus

$$\frac{MR^2}{2} \omega_0 + m \omega_0 R^2 = \frac{MR^2}{2} \omega \quad \text{or} \quad \omega = \omega_0 \left( 1 + \frac{2m}{M} \right)$$

- (b) From the equation of the increment of the mechanical energy of the system :

$$\Delta T = A_{ext}$$

$$\frac{1}{2} \frac{MR^2}{2} \omega^2 - \frac{1}{2} \left( \frac{MR^2}{2} + mR^2 \right) \omega_0^2 = A_{ext}$$

Putting the value of  $\omega$  from part (a) and solving we get

$$A_{ext} = \frac{m \omega_0^2 R^2}{2} \left( 1 + \frac{2m}{M} \right)$$

- 1.277** (a) Let  $z$  be the rotation axis of disc and  $\varphi$  be its rotation angle in accordance with right-hand screw rule (Fig.). ( $\varphi$  and  $\varphi'$  are to be measured in the same sense algebraically.) As  $M_z$  of the system (disc + man) is conserved and  $M_{z(initial)} = 0$ , we have at any instant,

$$0 = \frac{m_2 R^2}{2} \frac{d\varphi}{dt} + m_1 \left[ \left( \frac{d\varphi'}{dt} \right) R + \left( \frac{d\varphi}{dt} \right) R \right]$$

or, 
$$d\varphi = \left[ -\frac{m_1}{m_1 + (m_2/2)} \right] d\varphi'$$

On integrating 
$$\int_0^\varphi d\varphi = - \int_0^{\varphi'} \left( \frac{m_1}{m_1 + (m_2/2)} \right) d\varphi'$$

or, 
$$\varphi = - \left( \frac{m_1}{m_1 + \frac{m_2}{2}} \right) \varphi' \quad (1)$$

This gives the total angle of rotation of the disc.

(b) From Eq. (1)

$$\frac{d\varphi}{dt} = - \left( \frac{m_1}{m_1 + \frac{m_2}{2}} \right) \frac{d\varphi'}{dt} = - \left( \frac{m_1}{m_1 + \frac{m_2}{2}} \right) \frac{v'(t)}{R}$$

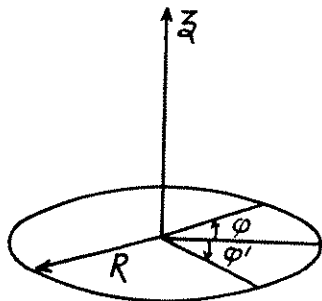
Differentiating with respect to time

$$\frac{d^2\varphi}{dt^2} = - \left( \frac{m_1}{m_1 + \frac{m_2}{2}} \right) \frac{1}{R} \frac{dv'(t)}{dt}$$

Thus the sought force moment from the Eq.  $N_z = I\beta_z$

$$N_z = \frac{m_2 R^2}{2} \frac{d^2\varphi}{dt^2} = - \frac{m_2 R^2}{2} \left( \frac{m_1}{m_1 + \frac{m_2}{2}} \right) \frac{1}{R} \frac{dv'(t)}{dt}$$

Hence 
$$N_z = - \frac{m_1 m_2 R}{2m_1 + m_2} \frac{dv'(t)}{dt}$$



**1.278** (a) From the law of conservation of angular momentum of the system relative to vertical axis  $z$ , it follows that:

$$I_1 \omega_{1z} + I_2 \omega_{2z} = (I_1 + I_2) \omega_z$$

Hence 
$$\omega_z = (I_1 \omega_{1z} + I_2 \omega_{2z}) / (I_1 + I_2) \quad (1)$$

Not that for  $\omega_z > 0$ , the corresponding vector  $\vec{\omega}$  coincides with the positive direction to the  $z$  axis, and vice versa. As both discs rotate about the same vertical axis  $z$ , thus in vector form.

$$\vec{\omega} = I_1 \vec{\omega}_1 + I_2 \vec{\omega}_2 / (I_1 + I_2)$$

However, the problem makes sense only if  $\vec{\omega}_1 \uparrow \vec{\omega}_2$  or  $\vec{\omega}_1 \downarrow \vec{\omega}_2$

(b) From the equation of increment of mechanical energy of a system:  $A_{fr} = \Delta T$ .

$$= \frac{1}{2} (I_1 + I_2) \omega_z^2 - \frac{1}{2} I_1 \omega_{1z}^2 + \frac{1}{2} I_2 \omega_{2z}^2$$

Using Eq. (1)

$$A_{fr} = - \frac{I_1 I_2}{2(I_1 + I_2)} (\omega_{1z} - \omega_{2z})^2$$

**1.279** For the closed system (disc + rod), the angular momentum is conserved about any axis. Thus from the conservation of angular momentum of the system about the rotation axis of rod passing through its C.M. gives :

$$mv \frac{l}{2} = mv' \frac{l}{2} + \frac{\eta ml^2}{12} \omega \quad (1)$$

( $v'$  is the final velocity of the disc and  $\omega$  angular velocity of the rod)

For the closed system linear momentum is also conserved. Hence

$$mv = mv' + \eta mv_c \quad (2)$$

(where  $v_c$  is the velocity of C.M. of the rod)

From Eqs (1) and (2) we get

$$v_c = \frac{l\omega}{3} \quad \text{and} \quad v - v' = \eta v_c$$

Applying conservation of kinetic energy, as the collision is elastic

$$\frac{1}{2}mv^2 = \frac{1}{2}mv'^2 + \frac{1}{2}\eta mv_c^2 + \frac{1}{2}\frac{\eta ml^2}{12}\omega^2 \quad (3)$$

or  $v^2 - v'^2 = 4\eta v_c^2$  and hence  $v + v' = 4v_c$

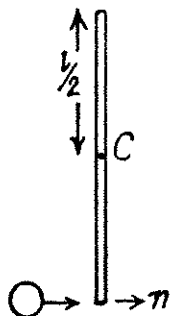
Then

$$v' = \frac{4-\eta}{4+\eta}v \quad \text{and} \quad \omega = \frac{12v}{(4+\eta)l}$$

Vectorially, noting that we have taken  $\vec{v}'$  parallel to  $\vec{v}$

$$\vec{u}' = \left( \frac{4-\eta}{4+\eta} \right) \vec{v}$$

So,  $\vec{u}' = 0$  for  $\eta = 4$  and  $\vec{u}' \downarrow \uparrow \vec{v}$  for  $\eta > 4$



**1.280** See the diagram in the book (Fig. 1.72)

(a) When the shaft  $BB'$  is turned through  $90^\circ$  the platform must start turning with angular velocity  $\Omega$  so that the angular momentum remains constant. Here

$$(I + I_0)\Omega = I_0\omega_0 \quad \text{or,} \quad \Omega = \frac{I_0\omega_0}{I + I_0}$$

The work performed by the motor is therefore

$$\frac{1}{2}(I + I_0)\Omega^2 = \frac{1}{2}\frac{I_0^2\omega_0^2}{I + I_0}$$

If the shaft is turned through  $180^\circ$ , angular velocity of the sphere changes sign. Thus from conservation of angular momentum,

$$I\Omega - I_0\omega_0 = I_0\omega_0$$

(Here  $-I_0\omega_0$  is the complete angular momentum of the sphere i. e. we assume that the angular velocity of the sphere is just  $-\omega_0$ ). Then

$$\Omega = 2I_0\frac{\omega_0}{I}$$

and the work done must be,

$$\frac{1}{2}I\Omega^2 + \frac{1}{2}I_0\omega_0^2 - \frac{1}{2}I_0\omega_0^2 = \frac{2I_0^2\omega_0^2}{I}$$

(b) In the case (a), first part, the angular momentum vector of the sphere is precessing with angular velocity  $\Omega$ . Thus a torque,

$$I_0 \omega_0 \Omega = \frac{I_0^2 \omega_0^2}{I + I_0} \text{ is needed.}$$

1.281 The total centrifugal force can be calculated by,

$$\int_0^{l_0} \frac{m}{l_0} \omega^2 x dx = \frac{1}{2} m l_0 \omega^2$$

Then for equilibrium,

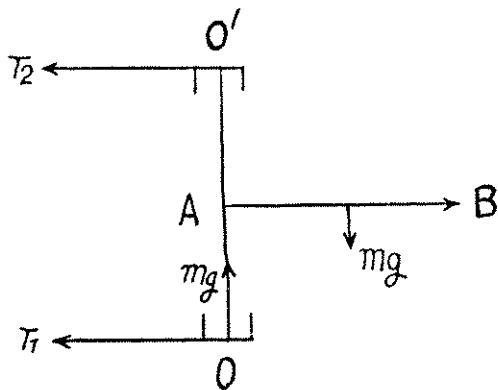
$$(T_2 - T_1) \frac{l}{2} = mg \frac{l_0}{2}$$

$$\text{and, } T_2 + T_1 = \frac{1}{2} m l_0 \omega^2$$

Thus  $T_1$  vanishes, when

$$\omega^2 = \frac{2g}{l}, \quad \omega = \sqrt{\frac{2g}{l}} = 6 \text{ rad/s}$$

$$\text{Then } T_2 = mg \frac{l_0}{l} = 25 \text{ N}$$



1.282 See the diagram in the book (Fig. 1.71).

(a) The angular velocity  $\vec{\omega}$  about  $OO'$  can be resolved into a component parallel to the rod and a component  $\omega \sin \theta$  perpendicular to the rod through C. The component parallel to the rod does not contribute so the angular momentum

$$M = I \omega \sin \theta = \frac{1}{12} m l^2 \omega \sin \theta$$

$$\text{Also, } M_z = M \sin \theta = \frac{1}{12} m l^2 \omega \sin^2 \theta$$

This can be obtained directly also,

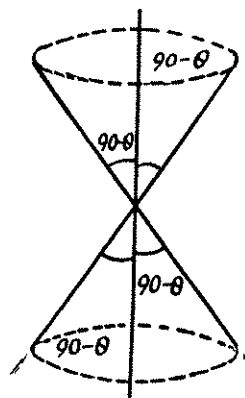
(b) The modulus of  $\vec{M}$  does not change but the modulus of the change of  $\vec{M}$  is  $|\Delta \vec{M}|$ .

$$|\Delta \vec{M}| = 2M \sin(90 - \theta) = \frac{1}{12} m l^2 \omega \sin 2\theta$$

(c) Here  $M_1 = M \cos \theta = I \omega \sin \theta \cos \theta$

$$\text{Now } \left| \frac{d\vec{M}}{dt} \right| = I \omega \sin \theta \cos \theta \frac{\omega dt}{dt} = \frac{1}{24} m l^2 \omega^2 \sin^2 \theta$$

as  $\vec{M}$  precesses with angular velocity  $\omega$ .





- 1.283 Here  $M = I\omega$  is along the symmetry axis. It has two components, the part  $I\omega \cos\theta$  is constant and the part  $M_{\perp} = I\omega \sin\theta$  precesses, then

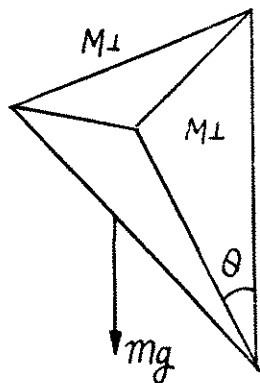
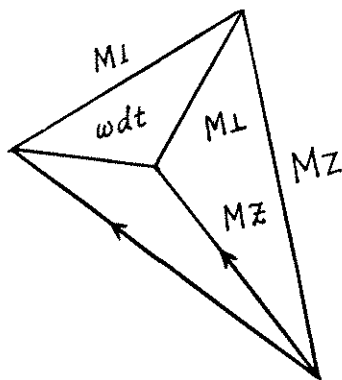
$$\left| \frac{d\vec{M}}{dt} \right| = I\omega \sin\theta \omega' = mgl \sin\theta$$

or,  $\omega' = \text{precession frequency} = \frac{mgl}{I\omega} = 0.7 \text{ rad/s}$

- (b) This force is the centripetal force due to precession. It acts inward and has the magnitude

$$|\vec{F}| = \left| \sum m_i \omega'^2 \vec{\rho}_i \right| = m \omega'^2 l \sin\theta = 12 \text{ mN.}$$

$\vec{\rho}_i$  is the distance of the  $i$ th element from the axis. This is the force that the table will exert on the top. See the diagram in the answer sheet



- 1.284 See the diagram in the book (Fig. 1.73).

The moment of inertia of the disc about its symmetry axis is  $\frac{1}{2}mR^2$ . If the angular velocity of the disc is  $\omega$  then the angular momentum is  $\frac{1}{2}mR^2\omega$ . The precession frequency being  $2\pi n$ ,

we have 
$$\left| \frac{d\vec{M}}{dt} \right| = \frac{1}{2}mR^2\omega \times 2\pi n$$

This must equal  $m(g + \omega)l$ , the effective gravitational torques ( $g$  being replaced by  $g + \omega$  in the elevator). Thus,

$$\omega = \frac{(g + \omega)l}{\pi R^2 n} = 300 \text{ rad/s}$$

- 1.285 The effective  $g$  is  $\sqrt{g^2 + w^2}$  inclined at angle  $\tan^{-1} \frac{w}{g}$  with the vertical. Then with reference to the new "vertical" we proceed as in problem 1.283. Thus

$$\omega' = \frac{ml\sqrt{g^2 + w^2}}{I\omega} = 0.8 \text{ rad/s.}$$

The vector  $\vec{\omega}'$  forms an angle  $\theta = \tan^{-1} \frac{w}{g} = 6^\circ$  with the normal vertical.

- 1.286 The moment of inertia of the sphere is  $\frac{2}{5}mR^2$  and hence the value of angular momentum is  $\frac{2}{5}mR^2\omega$ . Since it precesses at speed  $\omega'$  the torque required is

$$\frac{2}{5}mR^2\omega\omega' = F'l$$

So, 
$$F' = \frac{2}{5}mR^2\omega\omega'/l = 300 \text{ N}$$

(The force  $F'$  must be vertical.)

- 1.287 The moment of inertia is  $\frac{1}{2}mr^2$  and angular momentum is  $\frac{1}{2}mr^2\omega$ . The axle oscillates about a horizontal axis making an instantaneous angle.

$$\varphi = \varphi_m \sin \frac{2\pi t}{T}$$

This means that there is a variable precession with a rate of precession  $\frac{d\varphi}{dt}$ . The maximum value of this is  $\frac{2\pi\varphi_m}{T}$ . When the angle between the axle and the axis is at its maximum value, a torque  $I\omega\Omega$

$$= \frac{1}{2}mr^2\omega \frac{2\pi\varphi_m}{T} = \frac{\pi mr^2\omega\varphi_m}{T} \text{ acts on it.}$$

The corresponding gyroscopic force will be  $\frac{\pi mr^2\omega\varphi_m}{lT} = 90 \text{ N}$

- 1.288 The revolutions per minute of the flywheel being  $n$ , the angular momentum of the flywheel is  $I \times 2\pi n$ . The rate of precession is  $\frac{v}{R}$

Thus  $N = 2\pi I N V / R = 5.97 \text{ kN.m.}$

- 1.289 As in the previous problem a couple  $2\pi I n v / R$  must come in play. This can be done if a force,  $\frac{2\pi I n v}{Rl}$  acts on the rails in opposite directions in addition to the centrifugal and other forces. The force on the outer rail is increased and that on the inner rail decreased. The additional force in this case has the magnitude  $1.4 \text{ kN.m.}$

## 1.6 ELASTIC DEFORMATIONS OF A SOLID BODY

1.290 Variation of length with temperature is given by

$$l_t = l_0 (1 + \alpha \Delta t) \text{ or } \frac{\Delta l}{l_0} = \alpha \Delta t = \epsilon \quad (1)$$

But 
$$\epsilon = \frac{\sigma}{E},$$

Thus  $\sigma = \alpha \Delta t E$ , which is the sought stress of pressure.

Putting the value of  $\alpha$  and  $E$  from Appendix and taking  $\Delta t = 100^\circ\text{C}$ , we get

$$\sigma = 2.2 \times 10^3 \text{ atm.}$$

1.291 (a) Consider a transverse section of the tube and concentrate on an element which subtends an angle  $\Delta\varphi$  at the centre. The forces acting on a portion of length  $\Delta l$  on the element are

(1) tensile forces side ways of magnitude  $\sigma \Delta r \Delta l$ .

The resultant of these is

$$2\sigma \Delta r \Delta l \sin \frac{\Delta\varphi}{2} \approx \sigma \Delta r \Delta l \Delta\varphi$$

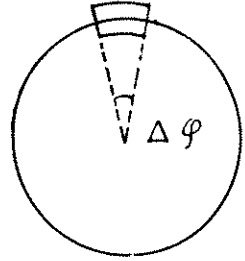
radially towards the centre.

(2) The force due to fluid pressure =  $p r \Delta\varphi \Delta l$

Since these balance, we get  $p_{\max} \approx \sigma_m \frac{\Delta r}{r}$

where  $\sigma_m$  is the maximum tensile force.

Putting the values we get  $p_{\max} = 19.7 \text{ atmos.}$



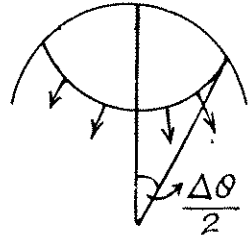
(b) Consider an element of area  $dS = \pi (r \Delta\theta/2)^2$  about  $z$ -axis chosen arbitrarily. There are tangential tensile forces all around the ring of the cap. Their resultant is

$$\sigma \left[ 2\pi \left( r \frac{\Delta\theta}{2} \right) \Delta r \right] \sin \frac{\Delta\theta}{2}$$

Hence in the limit

$$p_m \pi \left( \frac{r \Delta\theta}{2} \right)^2 = \sigma_m \pi \left( \frac{r \Delta\theta}{2} \right) \Delta r \Delta\theta$$

$$\text{or } p_m = \frac{2\sigma_m \Delta r}{r} = 39.5 \text{ atmos.}$$



1.292 Let us consider an element of rod at a distance  $x$  from its rotation axis (Fig.). From Newton's second law in projection form directed towards the rotation axis

$$-dT = (dm) \omega^2 x = \frac{m}{l} \omega^2 x dx$$

On integrating

$$-T = \frac{m\omega^2}{l} \frac{x^2}{2} + C (\text{constant})$$

But at  $x = \pm \frac{l}{2}$  or free end,  $T = 0$

Thus  $0 = \frac{m\omega^2 l^2}{2} \cdot \frac{1}{4} + C$  or  $C = -\frac{m\omega^2 l}{8}$

Hence  $T = \frac{m\omega^2}{2} \left( \frac{l}{4} - \frac{x^2}{l} \right)$

Thus  $T_{\max} = \frac{m\omega^2 l}{8}$  (at mid point)

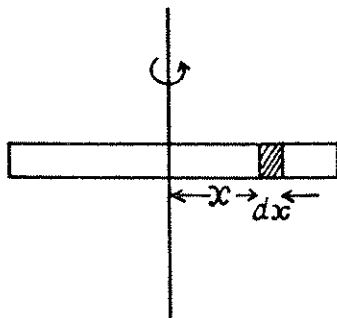
Condition required for the problem is

$$T_{\max} = S \sigma_m$$

So,  $\frac{m\omega^2 l}{8} = S \sigma_m$  or  $\omega = \frac{2}{l} \sqrt{\frac{2\sigma_m}{\rho}}$

Hence the sought number of rps

$$n = \frac{\omega}{2\pi} = \frac{1}{\pi l} \sqrt{\frac{2\sigma_m}{\rho}} \quad [\text{using the table } n = 0.8 \times 10^2 \text{ rps}]$$



1.293 Let us consider an element of the ring (Fig.). From Newton's law  $F_n = m\omega_n^2 r$  for this element, we get,

$$T d\theta = \left( \frac{m}{2\pi} d\theta \right) \omega^2 r \quad [\text{see solution of 1.93 or 1.92}]$$

So,  $T = \frac{m}{2\pi} \omega^2 r$

Condition for the problem is :

$$\frac{T}{\pi r^2} \leq \sigma_m \quad \text{or,} \quad \frac{m\omega^2 r}{2\pi^2 r^2} \leq \sigma_m$$

$$\text{or,} \quad \omega_{\max}^2 = \frac{2\pi^2 \sigma_m r}{\pi r^2 (2\pi \rho)} = \frac{\sigma_m}{\rho r^2}$$

Thus sought number of rps

$$n = \frac{\omega_{\max}}{2\pi} = \frac{1}{2\pi r} \sqrt{\frac{\sigma_m}{\rho}}$$

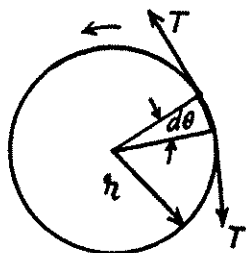
Using the table of appendices  $n = 23 \text{ rps}$

1.294 Let the point O descend by the distance  $x$  (Fig.). From the condition of equilibrium of point O.

$$2T \sin \theta = mg \quad \text{or} \quad T = \frac{mg}{2 \sin \theta} = \frac{mg}{2x} \sqrt{(l/2)^2 + x^2} \quad (1)$$

$$\text{Now,} \quad \frac{T}{\pi (d/2)^2} = \sigma = \epsilon E \quad \text{or} \quad T = \epsilon E \pi \frac{d^2}{4} \quad (2)$$

( $\sigma$  here is stress and  $\epsilon$  is strain.)



In addition to it,

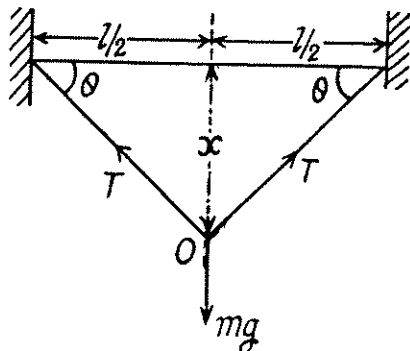
$$\varepsilon = \frac{\sqrt{(l/2)^2 + x^2} - \frac{l}{2}}{l/2} = \sqrt{1 + \left(\frac{2x}{l}\right)^2} - 1 \quad (3)$$

From Eqs. (1), (2) and (3)

$$x - \frac{x}{\sqrt{1 + \left(\frac{2x}{l}\right)^2}} = \frac{mgl}{\pi Ed^2} \quad \text{as } x \ll l$$

$$\text{So, } \frac{4x^3}{2l^2} \approx \frac{mgl}{\pi Ed^2}$$

$$\text{or, } x = l \left( \frac{mg}{2\pi Ed^2} \right)^{1/3} = 2.5 \text{ cm}$$



- 1.295** Let us consider an element of the rod at a distance  $x$  from the free end (Fig.). For the considered element 'T-T' are internal restoring forces which produce elongation and  $dT$  provides the acceleration to the element. For the element from Newton's law :

$$dT = (dm) w = \left( \frac{m}{l} dx \right) \frac{F_o}{m} = \frac{F_o}{l} dx$$

As free end has zero tension, on integrating the above expression,

$$\int_0^T dT = \frac{F_o}{l} \int_0^x dx \quad \text{or} \quad T = \frac{F_o}{l} x$$

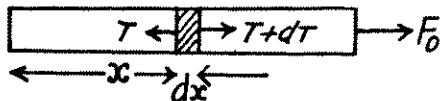
Elongation in the considered element of length  $dx$  :

$$\partial \xi = \frac{\sigma}{E} (x) dx = \frac{T}{SE} dx = \frac{F_o x dx}{SEL}$$

$$\text{Thus total elongation } \xi = \frac{F_o}{SEL} \int_0^l x dx = \frac{F_o l}{2SE}$$

Hence the sought strain

$$\sigma = \frac{\xi}{l} = \frac{F_o}{2SE}$$



- 1.296** Let us consider an element of the rod at a distance  $r$  from its rotation axis. As the element rotates in a horizontal circle of radius  $r$ , we have from Newton's second law in projection form directed toward the axis of rotation :

$$T - (T + dT) = (dm) \omega^2 r$$

$$\text{or, } -dT = \left( \frac{m}{l} dr \right) \omega^2 r = \frac{m}{l} \omega^2 r dr$$

At the free end tension becomes zero. Integrating the above expression we get, thus

$$-\int_T^0 dT = \frac{m}{l} \omega^2 \int_r^l r dr$$

Thus 
$$T = \frac{m\omega^2}{l} \left( \frac{l^2 - r^2}{2} \right) = \frac{m\omega^2 l}{2} \left( 1 - \frac{r^2}{l^2} \right)$$

Elongation in elemental length  $dr$  is given by :

$$\partial \xi = \frac{\sigma(r)}{E} dr = \frac{T}{SE} dr$$

(where  $S$  is the cross sectional area of the rod and  $T$  is the tension in the rod at the considered element)

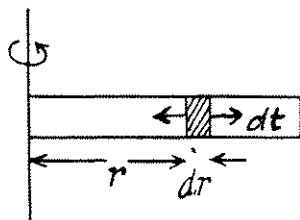
or, 
$$\partial \xi = \frac{m\omega^2 l}{2SE} \left( 1 - \frac{r^2}{l^2} \right) dr$$

Thus the sought elongation

$$\xi = \int_0^l d\xi = \frac{m\omega^2 l}{2SE} \int_0^l \left( 1 - \frac{r^2}{l^2} \right) dr$$

or, 
$$\xi = \frac{m\omega^2 l}{2SE} \frac{2l}{3} = \frac{(Sl\rho)}{3SE} \omega^2 l^3$$

$$= \frac{1}{3} \frac{\rho \omega^2 l^3}{E} \quad (\text{where } \rho \text{ is the density of the copper.})$$



### 1.297 Volume of a solid cylinder

$$V = \pi r^2 l$$

So, 
$$\frac{\Delta V}{V} = \frac{\pi 2r \Delta r l}{\pi r^2 l} + \frac{\pi r^2 \Delta l}{\pi r^2 l} = \frac{2\Delta r}{r} + \frac{\Delta l}{l} \quad (1)$$

But longitudinal strain  $\Delta l/l$  and accompanying lateral strain  $\Delta r/r$  are related as

$$\frac{\Delta r}{r} = -\mu \frac{\Delta l}{l} \quad (2)$$

Using (2) in (1), we get :

$$\frac{\Delta V}{V} = \frac{\Delta l}{l} (1 - 2\mu) \quad (3)$$

But 
$$\frac{\Delta l}{l} = \frac{-F/\pi r^2}{E}$$

(Because the increment in the length of cylinder  $\Delta l$  is negative)

So, 
$$\frac{\Delta V}{V} = \frac{-F}{\pi r^2 E} (1 - 2\mu)$$

Thus, 
$$\Delta V = \frac{-Fl}{E} (1 - 2\mu)$$

Negative sign means that the volume of the cylinder has decreased.

- 1.298** (a) As free end has zero tension, thus the tension in the rod at a vertical distance  $y$  from its lower end

$$T = \frac{m}{l} g y \quad (1)$$

Let  $\partial l$  be the elongation of the element of length  $dy$ , then

$$\begin{aligned} \partial l &= \frac{\sigma(y)}{E} dy \\ &= \frac{T}{SE} dy = \frac{mgydy}{SIE} = \rho g y dy / E \quad (\text{where } \rho \text{ is the density of the copper}) \end{aligned}$$

Thus the sought elongation

$$\Delta l = \int \partial l = \rho g \int_0^l \frac{y dy}{E} = \frac{1}{2} \rho g l^2 / E \quad (2)$$

- (b) If the longitudinal (tensile) strain is  $\epsilon = \frac{\Delta l}{l}$ , the accompanying lateral (compressive) strain is given by

$$\epsilon' = \frac{\Delta r}{r} = -\mu \epsilon \quad (3)$$

Then since  $V = \pi r^2 l$  we have

$$\begin{aligned} \frac{\Delta V}{V} &= \frac{2\Delta r}{r} + \frac{\Delta l}{l} \\ &= (1 - 2\mu) \frac{\Delta l}{l} \quad [\text{Using (3)}] \end{aligned}$$

where  $\frac{\Delta l}{l}$  is given in part (a),  $\mu$  is the Poisson ratio for copper.

- 1.299** Consider a cube of unit length before pressure is applied. The pressure acts on each face. The pressures on the opposite faces constitute a tensile stress producing longitudinal compression and lateral extension. The compressions is  $\frac{p}{E}$  and the lateral extension is  $\mu \frac{p}{E}$

The net result is a compression

$$\frac{p}{E} (1 - 2\mu) \text{ in each side.}$$

Hence  $\frac{\Delta V}{V} = -\frac{3p}{E} (1 - 2\mu)$  because from symmetry  $\frac{\Delta V}{V} = 3 \frac{\Delta l}{l}$

(b) Let us consider a cube under an equal compressive stress  $\sigma$ , acting on all its faces.

Then, 
$$\text{volume strain} = -\frac{\Delta V}{V} = \frac{\sigma}{k}, \quad (1)$$

where  $k$  is the bulk modulus of elasticity.

So 
$$\frac{\sigma}{k} = \frac{3\sigma}{E}(1 - 2\mu)$$

or, 
$$E = 3k(1 - 2\mu) = \frac{3}{\beta}(1 - 2\mu) \left( \text{as } k = \frac{1}{\beta} \right)$$

$$\mu \leq \frac{1}{2} \text{ if } E \text{ and } \beta \text{ are both to remain positive.}$$

**1.300** A beam clamped at one end and supporting an applied load at the free end is called a cantilever. The theory of cantilevers is discussed in advanced text book on mechanics. The key result is that elastic forces in the beam generate a couple, whose moment, called the moment of resistances, balances the external bending moment due to weight of the beam, load etc. The moment of resistance, also called internal bending moment (I.B.M) is given by

$$\text{I.B.M.} = EI/R$$

Here  $R$  is the radius of curvature of the beam at the representative point  $(x, y)$ .  $I$  is called the geometrical moment of inertia

$$I = \int z^2 ds$$

of the cross section relative to the axis passing through the natural layer which remains unstretched. (Fig.1.). The section of the beam beyond  $P$  exerts the bending moment  $N(x)$  and we have,

$$\frac{EI}{R} = N(x)$$

If there is no load other than that due to the weight of the beam, then

$$N(x) = \frac{1}{2} \rho g (l-x)^2 bh$$

where  $\rho$  = density of steel.

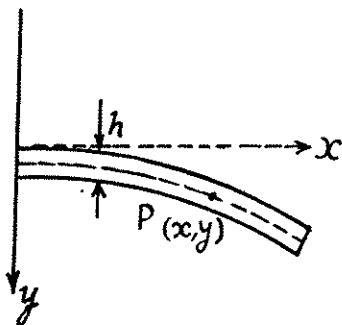
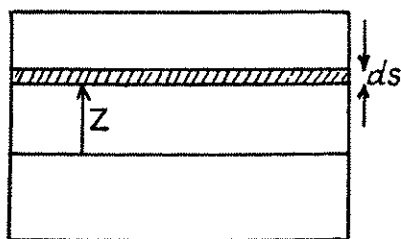
Hence, at  $x = 0$

$$\left( \frac{I}{R} \right)_0 = \frac{\rho g l^2 b h}{2EI}$$

Here  $b$  = width of the beam perpendicular to paper.

Also, 
$$I = \int_{-h/2}^{h/2} z^2 bdz = \frac{bh^3}{12}.$$

Hence, 
$$\left( \frac{1}{R} \right)_0 = \frac{6\rho g l^2}{Eh^2} = (0.121 \text{ km})^{-1}$$





1.301 We use the equation given above and use the result that when  $y$  is small

$$\frac{1}{R} \approx \frac{d^2 y}{dx^2}. \text{ Thus, } \frac{d^2 y}{dx^2} = \frac{N(x)}{EI}$$

(a) Here  $N(x) = N_0$  is a constant. Then integration gives,

$$\frac{dy}{dx} = \frac{N_0 x}{EI} + C_1$$

But  $\left(\frac{dy}{dx}\right) = 0$  for  $x = 0$ , so  $C_1 = 0$ . Integrating again,

$$y = \frac{N_0 x^2}{2EI}$$

where we have used  $y = 0$  for  $x = 0$  to set the constant of integration at zero. This is the equation of a parabola. The sag of the free end is

$$\lambda = y(x = l) = \frac{N_0 l^2}{2EI}$$

(b) In this case  $N(x) = F(l - x)$  because the load  $F$  at the extremity is balanced by a similar force at  $F$  directed upward and they constitute a couple. Then

$$\frac{d^2 y}{dx^2} = \frac{F(l - x)}{EI}$$

Integrating,  $\frac{dy}{dx} = \frac{F(lx - x^2/2)}{EI} + C_1$

As before  $C_1 = 0$ . Integrating again, using  $y = 0$  for  $x = 0$

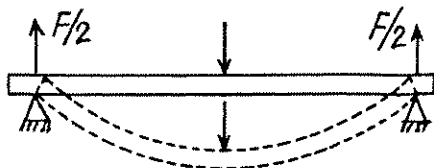
$$y = \frac{F \left( \frac{lx^2}{2} - \frac{x^3}{6} \right)}{EI} \text{ here } \lambda = \frac{Fl^3}{3EI}$$

Here for a square cross section

$$I = \int_{-a/2}^{a/2} z^2 a \, dz = a^4/12.$$

1.302 One can think of it as analogous to the previous case but with a beam of length  $l/2$  loaded upward by a force  $F/2$ .

Thus  $\lambda = \frac{Fl^3}{48EI}$ ,



On using the last result of the previous problem.

1.303 (a) In this case  $N(x) = \frac{1}{2} \rho g b h (l - x)^2$  where  $b$  = width of the girder.

Also  $I = b h^3/12$ . Then,

$$\frac{E b h^2}{12} \frac{d^2 y}{dx^2} = \frac{\rho g b h}{2} (l^2 - 2lx + x^2).$$

Integrating, 
$$\frac{dy}{dx} = \frac{6 \rho g}{E h^2} \left( l^2 x - lx^2 + \frac{x^3}{3} \right)$$

using  $\frac{dy}{dx} = 0$  for  $x = 0$ . Again integrating

$$y = \frac{6 \rho g}{E h^2} \left( \frac{l^2 x^2}{2} - \frac{lx^3}{3} + \frac{x^4}{12} \right)$$

Thus 
$$\lambda = \frac{6 \rho g l^4}{E h^2} \left( \frac{1}{2} - \frac{1}{3} + \frac{1}{12} \right)$$

$$= \frac{6 \rho g l^4}{E h^2} \cdot \frac{3}{12} = \frac{3 \rho g l^4}{2 E h^2}$$

(b) As before,  $EI \frac{d^2 y}{dx^2} = N(x)$  where  $N(x)$  is the bending moment due to section  $PB$ .

This bending moment is clearly

$$N = \int_x^{2l} w d\xi (\xi - x) - wl(2l - x)$$

$$= w \left( 2l^2 - 2xl + \frac{x^2}{2} \right) - wl(2l - x) = w \left( \frac{x^2}{2} - xl \right)$$

(Here  $w = \rho g b h$  is weight of the beam per unit length)

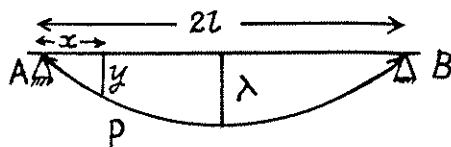
Now integrating,  $EI \frac{dy}{dx} = w \left( \frac{x^3}{6} - \frac{x^2 l}{2} \right) + c_0$

or since  $\frac{dy}{dx} = 0$  for  $x = l$ ,  $c_0 = wl^3/3$

Integrating again,  $EI y = w \left( \frac{x^4}{24} - \frac{x^3 l}{6} \right) + \frac{wl^3 x}{3} + c_1$

As  $y = 0$  for  $x = 0$ ,  $c_1 = 0$ . From this we find

$$\lambda = y(x = l) = \frac{5wl^4}{24} / EI = \frac{5\rho g l^4}{2 E h^2}$$



**1.304** The deflection of the plate can be noticed by going to a co-rotating frame. In this frame each element of the plate experiences a pseudo force proportional to its mass. These forces have a moment which constitutes the bending moment of the problem. To calculate this moment we note that the acceleration of an element at a distance  $\xi$  from the axis is  $a = \xi \beta$  and the moment of the forces exerted by the section between  $x$  and  $l$  is

$$N = \rho l h \beta \int_x^l \xi^2 d\xi = \frac{1}{3} \rho l h \beta (l^3 - x^3).$$

From the fundamental equation

$$EI \frac{d^2 y}{dx^2} = \frac{1}{3} \rho l h \beta (l^3 - x^3).$$

$$\text{The moment of inertia } I = \int_{-h/2}^{+h/2} z^2 l dz = \frac{lh^3}{12}.$$

Note that the neutral surface (i.e. the surface which contains lines which are neither stretched nor compressed) is a vertical plane here and  $z$  is perpendicular to it.

$$\frac{d^2 y}{dx^2} = \frac{4 \rho \beta}{E h^2} (l^3 - x^3). \text{ Integrating}$$

$$\frac{dy}{dx} = \frac{4 \rho \beta}{E h^2} \left( l^3 x - \frac{x^4}{4} \right) + c_1$$

Since  $\frac{dy}{dx} = 0$ , for  $x = 0$ ,  $c_1 = 0$ . Integrating again,

$$y = \frac{4 \rho \beta}{E h^2} \left( \frac{l^3 x^2}{2} - \frac{x^5}{20} \right) + c_2$$

$c_2 = 0$  because  $y = 0$  for  $x = 0$

$$\text{Thus } \lambda = y(x = l) = \frac{9 \rho \beta l^5}{5 E h^2}$$

- 1.305 (a) Consider a hollow cylinder of length  $l$ , outer radius  $r + \Delta r$  inner radius  $r$ , fixed at one end and twisted at the other by means of a couple of moment  $N$ . The angular displacement  $\varphi$ , at a distance  $l$  from the fixed end, is proportional to both  $l$  and  $N$ . Consider an element of length  $dx$  at the twisted end. It is moved by an angle  $\varphi$  as shown. A vertical section is also shown and the twisting of the parallelopipe of length  $l$  and area  $\Delta r dx$  under the action of the twisting couple can be discussed by elementary means. If  $f$  is the tangential force generated then shearing stress is  $f/\Delta r dx$  and this must equal

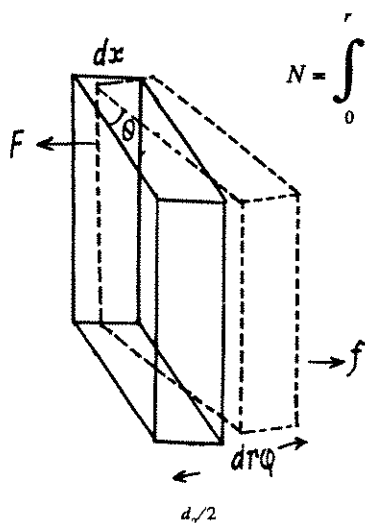
$$G \theta = G \frac{r \varphi}{l}, \text{ since } \theta = \frac{r \varphi}{l}.$$

$$\text{Hence, } f = G \Delta r dx \frac{r \varphi}{l}.$$

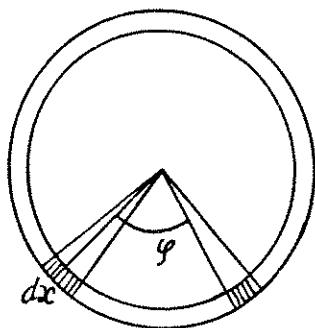
The force  $f$  has moment  $fr$  about the axis and so the total moment is

$$N = G \Delta r \frac{\varphi}{l} r^2 \int dx = \frac{2 \pi r^3 \Delta r \varphi}{l} G$$

(b) For a solid cylinder we must integrate over  $r$ . Thus



$$N = \int_0^r \frac{2\pi r^3 dr \phi G}{l} = \frac{\pi r^4 G \phi}{2l}$$



1.306 Clearly  $N = \int_{d_1/2}^{d_2/2} \frac{2\pi r^3 dr \phi G}{l} = \frac{\pi}{32l} G \phi (d_2^4 - d_1^4)$

using

$$G = 81 \text{ GPa} = 8.1 \times 10^{10} \frac{\text{N}}{\text{m}^2}$$

$$d_2 = 5 \times 10^{-2} \text{ m}, d_1 = 3 \times 10^{-2} \text{ m}$$

$$\phi = 2.0^\circ = \frac{\pi}{90} \text{ radians}, l = 3 \text{ m}$$

$$N = \frac{\pi \times 8.1 \times \pi}{32 \times 3 \times 90} (625 - 81) \times 10^2 \text{ N}\cdot\text{m}$$

$$= 0.5033 \times 10^3 \text{ N}\cdot\text{m} \approx 0.5 \text{ kN}\cdot\text{m}$$

1.307 The maximum power that can be transmitted by means of a shaft rotating about its axis is clearly  $N\omega$  where  $N$  is the moment of the couple producing the maximum permissible torsion,  $\phi$ . Thus

$$P = \frac{\pi r^4 G \phi}{2l} \cdot \omega = 16.9 \text{ kw}$$

1.308 Consider an elementary ring of width  $dr$  at a distant  $r$  from the axis. The part outside exerts a couple  $N + \frac{dN}{dr} dr$  on this ring while the part inside exerts a couple  $N$  in the opposite direction. We have for equilibrium

$$\frac{dN}{dr} dr = -dI\theta$$

where  $dI$  is the moment of inertia of the elementary ring,  $\beta$  is the angular acceleration and minus sign is needed because the couple  $N(r)$  decreases, with distance vanishing at the outer radius,  $N(r_2) = 0$ . Now

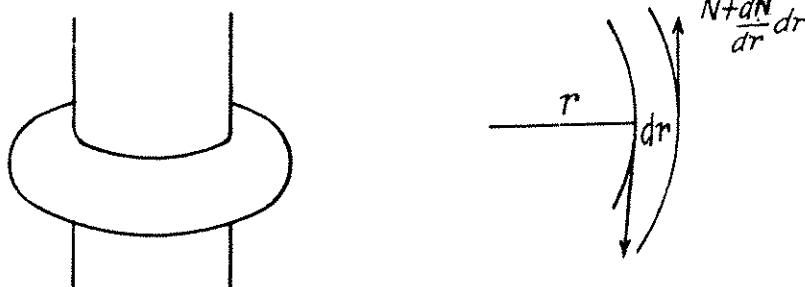
$$dI = \frac{m}{\pi(r_2^2 - r_1^2)} 2\pi r dr r^2$$

Thus

$$dN = \frac{2m\beta}{(r_2^2 - r_1^2)} r^3 dr$$

or,

$$N = \frac{1}{2} \frac{m\beta}{(r_2^2 - r_1^2)} (r_2^4 - r^4), \text{ on integration}$$



- 1.309 We assume that the deformation is wholly due to external load, neglecting the effect of the weight of the rod (see next problem). Then a well known formula says, elastic energy per unit volume

$$= \frac{1}{2} \text{stress} \times \text{strain} = \frac{1}{2} \sigma \epsilon$$

This gives  $\frac{1}{2} \frac{m}{\rho} E \epsilon^2 \approx 0.04 \text{ kJ}$  for the total deformation energy.

- 1.310 When a rod is deformed by its own weight the stress increases as one moves up, the stretching force being the weight of the portion below the element considered.

The stress on the element  $dx$  is

$$\rho \pi r^2 (l-x) g / \pi r^2 = \rho g (l-x)$$

The extension of the element is

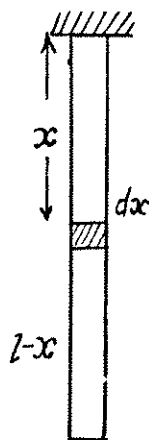
$$\Delta dx = d\Delta x = \rho g (l-x) dx / E$$

Integrating  $\Delta l = \frac{1}{2} \rho g l^2 / E$  is the extension of the whole rod. The elastic energy of the element is

$$\frac{1}{2} \rho g (l-x) \frac{\rho g (l-x)}{E} \pi r^2 dx$$

Integrating

$$\Delta U = \frac{1}{6} \pi r^2 \rho^2 g^2 l^3 / E = \frac{2}{3} \pi r^2 l E \left( \frac{\Delta l}{l} \right)^2$$



- 1.311 The work done to make a loop out of a steel band appears as the elastic energy of the loop and may be calculated from the same.

If the length of the band is  $l$ , the radius of the loop  $R = \frac{l}{2\pi}$ . Now consider an element  $ABCD$  of the loop. The elastic energy of this element can be calculated by the same sort of arguments as used to derive the formula for internal bending moment. Consider a fibre at a distance  $z$  from the neutral surface  $PQ$ . This fibre experiences a force  $p$  and undergoes an extension  $ds$  where  $ds = Z d\varphi$ , while  $PQ = s = R d\varphi$ . Thus strain  $\frac{ds}{s} = \frac{Z}{R}$ . If  $\alpha$  is the cross sectional area of the fibre, the elastic energy associated with it is

$$\frac{1}{2} E \left( \frac{Z}{R} \right)^2 R d\varphi \alpha$$

Summing over all the fibres we get

$$\frac{EI\varphi}{2R} \sum \alpha Z^2 = \frac{EI d\varphi}{2R}$$

For the whole loop this gives,

$$\text{using } \int d\varphi = 2\pi,$$

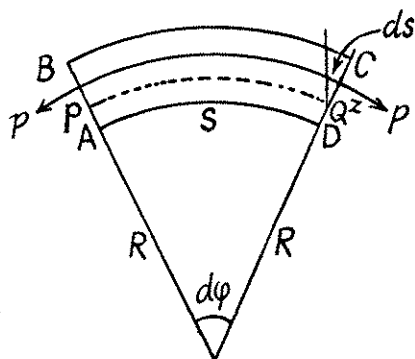
$$\frac{EI\pi}{R} = \frac{2EI\pi^2}{l}$$

Now

$$I = \int_{-\delta/2}^{\delta/2} Z^2 h dZ = \frac{h\delta^3}{12}$$

So the energy is

$$\frac{1}{6} \frac{\pi^2 E h \delta^3}{l} = 0.08 \text{ kJ}$$



- 1.312 When the rod is twisted through an angle  $\theta$ , a couple

$N(\theta) = \frac{\pi r^4 G}{2l} \theta$  appears to resist this. Work done in twisting the rod by an angle  $\varphi$  is then

$$\int_0^\varphi N(\theta) d\theta = \frac{\pi r^4 G}{4l} \varphi^2 = 7 \text{ J on putting the values.}$$

- 1.313 The energy between radii  $r$  and  $r + dr$  is, by differentiation,  $\frac{\pi r^3 dr}{l} G \varphi^2$

Its density is

$$\frac{\pi r^3 dr}{2\pi r dr l} \frac{G \varphi^2}{l} = \frac{1}{2} \frac{G \varphi^2 r^2}{l^2}$$

- 1.314 The energy density is as usual  $1/2$  stress  $\times$  strain. Stress is the pressure  $\rho gh$ . Strain is  $\beta \times \rho gh$  by definition of  $\beta$ . Thus

$$u = \frac{1}{2} \beta (\rho gh)^2 = 23.5 \text{ kJ/m}^3 \text{ on putting the values.}$$

## 1.7 HYDRODYNAMICS

- 1.315** Between 1 and 2 fluid particles are in nearly circular motion and therefore have centripetal acceleration. The force for this acceleration, like for any other situation in an ideal fluid, can only come from the pressure variation along the line joining 1 and 2. This requires that pressure at 1 should be greater than the pressure at 2 i.e.

$$P_1 > P_2$$

so that the fluid particles can have required acceleration. If there is no turbulence, the motion can be taken as irrotational. Then by considering

$$\oint \vec{v} \cdot d\vec{r} = 0$$

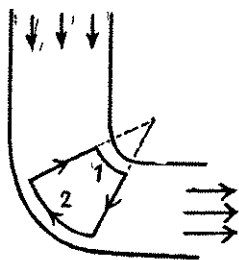
along the circuit shown we infer that

$$v_2 > v_1$$

(The portion of the circuit near 1 and 2 are streamlines while the other two arms are at right angle to streamlines)

In an incompressible liquid we also have  $\text{div } \vec{v} = 0$

By electrostatic analogy we then find that the density of streamlines is proportional to the velocity at that point.



- 1.316** From the conservation of mass

$$v_1 S_1 = v_2 S_2 \quad (1)$$

But  $S_1 < S_2$  as shown in the figure of the problem, therefore

$$v_1 > v_2$$

As every streamline is horizontal between 1 & 2, Bernoulli's theorem becomes

$$p + \frac{1}{2} \rho v^2 = \text{constant, which gives}$$

$$p_1 < p_2 \text{ as } v_1 > v_2$$

As the difference in height of the water column is  $\Delta h$ , therefore

$$p_2 - p_1 = \rho g \Delta h \quad (2)$$

From Bernoulli's theorem between points 1 and 2 of a streamline

$$p_1 + \frac{1}{2} \rho v_1^2 = p_2 + \frac{1}{2} \rho v_2^2$$

or, 
$$p_2 - p_1 = \frac{1}{2} \rho (v_1^2 - v_2^2)$$

or 
$$\rho g \Delta h = \frac{1}{2} \rho (v_1^2 - v_2^2) \quad (3) \text{ (using Eq. 2)}$$

using (1) in (3), we get

$$v_1 = S_2 \sqrt{\frac{2 g \Delta h}{S_2^2 - S_1^2}}$$



Hence the sought volume of water flowing per sec

$$Q = v_1 S_1 = S_1 S_2 \sqrt{\frac{2 g \Delta h}{S_2^2 - S_1^2}}$$

1.317 Applying Bernoulli's theorem for the point A and B,

$$p_A = p_B + \frac{1}{2} \rho v^2 \quad \text{as, } v_A = 0$$

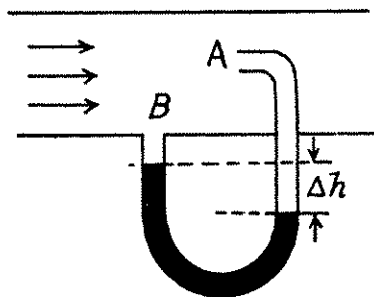
$$\text{or, } \frac{1}{2} \rho v^2 = p_A - p_B = \Delta h \rho_0 g$$

$$\text{So, } v = \sqrt{\frac{2 \Delta h \rho_0 g}{\rho}}$$

$$\text{Thus, rate of flow of gas, } Q = S v = S \sqrt{\frac{2 \Delta h \rho_0 g}{\rho}}$$

The gas flows over the tube past it at B. But at A the gas becomes stationary as the gas will move into the tube which already contains gas.

In applying Bernoulli's theorem we should remember that  $\frac{p}{\rho} + \frac{1}{2} v^2 + gz$  is constant along a streamline. In the present case, we are really applying Bernoulli's theorem somewhat indirectly. The streamline at A is not the streamline at B. Nevertheless the result is correct. To be convinced of this, we need only apply Bernoulli's theorem to the streamline that goes through A by comparing the situation at A with that above B on the same level. In steady conditions, this agrees with the result derived because there cannot be a transverse pressure differential.

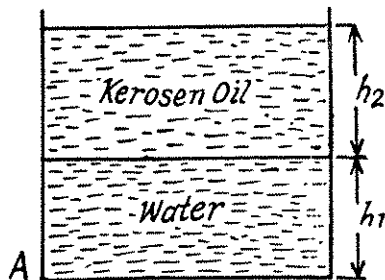


1.318 Since, the density of water is greater than that of kerosene oil, it will collect at the bottom. Now, pressure due to water level equals  $h_1 \rho_1 g$  and pressure due to kerosene oil level equals  $h_2 \rho_2 g$ . So, net pressure becomes  $h_1 \rho_1 g + h_2 \rho_2 g$ .

From Bernoulli's theorem, this pressure energy will be converted into kinetic energy while flowing through the whole A.

$$\text{i.e. } h_1 \rho_1 g + h_2 \rho_2 g = \frac{1}{2} \rho_1 v^2$$

$$\text{Hence } v = \sqrt{2 \left( h_1 + h_2 \frac{\rho_2}{\rho_1} \right) g} = 3 \text{ m/s}$$



1.319 Let,  $H$  be the total height of water column and the hole is made at a height  $h$  from the bottom.

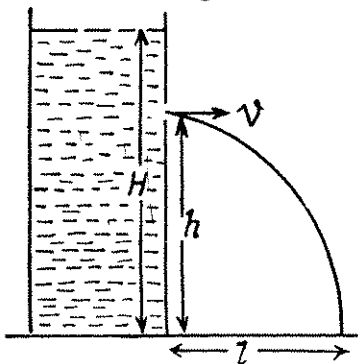
Then from Bernoulli's theorem

$$\frac{1}{2} \rho v^2 = (H - h) \rho g$$

or,  $v = \sqrt{(H - h) 2g}$ , which is directed horizontally.

For the horizontal range,  $l = v t$

$$= \sqrt{2g(H-h)} \cdot \sqrt{\frac{2h}{g}} = 2\sqrt{Hh - h^2}$$





Now, for maximum  $l$ ,  $\frac{d(Hh - h^2)}{dh} = 0$

which yields  $h = \frac{H}{2} = 25 \text{ cm.}$

**1.320** Let the velocity of the water jet, near the orifice be  $v'$ , then applying Bernoulli's theorem,

$$\frac{1}{2} \rho v'^2 = h_0 \rho g + \frac{1}{2} \rho v^2$$

or,  $v' = \sqrt{v^2 - 2g h_0}$  (1)

Here the pressure term on both sides is the same and equal to atmospheric pressure. (In the problem book Fig. should be more clear.)

Now, if it rises up to a height  $h$ , then at this height, whole of its kinetic energy will be converted into potential energy. So,

$$\begin{aligned} \frac{1}{2} \rho v'^2 &= \rho g h \quad \text{or} \quad h = \frac{v'^2}{2g} \\ &= \frac{v^2}{2g} - h_0 = 20 \text{ cm, [using Eq. (1)]} \end{aligned}$$

**1.321** Water flows through the small clearance into the orifice. Let  $d$  be the clearance. Then from the equation of continuity

$$(2\pi R_1 d) v_1 = (2\pi r d) v = (2\pi R_2 d) v_2$$

or  $v_1 R_1 = v r = v_2 R_2$  (1)

where  $v_1$ ,  $v_2$  and  $v$  are respectively the inward radial velocities of the fluid at 1, 2 and 3.

Now by Bernoulli's theorem just before 2 and just after it in the clearance

$$p_0 + h \rho g = p_2 + \frac{1}{2} \rho v_2^2 \quad (2)$$

Applying the same theorem at 3 and 1 we find that this also equals

$$p + \frac{1}{2} \rho v^2 = p_0 + \frac{1}{2} \rho v_1^2 \quad (3)$$

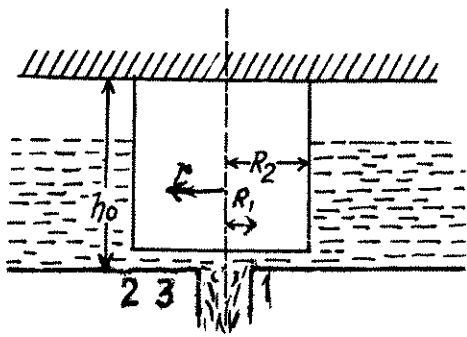
(since the pressure in the orifice is  $p_0$ )

From Eqs. (2) and (3) we also hence

$$v_1 = \sqrt{2gh} \quad (4)$$

and

$$\begin{aligned} p &= p_0 + \frac{1}{2} \rho v_1^2 \left( 1 - \left( \frac{v}{v_1} \right)^2 \right) \\ &= p_0 + h \rho g \left( 1 - \left( \frac{R_1}{r} \right)^2 \right) \quad [\text{Using (1) and (4)}] \end{aligned}$$



- 1.322 Let the force acting on the piston be  $F$  and the length of the cylinder be  $l$ .

Then, work done =  $F l$  (1)

Applying Bernoulli's theorem for points

$A$  and  $B$ ,  $p = \frac{1}{2} \rho v^2$  where  $\rho$  is the density and  $v$  is the velocity at point  $B$ . Now, force on the piston,

$$F = pA = \frac{1}{2} \rho v^2 A \quad (2)$$

where  $A$  is the cross section area of piston.

Also, discharge through the orifice during time interval  $t = Svt$  and this is equal to the volume of the cylinder, i.e.,

$$V = Svt \quad \text{or} \quad v = \frac{V}{St} \quad (3)$$

From Eq. (1), (2) and (3) work done

$$= \frac{1}{2} \rho v^2 A l = \frac{1}{2} \rho A \frac{V^2}{(St)^2} l = \frac{1}{2} \rho V^3 / S^3 t^2 \quad (\text{as } Al = V)$$

- 1.323 Let at any moment of time, water level in the vessel be  $H$  then speed of flow of water through the orifice, at that moment will be

$$v = \sqrt{2gH} \quad (1)$$

In the time interval  $dt$ , the volume of water ejected through orifice,

$$dV = s v dt \quad (2)$$

On the other hand, the volume of water in the vessel at time  $t$  equals

$$V = SH$$

Differentiating (3) with respect to time,

$$\frac{dV}{dt} = S \frac{dH}{dt} \quad \text{or} \quad dV = S dH \quad (4)$$

Eqs. (2) and (4)

$$S dH = s v dt \quad \text{or} \quad dt = \frac{S}{s} \frac{dH}{\sqrt{2gH}}, \text{ from (2)}$$

Integrating,

$$\int_0^t dt = \frac{S}{s\sqrt{2g}} \int_h^0 \frac{dh}{\sqrt{h}}$$

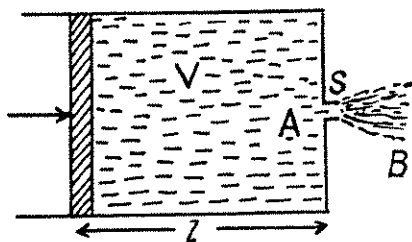
Thus,

$$t = \frac{S}{s} \sqrt{\frac{2h}{g}}$$

- 1.324 In a rotating frame (with constant angular velocity) the Eulerian equation is

$$-\vec{\nabla} p + \rho \vec{g} + 2\rho(\vec{v} \times \vec{\omega}) + \rho \omega^2 \vec{r} = \rho \frac{d\vec{v}}{dt}$$

In the frame of rotating tube the liquid in the "column" is practically static because the orifice is sufficiently small. Thus the Eulerian Eq. in projection form along  $\vec{r}$  (which is

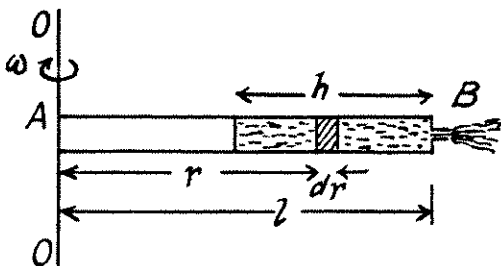


the position vector of an arbitrary liquid element of length  $dr$  relative to the rotation axis) reduces to

$$\frac{-dp}{dr} + \rho \omega^2 r = 0$$

or,  $dp = \rho \omega^2 r dr$

so,  $\int_{p_0}^p dp = \rho \omega^2 \int_{(l-h)}^r r dr$



Thus  $p(r) = p_0 + \frac{\rho \omega^2}{2} [r^2 - (l-h)^2]$  (1)

Hence the pressure at the end B just before the orifice i.e.

$$p(l) = p_0 + \frac{\rho \omega^2}{2} (2lh - h^2)$$
 (2)

Then applying Bernoulli's theorem at the orifice for the points just inside and outside of the end B

$$p_0 + \frac{1}{2} \rho \omega^2 (2lh - h^2) = p_0 + \frac{1}{2} \rho v^2 \quad (\text{where } v \text{ is the sought velocity})$$

So,  $v = \omega h \sqrt{\frac{2l}{h} - 1}$

1.325 The Euler's equation is  $\rho \frac{d\vec{v}}{dt} = \vec{f} - \vec{\nabla} p = -\vec{\nabla} (p + \rho gz)$ , where  $z$  is vertically upwards.

Now  $\frac{d\vec{v}}{dt} = \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla}) \vec{v}$  (1)

But  $(\vec{v} \cdot \vec{\nabla}) \vec{v} = \vec{\nabla} \left( \frac{1}{2} v^2 \right) - \vec{v} \times \text{Curl } \vec{v}$  (2)

we consider the steady (i.e.  $\partial \vec{v} / \partial t = 0$ ) flow of an incompressible fluid then  $\rho = \text{constant}$ . and as the motion is irrotational  $\text{Curl } \vec{v} = 0$

So from (1) and (2)  $\rho \vec{\nabla} \left( \frac{1}{2} v^2 \right) = -\vec{\nabla} (p + \rho gz)$

or,  $\vec{\nabla} \left( p + \frac{1}{2} \rho v^2 + \rho gz \right) = 0$

Hence  $p + \frac{1}{2} \rho v^2 + \rho gz = \text{constant}.$

1.326 Let the velocity of water, flowing through A be  $v_A$  and that through B be  $v_B$ , then discharging rate through A =  $Q_A = S v_A$  and similarly through B =  $S v_B$ .

Now, force of reaction at A,

$$F_A = \rho Q_A v_A = \rho S v_B^2$$

Hence, the net force,

$$F = \rho S (v_A^2 - v_B^2) \text{ as } \vec{F}_A \uparrow \vec{F}_B \downarrow \quad (1)$$

Applying Bernoulli's theorem to the liquid flowing out of A we get

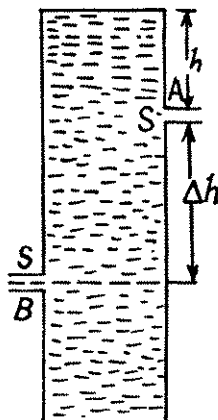
$$\rho_0 + \rho gh = \rho_0 + \frac{1}{2} \rho v_A^2$$

and similarly at B

$$\rho_0 + \rho g(h + \Delta h) = \rho_0 + \frac{1}{2} \rho v_B^2$$

Hence 
$$(v_B^2 - v_A^2) \frac{\rho}{2} = \Delta h \rho g$$

Thus 
$$F = 2\rho g S \Delta h = 0.50 \text{ N}$$



- 1.327 Consider an element of height  $dy$  at a distance  $y$  from the top. The velocity of the fluid coming out of the element is

$$v = \sqrt{2gy}$$

The force of reaction  $dF$  due to this is  $dF = \rho dA v^2$ , as in the previous problem,  
 $= \rho (b dy) 2gy$

Integrating

$$F = \rho gb \int_{h-l}^h 2y dy$$

$$= \rho gb [h^2 - (h-l)^2] = \rho gbl (2h-l)$$

(The slit runs from a depth  $h-l$  to a depth  $h$  from the top.)

- 1.328 Let the velocity of water flowing through the tube at a certain instant of time be  $u$ , then

$u = \frac{Q}{\pi r^2}$ , where  $Q$  is the rate of flow of water and  $\pi r^2$  is the cross section area of the tube.

From impulse momentum theorem, for the stream of water striking the tube corner, in  $x$ -direction in the time interval  $dt$ ,

$$F_x dt = -\rho Q u dt \text{ or } F_x = -\rho Q u$$

and similarly,  $F_y = \rho Q u$

Therefore, the force exerted on the water stream by the tube,

$$\vec{F} = -\rho Q u \vec{i} + \rho Q u \vec{j}$$

According to third law, the reaction force on the tube's wall by the stream equals  $(-F)$

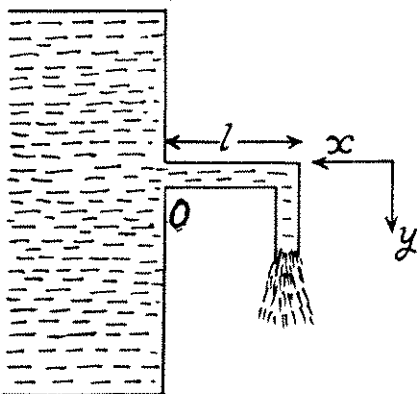
$$= \rho Q u \vec{i} - \rho Q u \vec{j}$$

Hence, the sought moment of force about 0 becomes

$$\vec{N} = l(-\vec{i}) \times (\rho Q u \vec{i} - \rho Q u \vec{j}) = \rho Q u l \vec{k} = \frac{\rho Q^2}{\pi r^2} l \vec{k}$$

and

$$|\vec{N}| = \frac{\rho Q^2 l}{\pi r^2} = 0.70 \text{ N}\cdot\text{m}$$



- 1.329 Suppose the radius at  $A$  is  $R$  and it decreases uniformly to  $r$  at  $B$  where  $S = \pi R^2$  and  $s = \pi r^2$ . Assume also that the semi vertical angle at  $O$  is  $\alpha$ . Then

$$\frac{R}{L_2} = \frac{r}{L_1} = \frac{y}{x}$$

So 
$$y = r + \frac{R-r}{L_2-L_1} (x - L_1)$$

where  $y$  is the radius at the point  $P$  distant  $x$  from the vertex  $O$ . Suppose the velocity with which the liquid flows out is  $V$  at  $A$ ,  $v$  at  $B$  and  $u$  at  $P$ . Then by the equation of continuity

$$\pi R^2 V = \pi r^2 v = \pi y^2 u$$

The velocity  $v$  of efflux is given by

$$v = \sqrt{2gh}$$

and Bernoulli's theorem gives

$$p_p + \frac{1}{2} \rho u^2 = p_0 + \frac{1}{2} \rho v^2$$

where  $p_p$  is the pressure at  $P$  and  $p_0$  is the atmospheric pressure which is the pressure just outside of  $B$ . The force on the nozzle tending to pull it out is then

$$F = \int (p_p - p_0) \sin \theta \, 2\pi y \, ds$$

We have subtracted  $p_0$  which is the force due to atmospheric pressure the factor  $\sin \theta$  gives horizontal component of the force and  $ds$  is the length of the element of nozzle surface,  $ds = dx \sec \theta$  and

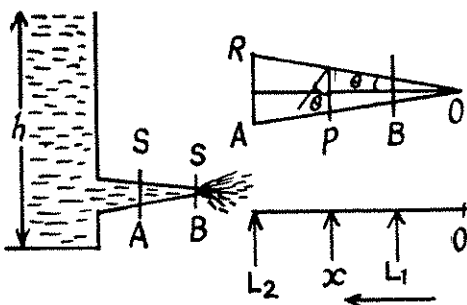
$$\tan \theta = \frac{R-r}{L_2-L_1}$$

Thus

$$\begin{aligned} F &= \int_{L_1}^{L_2} \frac{1}{2} (v^2 - u^2) \rho \, 2\pi y \, \frac{R-r}{L_2-L_1} \, dx \\ &= \pi \rho \int_r^R v^2 \left( 1 - \frac{r^4}{y^4} \right) y \, dy \\ &= \pi \rho v^2 \frac{1}{2} \left( R^2 - r^2 + \frac{r^4}{R^2} - r^2 \right) = \rho g h \left( \frac{\pi(R^2 - r^2)^2}{R^2} \right) \\ &= \rho g h (S - s)^2 / S = 6.02 \text{ N on putting the values.} \end{aligned}$$

**Note :** If we try to calculate  $F$  from the momentum change of the liquid flowing out we will be wrong even as regards the sign of the force.

There is of course the effect of pressure at  $S$  and  $s$  but quantitative derivation of  $F$  from Newton's law is difficult.



- 1.330 The Euler's equation is  $\rho \frac{d\vec{v}}{dt} = \vec{f} - \vec{\nabla} p$  in the space fixed frame where  $\vec{f} = -\rho g \vec{k}$  downward. We assume incompressible fluid so  $\rho$  is constant. Then  $\vec{f} = -\vec{\nabla}(\rho g z)$  where  $z$  is the height vertically upwards from some fixed origin. We go to rotating frame where the equation becomes

$$\rho \frac{d\vec{v}'}{dt} = -\vec{\nabla}(p + \rho g z) + \rho \omega^2 \vec{r} + 2\rho (\vec{v}' \times \vec{\omega})$$

the additional terms on the right are the well known coriolis and centrifugal forces. In the frame rotating with the liquid  $\vec{v}' = 0$  so

$$\vec{\nabla} \left( p + \rho g z - \frac{1}{2} \rho \omega^2 r^2 \right) = 0$$

or 
$$p + \rho g z - \frac{1}{2} \rho \omega^2 r^2 = \text{constant}$$

On the free surface  $p = \text{constant}$ , thus

$$z = \frac{\omega^2}{2g} r^2 + \text{constant}$$

If we choose the origin at point  $r = 0$  (i.e. the axis) of the free surface then "constant" = 0 and

$$z = \frac{\omega^2}{2g} r^2 \quad (\text{The paraboloid of revolution})$$

At the bottom  $z = \text{constant}$

So 
$$p = \frac{1}{2} \rho \omega^2 r^2 + \text{constant}$$

If  $p = p_0$  on the axis at the bottom, then

$$p = p_0 + \frac{1}{2} \rho \omega^2 r^2.$$

- 1.331 When the disc rotates the fluid in contact with, corotates but the fluid in contact with the walls of the cavity does not rotate. A velocity gradient is then set up leading to viscous forces. At a distance  $r$  from the axis the linear velocity is  $\omega r$  so there is a velocity gradient  $\frac{\omega r}{h}$  both in the upper and lower clearance. The corresponding force on the element whose radial width is  $dr$  is

$$\eta 2\pi r dr \frac{\omega r}{h} \quad (\text{from the formula } F = \eta A \frac{dv}{dx})$$

The torque due to this force is

$$\eta 2\pi r dr \frac{\omega r}{h} r$$

and the net torque considering both the upper and lower clearance is

$$\begin{aligned} 2 \int_0^R \eta 2\pi r^3 dr \frac{\omega}{h} \\ = \pi R^4 \omega \eta / h \end{aligned}$$

So power developed is

$$P = \pi R^4 \omega^2 \eta / h = 9.05 \text{ W (on putting the values).}$$

(As instructed end effects i.e. rotation of fluid in the clearance  $r > R$  has been neglected.)

1.332 Let us consider a coaxial cylinder of radius  $r$  and thickness  $dr$ , then force of friction or viscous force on this elemental layer,  $F = 2\pi r l \eta \frac{dv}{dr}$ .

This force must be constant from layer to layer so that steady motion may be possible.

$$\text{or, } \frac{F dr}{r} = 2\pi l \eta dv. \quad (1)$$

Integrating,

$$F \int_{R_2}^r \frac{dr}{r} = 2\pi l \eta \int_0^v dv$$

$$\text{or, } F \ln \left( \frac{r}{R_2} \right) = 2\pi l \eta v \quad (2)$$

Putting

$r = R_1$ , we get

$$F \ln \frac{R_1}{R_2} = 2\pi l \eta v_0$$

From (2) by (3) we get,

$$v = v_0 \frac{\ln r/R_2}{\ln R_1/R_2}$$

Note : The force  $F$  is supplied by the agency which tries to carry the inner cylinder with velocity  $v_0$ .

1.333 (a) Let us consider an elemental cylinder of radius  $r$  and thickness  $dr$  then from Newton's formula

$$F = 2\pi r l \eta r \frac{d\omega}{dr} = 2\pi l \eta r^2 \frac{d\omega}{dr}$$

and moment of this force acting on the element,

$$N = 2\pi r^2 l \eta \frac{d\omega}{dr} r = 2\pi r^3 l \eta \frac{d\omega}{dr}$$

$$\text{or, } 2\pi l \eta d\omega = N \frac{dr}{r^3} \quad (2)$$

As in the previous problem  $N$  is constant when conditions are steady

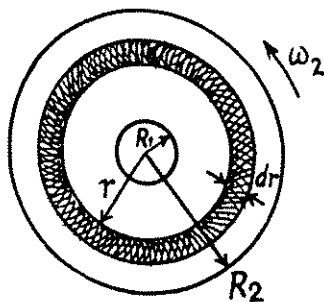
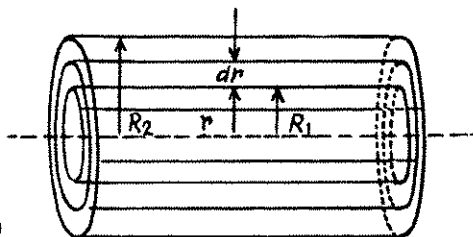
$$\text{Integrating, } 2\pi l \eta \int_0^\omega d\omega = N \int_{R_1}^r \frac{dr}{r^3}$$

$$\text{or, } 2\pi l \eta \omega = \frac{N}{2} \left[ \frac{1}{R_1^2} - \frac{1}{r^2} \right] \quad (3)$$

Putting

$r = R_2$ ,  $\omega = \omega_2$ , we get

$$2\pi l \eta \omega_2 = \frac{N}{2} \left[ \frac{1}{R_1^2} - \frac{1}{R_2^2} \right] \quad (4)$$



From (3) and (4),

$$\omega = \omega_2 \frac{R_1^2 R_2^2}{R_2^2 - R_1^2} \left[ \frac{1}{R_1^2} - \frac{1}{r^2} \right]$$

(b) From Eq. (4),

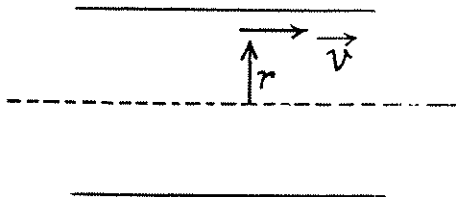
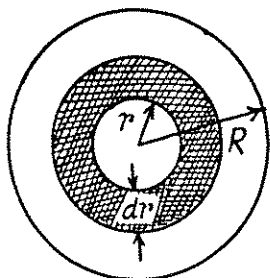
$$N_1 = \frac{N}{l} = 4 \pi \eta \omega_2 \frac{R_1^2 R_2^2}{R_2^2 - R_1^2}$$

1.334 (a) Let  $dV$  be the volume flowing per second through the cylindrical shell of thickness  $dr$  then,

$$dV = -(2 \pi r dr) v_0 \left( 1 - \frac{r^2}{R^2} \right) = 2 \pi v_0 \left( r - \frac{r^3}{R^2} \right) dr$$

and the total volume,

$$V = 2 \pi v_0 \int_0^R \left( r - \frac{r^3}{R^2} \right) dr = 2 \pi v_0 \frac{R^2}{4} = \frac{\pi}{2} R^2 v_0$$



(b) Let,  $dE$  be the kinetic energy, within the above cylindrical shell. Then

$$\begin{aligned} dT &= \frac{1}{2} (dm) v^2 = \frac{1}{2} (2 \pi r l dr \rho) v^2 \\ &= \frac{1}{2} (2 \pi l \rho) r dr v_0^2 \left( 1 - \frac{r^2}{R^2} \right) = \pi l \rho v_0^2 \left[ r - \frac{2r^3}{R^2} + \frac{r^5}{R^4} \right] dr \end{aligned}$$

Hence, total energy of the fluid,

$$T = \pi l \rho v_0^2 \int_0^R \left( r - \frac{2r^3}{R^2} + \frac{r^5}{R^4} \right) dr = \frac{\pi R^2 \rho l v_0^2}{6}$$

(c) Here frictional force is the shearing force on the tube, exerted by the fluid, which equals  $-\eta S \frac{dv}{dr}$ .

Given,

$$v = v_0 \left( 1 - \frac{r^2}{R^2} \right)$$

So,

$$\frac{dv}{dr} = -2 v_0 \frac{r}{R^2}$$

And at

$$r = R, \quad \frac{dv}{dr} = -\frac{2 v_0}{R}$$



Then, viscous force is given by,  $F = -\eta (2\pi Rl) \left( \frac{dv}{dr} \right)_{r=R}$

$$= -2\pi R \eta l \left( -\frac{2v_0}{R} \right) = 4\pi \eta v_0 l$$

(d) Taking a cylindrical shell of thickness  $dr$  and radius  $r$  viscous force,

$$F = -\eta (2\pi r l) \frac{dv}{dr},$$

Let  $\Delta p$  be the pressure difference, then net force on the element  $= \Delta p \pi r^2 + 2\pi \eta l r \frac{dv}{dr}$

But, since the flow is steady,  $F_{net} = 0$

$$\text{or, } \Delta p = \frac{-2\pi \eta l r \frac{dv}{dr}}{\pi r^2} = \frac{-2\pi l \eta r \left( -2v_0 \frac{r}{R^2} \right)}{\pi r^2} = 4\eta v_0 l / R^2$$

- 1.335 The loss of pressure head in travelling a distance  $l$  is seen from the middle section to be  $h_2 - h_1 = 10$  cm. Since  $h_2 - h_1 = h_1$  in our problem and  $h_3 - h_2 = 15$  cm  $= 5 + h_2 - h_1$ , we see that a pressure head of 5 cm remains uncompensated and must be converted into kinetic energy, the liquid flowing out. Thus

$$\frac{\rho v^2}{2} = \rho g \Delta h \quad \text{where } \Delta h = h_3 - h_2$$

Thus

$$v = \sqrt{2g\Delta h} = 1 \text{ m/s}$$

- 1.336 We know that, Reynold's number ( $R_e$ ) is defined as,  $R_e = \rho v l / \eta$ , where  $v$  is the velocity  $l$  is the characteristic length and  $\eta$  the coefficient of viscosity. In the case of circular cross section the characteristic length is the diameter of cross-section  $d$ , and  $v$  is taken as average velocity of flow of liquid.

Now,  $R_{e_1}$  (Reynold's number at  $x_1$  from the pipe end)  $= \frac{\rho d_1 v_1}{\eta}$  where  $v_1$  is the velocity at distance  $x_1$

$$\text{and similarly, } R_{e_2} = \frac{\rho d_2 v_2}{\eta} \quad \text{so } \frac{R_{e_1}}{R_{e_2}} = \frac{d_1 v_1}{d_2 v_2}$$

From equation of continuity,  $A_1 v_1 = A_2 v_2$

$$\text{or, } \pi r_1^2 v_1 = \pi r_2^2 v_2 \quad \text{or } d_1 v_1 r_1 = d_2 v_2 r_2$$

$$\frac{d_1 v_1}{d_2 v_2} = \frac{r_2}{r_1} = \frac{r_0 e^{-\alpha x_2}}{r_0 e^{-\alpha x_1}} = e^{-\alpha \Delta x} \quad (\text{as } x_2 - x_1 = \Delta x)$$

Thus

$$\frac{R_{e_2}}{R_{e_1}} = e^{\alpha \Delta x} = 5$$

- 1.337 We know that Reynold's number for turbulent flow is greater than that on laminar flow:

$$\text{Now, } (R_e)_l = \frac{\rho v d}{\eta} = \frac{2 \rho_1 v_1 r_1}{\eta_1} \quad \text{and } (R_e)_t = \frac{2 \rho_2 v_2 r_2}{\eta}$$

But,  $(R_e)_t \approx (R_e)_l$

so  $v_{2_{\text{min}}} = \frac{\rho_1 v_1 r_1 \eta_2}{\rho_2 r_2 \eta_1} = 5 \mu \text{ m/s}$  on putting the values.

1.338 We have  $R = \frac{v \rho_0 d}{\eta}$  and  $v$  is given by

$$6 \pi \eta r v = \frac{4 \pi}{3} r^2 (\rho - \rho_0) g$$

( $\rho$  = density of lead,  $\rho_0$  = density of glycerine.)

$$v = \frac{2}{9 \eta} (\rho - \rho_0) g r^2 = \frac{1}{18 \eta} (\rho - \rho_0) g d^2$$

Thus 
$$\frac{1}{2} = \frac{1}{18 \eta^2} (\rho - \rho_0) g \rho_0 d^3$$

and  $d = [9 \eta^2 / \rho_0 (\rho - \rho_0) g]^{1/3} = 5.2 \text{ mm}$  on putting the values.

1.339  $m \frac{dv}{dt} = mg - 6 \pi \eta r v$

or 
$$\frac{dv}{dt} + \frac{6 \pi \eta r}{m} v = g$$

or 
$$\frac{dv}{dt} + kv = g, k = \frac{6 \pi \eta r}{m}$$

or 
$$e^{kt} \frac{dv}{dt} + k e^{kt} v = g e^{kt} \text{ or } \frac{d}{dt} e^{kt} v = g e^{kt}$$

or 
$$v e^{kt} = \frac{g}{k} e^{kt} + C \text{ or } v = \frac{g}{k} + C e^{-kt} \text{ (where } C \text{ is const.)}$$

Since 
$$v = 0 \text{ for } t = 0, 0 = \frac{g}{k} + C$$

So 
$$C = -\frac{g}{k}$$

Thus 
$$v = \frac{g}{k} (1 - e^{-kt})$$

The steady state velocity is  $\frac{g}{k}$ .

$v$  differs from  $\frac{g}{k}$  by  $n$  where  $e^{-kt} = n$

or 
$$t = \frac{1}{k} \ln n$$

Thus 
$$\frac{1}{k} = -\frac{\frac{4 \pi}{3} r^3 \rho}{6 \pi \eta r} = -\frac{4 r^2 \rho}{18 \eta} = -\frac{d^2 \rho}{18 \eta}$$

We have neglected buoyancy in olive oil.

## 1.8 RELATIVISTIC MECHANICS

1.340 From the formula for length contraction

$$\left( l_0 - l_0 \sqrt{1 - \frac{v^2}{c^2}} \right) = \eta l_0$$

So,  $1 - \frac{v^2}{c^2} = (1 - \eta)^2$  or  $v = c \sqrt{\eta(2 - \eta)}$

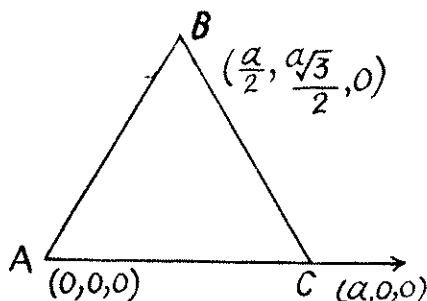
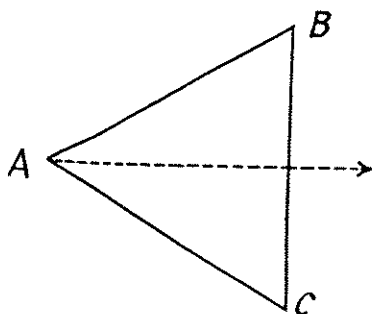
1.341 (a) In the frame in which the triangle is at rest the space coordinates of the vertices are  $(000)$ ,  $\left(a \frac{\sqrt{3}}{2}, +\frac{a}{2}, 0\right)$ ,  $\left(a \frac{\sqrt{3}}{2}, -\frac{a}{2}, 0\right)$ , all measured at the same time  $t$ . In the moving frame the corresponding coordinates at time  $t'$  are

$$A : (vt', 0, 0), B : \left(\frac{a}{2}\sqrt{3}\sqrt{1-\beta^2} + vt', \frac{a}{2}, 0\right) \text{ and } C : \left(\frac{a}{2}\sqrt{3}\sqrt{1-\beta^2} + vt', -\frac{a}{2}, 0\right)$$

The perimeter  $P$  is then

$$P = a + 2a \left( \frac{3}{4}(1 - \beta^2) + \frac{1}{4} \right)^{1/2} = a \left( 1 + \sqrt{4 - 3\beta^2} \right)$$

(b) The coordinates in the first frame are shown at time  $t$ . The coordinates in the moving frame are,



$$A : (vt', 0, 0), B : \left(\frac{a}{2}\sqrt{1-\beta^2} + vt', a \frac{\sqrt{3}}{2}, 0\right), C : \left(a\sqrt{1-\beta^2} + vt', 0, 0\right)$$

The perimeter  $P$  is then

$$P = a\sqrt{1-\beta^2} + \frac{a}{2} \left[ 1 - \beta^2 + 3 \right]^{1/2} \times 2 = a \left( \sqrt{1-\beta^2} + \sqrt{4-\beta^2} \right) \text{ here } \beta = \frac{v}{c}$$

1.342 In the rest frame, the coordinates of the ends of the rod in terms of proper length  $l_0$

$$A : (0, 0, 0) \quad B : (l_0 \cos \theta_0, l_0 \sin \theta_0, 0)$$

at time  $t$ . In the laboratory frame the coordinates at time  $t'$  are

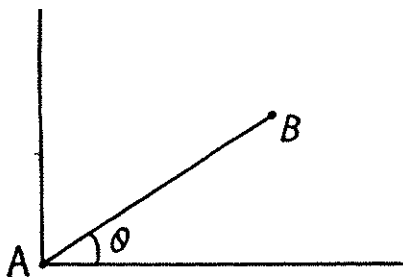
$$A : (vt', 0, 0), B : \left( l_0 \cos \theta_0 \sqrt{1 - \beta^2} + vt', l_0 \sin \theta_0, 0 \right)$$

Therefore we can write,

$$l \cos \theta_0 = l_0 \cos \theta_0 \sqrt{1 - \beta^2} \quad \text{and} \quad l \sin \theta = l_0 \sin \theta_0$$

$$\text{Hence } l_0^2 = (l^2) \left( \frac{\cos^2 \theta + (1 - \beta^2) \sin^2 \theta}{1 - \beta^2} \right)$$

$$\text{or, } l_0 = \frac{\sqrt{1 - \beta^2 \sin^2 \theta}}{1 - \beta^2}$$



- 1.343 In the frame  $K$  in which the cone is at rest the coordinates of  $A$  are  $(0,0,0)$  and of  $B$  are  $(h, h \tan \theta, 0)$ . In the frame  $K'$ , which is moving with velocity  $v$  along the axis of the cone, the coordinates of  $A$  and  $B$  at time  $t'$  are

$$A : (-vt', 0, 0), B : (h\sqrt{1 - \beta^2} - vt', h \tan \theta, 0)$$

Thus the taper angle in the frame  $K'$  is

$$\tan \theta' = \frac{\tan \theta}{\sqrt{1 - \beta^2}} \left( = \frac{y'_B - y'_A}{x'_B - x'_A} \right)$$

and the lateral surface area is,

$$S = \pi h'^2 \sec \theta' \tan \theta'$$

$$= \pi h^2 (1 - \beta^2) \frac{\tan \theta}{\sqrt{1 - \beta^2}} \sqrt{1 + \frac{\tan^2 \theta}{1 - \beta^2}} = S_0 \sqrt{1 - \beta^2 \cos^2 \theta}$$

Here  $S_0 = \pi h^2 \sec \theta \tan \theta$  is the lateral surface area in the rest frame and

$$h' = h\sqrt{1 - \beta^2}, \quad \beta = v/c.$$

- 1.344 Because of time dilation, a moving clock reads less time. We write,

$$t - \Delta t = t\sqrt{1 - \beta^2}, \quad \beta = \frac{v}{c}$$

$$\text{Thus, } 1 - \frac{2\Delta t}{t} + \left(\frac{\Delta t}{t}\right)^2 = 1 - \beta^2$$

$$\text{or, } v = c \sqrt{\frac{\Delta t}{t} \left(2 - \frac{\Delta t}{t}\right)}$$

- 1.345 In the frame  $K$  the length  $l$  of the rod is related to the time of flight  $\Delta t$  by

$$l = v \Delta t$$

In the reference frame fixed to the rod (frame  $K'$ ) the proper length  $l_0$  of the rod is given by

$$l_0 = v \Delta t'$$

But

$$l_0 = \frac{l}{\sqrt{1 - \beta^2}} = \frac{v \Delta t}{\sqrt{1 - \beta^2}}, \quad \beta = \frac{v}{c}$$

Thus, 
$$v \Delta t' = \frac{v \Delta t}{\sqrt{1 - \beta^2}}$$

So 
$$1 - \beta^2 = \left( \frac{\Delta t'}{\Delta t} \right)^2 \quad \text{or} \quad v = c \sqrt{1 - \left( \frac{\Delta t'}{\Delta t} \right)^2}$$

and 
$$l_0 = c \sqrt{(\Delta t')^2 - (\Delta t)^2} = c \Delta t' \sqrt{1 - \left( \frac{\Delta t'}{\Delta t} \right)^2}$$

- 1.346** The distance travelled in the laboratory frame of reference is  $v \Delta t$  where  $v$  is the velocity of the particle. But by time dilation

$$\Delta t = \frac{\Delta t_0}{\sqrt{1 - v^2/c^2}} \quad \text{So} \quad v = c \sqrt{1 - (\Delta t_0/\Delta t)^2}$$

Thus the distance traversed is

$$c \Delta t \sqrt{1 - (\Delta t_0/\Delta t)^2}$$

- 1.347** (a) If  $\tau_0$  is the proper life time of the muon the life time in the moving frame is

$$\frac{\tau_0}{\sqrt{1 - v^2/c^2}} \quad \text{and hence} \quad l = \frac{v \tau_0}{\sqrt{1 - v^2/c^2}}$$

Thus 
$$\tau_0 = \frac{l}{v} \sqrt{1 - v^2/c^2}$$

(The words "from the muon's stand point" are not part of any standard terminology)

- 1.348** In the frame  $K$  in which the particles are at rest, their positions are  $A$  and  $B$  whose coordinates may be taken as,

$$A : (0,0,0), B = (l_0, 0, 0)$$

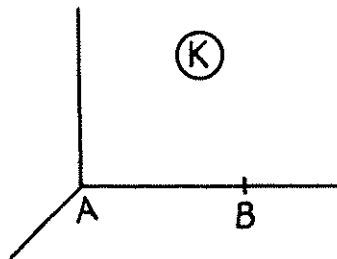
In the frame  $K'$  with respect to which  $K$  is moving with a velocity  $v$  the coordinates of  $A$  and  $B$  at time  $t'$  in the moving frame are

$$A = (vt', 0, 0) \quad B = \left( l_0 \sqrt{1 - \beta^2} + vt', 0, 0 \right), \quad \beta = \frac{v}{c}$$

Suppose  $B$  hits a stationary target in  $K'$  after time  $t'_B$  while  $A$  hits it after time  $t'_B + \Delta t$ . Then,

$$l_0 \sqrt{1 - \beta^2} + vt'_B = v(t'_B + \Delta t)$$

So, 
$$l_0 \frac{v \Delta t}{\sqrt{1 - v^2/c^2}}$$



- 1.349** In the reference frame fixed to the ruler the rod is moving with a velocity  $v$  and suffers Lorentz contraction. If  $l_0$  is the proper length of the rod, its measured length will be

$$\Delta x_1 = l_0 \sqrt{1 - \beta^2}, \quad \beta = \frac{v}{c}$$

In the reference frame fixed to the rod the ruler suffers Lorentz contraction and we must have

$$\Delta x_2 \sqrt{1 - \beta^2} = l_0 \text{ thus } l_0 = \sqrt{\Delta x_1 \Delta x_2}$$

and 
$$1 - \beta^2 = \frac{\Delta x_1}{\Delta x_2} \text{ or } v = c \sqrt{1 - \frac{\Delta x_1}{\Delta x_2}}$$

- 1.350** The coordinates of the ends of the rods in the frame fixed to the left rod are shown. The points  $B$  and  $D$  coincide when

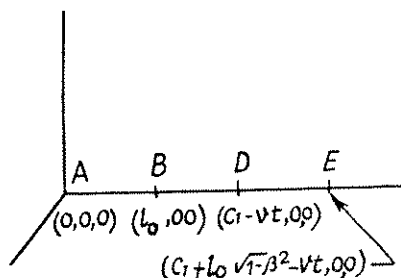
$$l_0 = c_1 - vt_0 \text{ or } t_0 = \frac{c_1 - l_0}{v}$$

The points  $A$  and  $E$  coincide when

$$0 = c_1 + l_0 \sqrt{1 - \beta^2} - vt_1, \quad t_1 = \frac{c_1 + l_0 \sqrt{1 - \beta^2}}{v}$$

Thus 
$$\Delta t = t_1 - t_0 = \frac{l_0}{v} \left( 1 + \sqrt{1 - \beta^2} \right)$$

or 
$$\left( \frac{v \Delta t}{l_0} - 1 \right)^2 = 1 - \beta^2 = 1 - \frac{v^2}{c^2}$$



From this 
$$v = \frac{2c^2 \Delta t / l_0}{1 + c^2 \Delta t^2 / l_0^2} = \frac{2l_0 / \Delta t}{1 + (l_0 / c \Delta t)^2}$$

- 1.351** In  $K_0$  the rest frame of the particles, the events corresponding to the decay of the particles are,

$$A : (0, 0, 0, 0) \text{ and } (0, l_0, 0, 0) = B$$

In the reference frame  $K$ , the corresponding coordinates are by Lorentz transformation

$$A : (0, 0, 0, 0), \quad B : \left( \frac{vl_0}{c^2 \sqrt{1 - \beta^2}}, \frac{l_0}{\sqrt{1 - \beta^2}}, 0, 0 \right)$$

Now 
$$l_0 \sqrt{1 - \beta^2} = l$$

by Lorentz Fitzgerald contraction formula. Thus the time lag of the decay time of  $B$  is

$$\Delta t = \frac{vl_0}{c^2 \sqrt{1 - \beta^2}} = \frac{vl}{c^2 (1 - \beta^2)} = \frac{vl}{c^2 - v^2}$$

$B$  decays later ( $B$  is the forward particle in the direction of motion)

- 1.352** (a) In the reference frame  $K$  with respect to which the rod is moving with velocity  $v$ , the coordinates of  $A$  and  $B$  are

$$A : t, x_A + v(t - t_A), 0, 0$$

$$B : t, x_B + v(t - t_B), 0, 0$$

Thus  $l = x_A - x_B - v(t_A - t_B) = l_0 \sqrt{1 - \beta^2}$

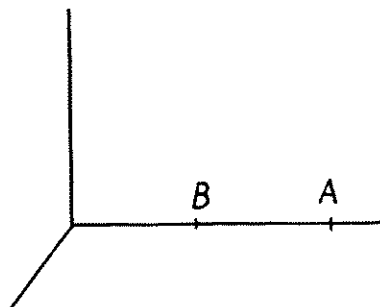
So  $l_0 = \frac{x_A - x_B - v(t_A - t_B)}{\sqrt{1 - v^2/c^2}}$

(b)  $\pm l_0 - v(t_A - t_B) = l = l_0 \sqrt{1 - v^2/c^2}$   
(since  $x_A - x_B$  can be either  $+l_0$  or  $-l_0$ )

Thus  $v(t_A - t_B) = (\pm 1 - \sqrt{1 - v^2/c^2}) l_0$

i.e.  $t_A - t_B = \frac{l_0}{v} \left( 1 - \sqrt{1 - \frac{v^2}{c^2}} \right)$

or  $t_B - t_A = \frac{l_0}{v} \left( 1 + \sqrt{1 - v^2/c^2} \right)$



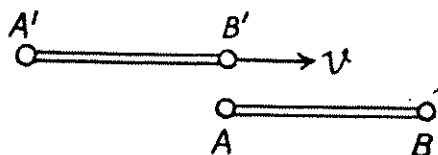
1.353 At the instant the picture is taken the coordinates of  $A, B, A', B'$  in the rest frame of  $A, B$  are

$$A : (0, 0, 0, 0)$$

$$B : (0, l_0, 0, 0)$$

$$B' : (0, 0, 0, 0)$$

$$A' : (0, -l_0 \sqrt{1 - v^2/c^2}, 0, 0)$$



In this frame the coordinates of  $B'$  at other times are  $B' : (t, vt, 0, 0)$ . So  $B'$  is opposite to  $B$  at time  $t(B) = \frac{l_0}{v}$ . In the frame in which  $B', A'$  is at rest the time corresponding this is by Lorentz transformation.

$$t^0(B') = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \left( \frac{l_0}{v} - \frac{vl_0}{c^2} \right) = \frac{l_0}{v} \sqrt{1 - v^2/c^2}$$

Similarly in the rest frame of  $A, B$ , the coordinates of  $A$  at other times are

$$A' : \left( t, -l_0 \sqrt{1 - \frac{v^2}{c^2}} + vt, 0, 0 \right)$$

$$A' \text{ is opposite to } A \text{ at time } t(A) = \frac{l_0}{v} \sqrt{1 - \frac{v^2}{c^2}}$$

The corresponding time in the frame in which  $A', B'$  are at rest is

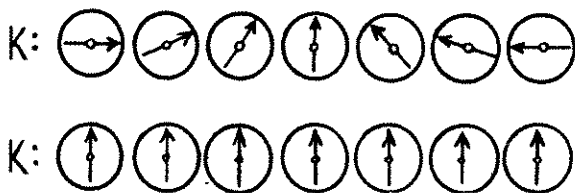
$$t(A') = \gamma t(A) = \frac{l_0}{v}$$

1.354 By Lorentz transformation  $t' = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \left( t - \frac{vx}{c^2} \right)$

So at time

$$t = 0, t' = \frac{vx}{c^2 \sqrt{1 - v^2/c^2}}$$

If  $x > 0$   $t' < 0$ , if  $x < 0$ ,  $t' > 0$  and we get the diagram given below "in terms of the  $K$ -clock".



The situation in terms of the  $K'$  clock is reversed.

- 1.355** Suppose  $x(t)$  is the locus of points in the frame  $K$  at which the readings of the clocks of both reference system are permanently identical, then by Lorentz transformation

$$t' = \frac{1}{\sqrt{1 - V^2/c^2}} \left( t - \frac{Vx(t)}{c^2} \right) = t$$

So differentiating  $x(t) = \frac{c^2}{V} \left( 1 - \sqrt{1 - \frac{V^2}{c^2}} \right) = \frac{c}{\beta} (1 - \sqrt{1 - \beta^2})$ ,  $\beta = \frac{V}{c}$

Let

$$\beta = \tan h\theta, \quad 0 \leq \theta < \infty, \text{ Then}$$

$$\begin{aligned} x(t) &= \frac{c}{\tan h\theta} (1 - \sqrt{1 - \tan^2 h\theta}) = c \frac{\cos h\theta}{\sin h\theta} \left( 1 - \frac{1}{\cos h\theta} \right) \\ &= c \frac{\cos h\theta - 1}{\sin h\theta} = c \sqrt{\frac{\cos h\theta - 1}{\cos h\theta + 1}} = c \tan h \frac{\theta}{2} \leq v \end{aligned}$$

( $\tan h\theta$  is a monotonically increasing function of  $\theta$ )

- 1.356** We can take the coordinates of the two events to be

$$A : (0, 0, 0, 0) \quad B : (\Delta t, a, 0, 0)$$

For  $B$  to be the effect and  $A$  to be cause we must have  $\Delta t > \frac{|a|}{c}$ .

In the moving frame the coordinates of  $A$  and  $B$  become

$$A : (0, 0, 0, 0), B : \left[ \gamma \left( \Delta t - \frac{aV}{c^2} \right), \gamma (a - V \Delta t), 0, 0 \right] \text{ where } \gamma = \frac{1}{\sqrt{1 - \left( \frac{V^2}{c^2} \right)}}$$

Since

$$(\Delta t')^2 - \frac{a'^2}{c^2} = \gamma^2 \left[ \left( \Delta t - \frac{aV}{c^2} \right)^2 - \frac{1}{c^2} (a - V \Delta t)^2 \right] = (\Delta t)^2 - \frac{a^2}{c^2} > 0$$

we must have  $\Delta t' > \frac{|a'|}{c}$



- 1.357 (a) The four-dimensional interval between  $A$  and  $B$  (assuming  $\Delta y = \Delta z = 0$ ) is :

$$5^2 - 3^2 = 16 \text{ units}$$

Therefore the time interval between these two events in the reference frame in which the events occurred at the same place is

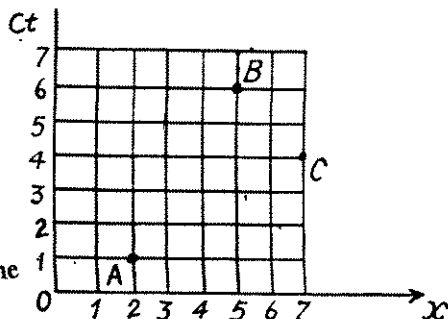
$$c(t'_B - t'_A) = \sqrt{16} = 4 \text{ m}$$

$$\text{or } t'_B - t'_A = \frac{4}{c} = \frac{4}{3} \times 10^{-8} \text{ s}$$

- (b) The four dimensional interval between  $A$  and  $C$  is (assuming  $\Delta y = \Delta z = 0$ )

$$3^2 - 5^2 = -16$$

So the distance between the two events in the frame in which they are simultaneous is 4 units = 4m.



- 1.358 By the velocity addition formula

$$v'_x = \frac{v_x - V}{1 - \frac{V v_x}{c^2}}, \quad v'_y = \frac{v_y \sqrt{1 - V^2/c^2}}{1 - \frac{v_x V}{c^2}}$$

$$\text{and } v' = \sqrt{v'^2_x + v'^2_y} = \frac{\sqrt{(v_x - V)^2 + v_y^2 (1 - V^2/c^2)}}{1 - \frac{v_x V}{c^2}}$$

- 1.359 (a) By definition the velocity of approach is

$$v_{\text{approach}} = \frac{dx_1}{dt} - \frac{dx_2}{dt} = v_1 - (-v_2) = v_1 + v_2$$

in the reference frame  $K$ .

- (b) The relative velocity is obtained by the transformation law

$$v_r = \frac{v_1 - (-v_2)}{1 - \frac{v_1 (-v_2)}{c^2}} = \frac{v_1 + v_2}{1 + \frac{v_1 v_2}{c^2}}$$

- 1.360 The velocity of one of the rods in the reference frame fixed to the other rod is

$$V = \frac{v + v}{1 + \frac{v^2}{c^2}} = \frac{2v}{1 + \beta^2}$$

The length of the moving rod in this frame is

$$l = l_0 \sqrt{1 - \frac{4v^2/c^2}{(1 + \beta^2)^2}} = l_0 \frac{1 - \beta^2}{1 + \beta^2}$$

- 1.361 The approach velocity is defined by

$$\vec{V}_{\text{approach}} = \frac{d\vec{r}_1}{dt} - \frac{d\vec{r}_2}{dt} = \vec{V}_1 - \vec{V}_2$$

in the laboratory frame. So  $V_{\text{approach}} = \sqrt{v_1^2 + v_2^2}$

On the other hand, the relative velocity can be obtained by using the velocity addition formula and has the components

$$\left[ -v_1, v_2 \sqrt{1 - \left(\frac{v_1^2}{c^2}\right)} \right] \text{ so } V_r = \sqrt{v_1^2 + v_2^2 - \frac{v_1 v_2^2}{c^2}}$$

1.362 The components of the velocity of the unstable particle in the frame  $K$  are

$$\left( V, v' \sqrt{1 - \frac{V^2}{c^2}}, 0 \right)$$

so the velocity relative to  $K$  is

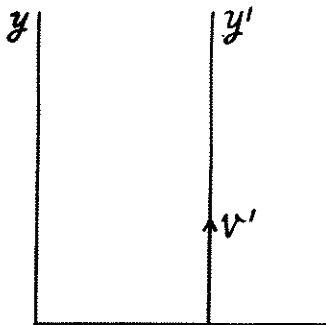
$$\sqrt{V^2 + v'^2 - \frac{v'^2 V^2}{c^2}}$$

The life time in this frame dilates to

$$\Delta t_0 / \sqrt{1 - \frac{V^2}{c^2} - \frac{v'^2}{c^2} + \frac{v'^2 V^2}{c^4}}$$

and the distance traversed is

$$\Delta t_0 \frac{\sqrt{V^2 + v'^2 - (v'^2 V^2)/c^2}}{\sqrt{1 - V^2/c^2} \sqrt{1 - v'^2/c^2}}$$

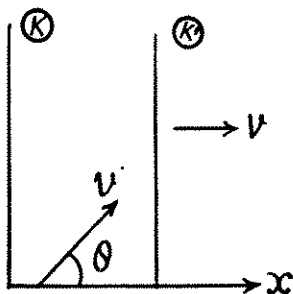


1.363 In the frame  $K'$  the components of the velocity of the particle are

$$v'_x = \frac{v \cos \theta - V}{1 - \frac{v V \cos \theta}{c^2}}$$

$$v'_y = \frac{v \sin \theta \sqrt{1 - V^2/c^2}}{1 - \frac{v V}{c^2} \cos \theta}$$

$$\text{Hence, } \tan \theta' = \frac{v'_y}{v'_x} = \frac{v \sin \theta}{v \cos \theta - V} \sqrt{(1 - V^2)/c^2}$$



1.364 In  $K'$  the coordinates of  $A$  and  $B$  are

$$A : (t', 0, -v' t', 0); B : (t', l, -v' t', 0)$$

After performing Lorentz transformation to the frame  $K$  we get

$$A : t = \gamma t' \quad B : t = \gamma \left( t' + \frac{V l}{c^2} \right)$$

$$x = \gamma V t' \quad x = \gamma (l + V t')$$

$$y = v' t' \quad y = -v' t'$$

$$z = 0 \quad z = 0$$

By translating  $t' \rightarrow t' - \frac{V l}{c^2}$ , we can write

the coordinates of  $B$  as  $B : t = \gamma t'$

$$x = \gamma l \left( 1 - \frac{V^2}{c^2} \right) + V t' \gamma = l \sqrt{1 - \frac{v^2}{c^2}} + V t' \gamma$$

$$y = -v' \left( t' - \frac{Vl}{c^2} \right), \quad z = 0$$

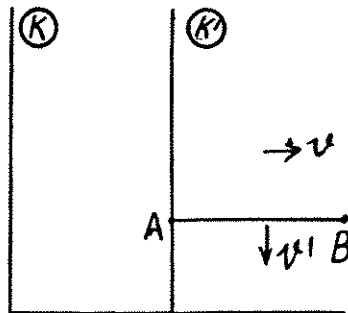
Thus

$$\Delta x = l \sqrt{1 - \left( \frac{V^2}{c^2} \right)}, \quad \Delta y = \frac{v' V l}{c^2}$$

Hence

$$\tan \theta' = \frac{v' V}{c^2 \sqrt{1 - \frac{v' V}{c^2}}}$$

$$1.365 \quad \frac{t}{\vec{v}} \quad \frac{l + dt}{\vec{v} + \vec{w} dt} \quad \textcircled{K}$$



In  $K$  the velocities at time  $t$  and  $t + dt$  are respectively  $v$  and  $v + w dt$  along  $x$ -axis which is parallel to the vector  $\vec{V}$ . In the frame  $K'$  moving with velocity  $\vec{V}$  with respect to  $K$ , the velocities are respectively,

$$\frac{v - V}{1 - \frac{vV}{c^2}} \quad \text{and} \quad \frac{v + w dt - V}{1 - (v + w dt) \frac{V}{c^2}}$$

The latter velocity is written as

$$\frac{v - V}{1 - \frac{vV}{c^2}} + \frac{w dt}{1 - \frac{vV}{c^2}} + \frac{v - V}{\left( 1 - \frac{vV}{c^2} \right)} \frac{w V}{c^2} dt = \frac{v - V}{1 - \frac{vV}{c^2}} + \frac{w dt \left( 1 - \frac{V^2}{c^2} \right)}{\left( 1 - \frac{vV}{c^2} \right)^2}$$

Also by Lorentz transformation

$$dt' = \frac{dt - V dx/c^2}{\sqrt{1 - V^2/c^2}} = dt \frac{1 - vV/c^2}{\sqrt{1 - V^2/c^2}}$$

Thus the acceleration in the  $K'$  frame is

$$w' = \frac{dv'}{dt'} = \frac{w}{\left( 1 - \frac{vV}{c^2} \right)^3} \left( 1 - \frac{V^2}{c^2} \right)^{3/2}$$

(b) In the  $K$  frame the velocities of the particle at the time  $t$  and  $t + dt$  are respectively  $(0, v, 0)$  and  $(0, v + w dt, 0)$

where  $\vec{V}$  is along  $x$ -axis. In the  $K'$  frame the velocities are

$$(-V, v \sqrt{1 - V^2/c^2}, 0)$$

and

$$(-V, (v + w dt) \sqrt{1 - V^2/c^2}, 0) \text{ respectively}$$

Thus the acceleration

$$w' = \frac{w dt \sqrt{1 - V^2/c^2}}{dt'} = w \left(1 - \frac{V^2}{c^2}\right) \text{ along the } y\text{-axis.}$$

We have used  $dt' = \frac{dt}{\sqrt{1 - V^2/c^2}}$

1.366 In the instantaneous rest frame  $v = V$  and

$$w' = \frac{w}{\left(1 - \frac{V^2}{c^2}\right)^{3/2}} \text{ (from 1.365a)}$$

So,

$$= \frac{dv}{\left(1 - \frac{V^2}{c^2}\right)^{3/2}} = w' dt$$

$w'$  is constant by assumption. Thus integration gives

$$v = \frac{w' t}{\sqrt{1 + \left(\frac{w' t}{c}\right)^2}}$$

Integrating once again  $x = \frac{c^2}{w'} \left( \sqrt{1 + \left(\frac{w' t}{c}\right)^2} - 1 \right)$

1.367 The boost time  $\tau_0$  in the reference frame fixed to the rocket is related to the time  $\tau$  elapsed on the earth by

$$\begin{aligned} \tau_0 &= \int_0^\tau \sqrt{1 - \frac{v^2}{c^2}} dt = \int_0^\tau \left[ 1 - \frac{\left(\frac{w' t}{c}\right)^2}{1 + \left(\frac{w' t}{c}\right)^2} \right]^{1/2} dt \\ &= \int_0^\tau \frac{dt}{\sqrt{1 + \left(\frac{w' t}{c}\right)^2}} = \frac{c}{w'} \int_0^{(w' \tau)/c} \frac{d\xi}{\sqrt{1 + \xi^2}} = \frac{c}{w'} \ln \left[ \frac{w' \tau}{c} + \sqrt{1 + \left(\frac{w' \tau}{c}\right)^2} \right] \end{aligned}$$

1.368  $m = \frac{m_0}{\sqrt{1 - \beta^2}}$

For  $\beta = 1, \frac{m}{m_0} = \frac{1}{\sqrt{2(1 - \beta)}} = \frac{1}{\sqrt{2}\eta}$

1.369 We define the density  $\rho$  in the frame  $K$  in such a way that  $\rho dx dy dz$  is the rest mass  $dm_0$  of the element. That is  $\rho dx dy dz = \rho_0 dx_0 dy_0 dz_0$ , where  $\rho_0$  is the proper density  $dx_0, dy_0, dz_0$  are the dimensions of the element in the rest frame  $K_0$ . Now

$$dy = dy_0, dz = dz_0, dx = dx_0 \sqrt{1 - \frac{v^2}{c^2}}$$

if the frame  $K$  is moving with velocity,  $v$  relative to the frame  $K_0$ . Thus

$$\rho = \frac{\rho_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Defining  $\eta$  by  $\rho = \rho_0(1 + \eta)$

We get  $1 + \eta = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$  or,  $\frac{v^2}{c^2} = 1 - \frac{1}{(1 + \eta)^2} = \frac{\eta(2 + \eta)}{(1 + \eta)^2}$

or  $v = c \frac{\sqrt{\eta(2 + \eta)}}{(1 + \eta)^2} = \frac{c \sqrt{\eta(2 + \eta)}}{1 + \eta}$

1.370 We have

$$\frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}} = p \quad \text{or,} \quad \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} = \sqrt{m_0^2 + \frac{p^2}{c^2}}$$

or  $1 - \frac{v^2}{c^2} = \frac{m_0^2 c^2}{m_0^2 c^2 + p^2} = 1 - \frac{p^2}{p^2 + m_0^2 c^2}$

or  $v = \frac{c p}{\sqrt{p^2 + m_0^2 c^2}} = \frac{c}{\sqrt{1 + \left(\frac{m_0 c}{p}\right)^2}}$

So  $\frac{c - v}{c} = \left[ 1 - \left( 1 + \left( \frac{m_0 c}{p} \right)^2 \right)^{-1/2} \right] \times 100 \% = \frac{1}{2} \left( \frac{m_0 c}{p} \right)^2 \times 100 \%$

1.371 By definition of  $\eta$ ,

$$\frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}} = \eta m_0 v \quad \text{or} \quad 1 - \frac{v^2}{c^2} = \frac{1}{\eta^2}$$

or  $v = c \sqrt{1 - \frac{1}{\eta^2}} = \frac{c}{\eta} \sqrt{\eta^2 - 1}$

1.372 The work done is equal to change in kinetic energy which is different in the two cases Classically i.e. in nonrelativistic mechanics, the change in kinetic energy is

$$\frac{1}{2} m_0 c^2 \left( (0.8)^2 - (0.6)^2 \right) = \frac{1}{2} m_0 c^2 0.28 = 0.14 m_0 c^2$$

Relativistically it is,

$$\begin{aligned} \frac{m_0 c^2}{\sqrt{1 - (0.8)^2}} - \frac{m_0 c^2}{\sqrt{1 - (0.6)^2}} &= \frac{m_0 c^2}{0.6} - \frac{m_0 c^2}{0.8} = m_0 c^2 (1.666 - 1.250) \\ &= 0.416 m_0 c^2 = 0.42 m_0 c^2 \end{aligned}$$

$$1.373 \quad \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}} = 2 m_0 c^2$$

$$\text{or} \quad \sqrt{1 - \frac{v^2}{c^2}} = \frac{1}{2} \quad \text{or} \quad 1 - \frac{v^2}{c^2} = \frac{1}{4}$$

$$\text{or} \quad \frac{v}{c} = \frac{\sqrt{3}}{2} \quad \text{i.e.} \quad v = c \frac{\sqrt{3}}{2}$$

1.374 Relativistically

$$\frac{T}{m_0 c^2} = \left( \frac{1}{\sqrt{1 - \beta^2}} - 1 \right) = \frac{1}{2} \beta^2 + \frac{3}{8} \beta^4$$

$$\text{So} \quad \beta_{rel}^2 = \frac{2T}{m_0 c^2} - \frac{3}{4} (\beta_{rel}^2)^2 = \frac{2T}{m_0 c^2} - \frac{3}{4} \left( \frac{2T}{m_0 c^2} \right)^2$$

$$\text{Thus} \quad -\beta_{rel} = \left[ \frac{2T}{m_0 c^2} - 3 \frac{T^2}{m_0^2 c^4} \right]^{1/2} = \sqrt{\frac{2T}{m_0 c^2}} \left( 1 - \frac{3}{4} \frac{T}{m_0 c^2} \right)$$

$$\text{But Classically, } \beta_{cl} = \sqrt{\frac{2T}{m_0 c^2}} \quad \text{so} \quad \frac{\beta_{rel} - \beta_{cl}}{\beta_{cl}} = \frac{3}{4} \frac{T}{m_0 c^2} = \epsilon$$

$$\text{Hence if} \quad \frac{T}{m_0 c^2} < \frac{4}{3} \epsilon$$

the velocity  $\beta$  is given by the classical formula with an error less than  $\epsilon$ .

1.375 From the formula

$$E = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}}, \quad p = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\text{we find} \quad E^2 = c^2 p^2 + m_0^2 c^4 \quad \text{or} \quad (m_0 c^2 + T)^2 = c^2 p^2 + m_0^2 c^4$$

$$\text{or} \quad T(2m_0 c^2 + T) = c^2 p^2 \quad \text{i.e.} \quad p = \frac{1}{c} \sqrt{T(2m_0 c^2 + T)}$$

1.376 Let the total force exerted by the beam on the target surface be  $F$  and the power liberated there be  $P$ . Then, using the result of the previous problem we see

$$F = Np = \frac{N}{c} \sqrt{T(2m_0 c^2 + T)} = \frac{I}{ec} \sqrt{T(2m_0 c^2 + T)}$$

since  $I = Ne$ ,  $N$  being the number of particles striking the target per second. Also,

$$P = N \left( \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}} - m_0 c^2 \right) = \frac{I}{e} T$$

These will be, respectively, equal to the pressure and power developed per unit area of the target if  $I$  is current density.

**1.377** In the frame fixed to the sphere :- The momentum transferred to the elastically scattered particle is

$$\frac{2mv}{\sqrt{1 - \frac{v^2}{c^2}}}$$

The density of the moving element is, from 1.369,  $n \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

and the momentum transferred per unit time per unit area is

$$p = \text{the pressure} = \frac{2mv}{\sqrt{1 - \frac{v^2}{c^2}}} n \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \cdot v = \frac{2mnv^2}{1 - \frac{v^2}{c^2}}$$

In the frame fixed to the gas :- When the sphere hits a stationary particle, the latter recoils with a velocity

$$= \frac{v + v}{1 + \frac{v^2}{c^2}} = \frac{2v}{1 + \frac{v^2}{c^2}}$$

The momentum transferred is  $\frac{m \cdot 2v}{1 + v^2/c^2} \cdot \frac{1}{\sqrt{1 - \frac{4v^2/c^2}{(1 - v^2/c^2)^2}}} = \frac{2mv}{1 - \frac{v^2}{c^2}}$

and the pressure is  $\frac{2mv}{1 - \frac{v^2}{c^2}} \cdot n \cdot v = \frac{2mnv^2}{1 - \frac{v^2}{c^2}}$

**1.378** The equation of motion is

$$\frac{d}{dt} \left( \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}} \right) = F$$

Integrating  $= \frac{v/c}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{\beta}{\sqrt{1 - \beta^2}} = \frac{Ft}{m_0 c}$ , using  $v = 0$  for  $t = 0$

$$\frac{\beta^2}{1 - \beta^2} = \left( \frac{Ft}{m_0 c} \right)^2 \quad \text{or,} \quad \beta^2 = \frac{(Ft)^2}{(Ft)^2 + (m_0 c)^2} \quad \text{or,} \quad v = \frac{Fct}{\sqrt{(m_0 c)^2 + (Ft)^2}}$$

$$\text{or } x = \int \frac{Fct \, dt}{\sqrt{F^2 t^2 + m_0^2 c^2}} = \frac{c}{F} \int \frac{\xi \, d\xi}{\sqrt{\xi^2 + (m_0 c)^2}} = \frac{c}{F} \sqrt{F^2 t^2 + m_0^2 c^2} + \text{constant}$$

$$\text{or using } x = 0 \text{ at } t = 0, \text{ we get, } x = \sqrt{c^2 t^2 + \left( \frac{m_0 c^2}{F} \right)^2} - \frac{m_0 c^2}{F}$$

1.379  $x = \sqrt{a^2 + c^2 t^2}$ , so  $\dot{x} = v = \frac{c^2 t}{a^2 + c^2 t^2}$

or, 
$$\frac{v}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{c^2 t}{a}. \text{ Thus } \frac{d}{dt} \left( \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}} \right) = \frac{m_0 c^2}{a} = F$$

1.380 
$$\vec{F} = \frac{d}{dt} \left( \frac{m_0 \vec{v}}{\sqrt{1 - \frac{v^2}{c^2}}} \right) = m_0 \frac{\dot{\vec{v}}}{\sqrt{1 - \frac{v^2}{c^2}}} + m_0 \frac{\vec{v}}{c^2} \vec{v} \cdot \dot{\vec{v}} \frac{1}{\left(1 - \frac{v^2}{c^2}\right)^{3/2}}$$

Thus 
$$\vec{F}_\perp = m_0 \frac{\vec{w}}{\sqrt{1 - \beta^2}}, \quad \vec{w} = \dot{\vec{v}}, \quad \vec{w}_\perp \perp \vec{v}$$

$$\vec{F}_\parallel = m_0 \frac{\vec{w}}{(1 - \beta^2)^{3/2}}, \quad \vec{w} = \dot{\vec{v}}, \quad \vec{w}_\parallel \parallel \vec{v}$$

1.381 By definition,

$$E = m_0 \frac{c^2}{\sqrt{1 - \frac{v_x^2}{c^2}}} = \frac{m_0 c^3 dt}{ds}, \quad p_x = m_0 \frac{v_x}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{c m_0 dx}{ds}$$

where  $ds^2 = c^2 dt^2 - dx^2$  is the invariant interval ( $dy = dz = 0$ )

Thus, 
$$p'_x = cm_0 \frac{dx'}{ds} = cm_0 \gamma \frac{(dx - V dt)}{ds} = \frac{p_x - VE/c^2}{\sqrt{1 - V^2/c^2}}$$

$$E' = m_0 c^3 \frac{dt'}{ds} = c^3 m_0 \gamma \frac{\left(dt - \frac{V dx}{c^2}\right)}{ds} = \frac{E - V p_x}{\sqrt{1 - \frac{V^2}{c^2}}}$$

1.382 For a photon moving in the  $x$  direction

$$\epsilon = cp_x, \quad p_y = p_z = 0,$$

In the moving frame,  $\epsilon' = \frac{1}{\sqrt{1 - \beta^2}} \left( \epsilon - V \frac{\epsilon}{c} \right) = \epsilon \sqrt{\frac{1 - V/c}{1 + V/c}}$

Note that  $\epsilon' = \frac{\epsilon}{2}$  if,  $\frac{1}{4} = \frac{1 - \beta}{1 + \beta}$  or  $\beta = \frac{3}{5}$ ,  $V = \frac{3c}{5}$ .

1.383 As before

$$E = m_0 c^3 \frac{dt}{ds}, \quad p_x = m_0 c \frac{dx}{ds}.$$



Similarly  $p_y = m_0 c \frac{dy}{ds}, p_z = m_0 c \frac{dz}{ds}$

Then  $E^2 - c^2 p^2 = E^2 - c^2 (p_x^2 + p_y^2 + p_z^2)$   
 $= m_0^2 c^4 \frac{(c^2 dt^2 - dx^2 - dy^2 - dz^2)}{ds^2} = m_0^2 c^4$  is invariant

1.384 (b) & (a) In the CM frame, the total momentum is zero, Thus

$$\frac{V}{c} = \frac{cp_{1x}}{E_1 + E_2} = \frac{\sqrt{T(T + 2m_0 c^2)}}{T + 2m_0 c^2} = \sqrt{\frac{T}{T + 2m_0 c^2}}$$

where we have used the result of problem (1.375)

Then

$$\frac{1}{\sqrt{1 - V^2/c^2}} = \frac{1}{\sqrt{1 - \frac{T}{T + 2m_0 c^2}}} = \sqrt{\frac{T + 2m_0 c^2}{2m_0 c^2}}$$

Total energy in the CM frame is

$$\frac{2m_0 c^2}{\sqrt{1 - V^2/c^2}} = 2m_0 c^2 \sqrt{\frac{T + 2m_0 c^2}{2m_0 c^2}} = \sqrt{2m_0 c^2 (T + 2m_0 c^2)} = \tilde{T} + 2m_0 c^2$$

So 
$$\tilde{T} = 2m_0 c^2 \left( \sqrt{1 + \frac{T}{2m_0 c^2}} - 1 \right)$$

Also  $2\sqrt{c^2 \tilde{p}^2 + m_0^2 c^4} = \sqrt{2m_0 c^2 (T + 2m_0 c^2)}, 4c^2 \tilde{p}^2 = 2m_0 c^2 T, \text{ or } \tilde{p} = \sqrt{\frac{1}{2} m_0 T}$

1.385  $M_0 c^2 = \sqrt{E^2 - c^2 p^2}$

$$\sqrt{(2m_0 c^2 + T)^2 - T(2m_0 c^2 + T)} = \sqrt{2m_0 c^2 (2m_0 c^2 + T)} = c \sqrt{2m_0 (2m_0 c^2 + T)}$$

Also  $cp = \sqrt{T(T + 2m_0 c^2)}, v = \frac{c^2 p}{E} = c \sqrt{\frac{T}{T + 2m_0 c^2}}$

1.386 Let  $T'$  = kinetic energy of a proton striking another stationary particle of the same rest mass. Then, combined kinetic energy in the CM frame

$$= 2m_0 c^2 \left( \sqrt{1 + \frac{T'}{2m_0 c^2}} - 1 \right) = 2T, \left( \frac{T}{m_0 c^2} + 1 \right)^2 = 1 + \frac{T'}{2m_0 c^2}$$

$$\frac{T'}{2m_0 c^2} = \frac{T(2m_0 c^2 + T)}{m_0^2 c^4}, T' = \frac{2T(T + 2m_0 c^2)}{m_0 c^2}$$

1.387 We have

$$E_1 + E_2 + E_3 = m_0 c^2, \quad \vec{p}_1 + \vec{p}_2 + \vec{p}_3 = 0$$

Hence  $(m_0 c^2 - E_1)^2 - c^2 \vec{p}_1^2 = (E_2 + E_3)^2 - (\vec{p}_2 + \vec{p}_3)^2 c^2$

The L.H.S.  $= (m_0^2 c^4 - E_1^2) - c^2 \vec{p}_1^2 = (m_0^2 + m_1^2) c^4 - 2m_0 c^2 E_1$

The R.H.S. is an invariant. We can evaluate it in any frame. Choose the CM frame of the particles 2 and 3.

In this frame R.H.S.  $= (E'_2 + E'_3)^2 = (m_2 + m_3)^2 c^4$

Thus  $(m_0^2 + m_1^2) c^4 - 2m_0 c^2 E_1 = (m_2 + m_3)^2 c^4$

or  $2m_0 c^2 E_1 = \{m_0^2 + m_1^2 - (m_2 + m_3)^2\} c^4$ , or  $E_1 = \frac{m_0^2 + m_1^2 - (m_2 + m_3)^2}{2m_0} c^2$

1.388 The velocity of ejected gases is  $u$  relative to the rocket. In an earth centred frame it is

$$\frac{v - u}{1 - \frac{vu}{c^2}}$$

in the direction of the rocket. The momentum conservation equation then reads

$$(m + dm)(v + dv) + \frac{v - u}{1 - \frac{uv}{c^2}} (-dm) = mv$$

or  $mdv - \left( \frac{v - u}{1 - \frac{uv}{c^2}} - v \right) dm = 0$

Here  $-dm$  is the mass of the ejected gases. so

$$mdv - \frac{-u + \frac{uv^2}{c^2}}{1 - \frac{uv}{c^2}} dm = 0, \quad \text{or} \quad mdv + u \left( 1 - \frac{v^2}{c^2} \right) dm = 0$$

(neglecting  $1 - \frac{uv}{c^2}$  since  $u$  is non-relativistic.)

Integrating  $\left( \beta = \frac{v}{c} \right), \int \frac{d\beta}{1 - \beta^2} + \frac{u}{c} \int \frac{dm}{m} = 0, \quad \ln \frac{1 + \beta}{1 - \beta} + \frac{u}{c} \ln m = \text{constant}$

The constant  $= \frac{u}{c} \ln m_0$  since  $\beta = 0$  initially.

Thus  $\frac{1 - \beta}{1 + \beta} = \left( \frac{m}{m_0} \right)^{u/c}$  or  $\beta = \frac{1 - \left( \frac{m}{m_0} \right)^{u/c}}{1 + \left( \frac{m}{m_0} \right)^{u/c}}$

## PART TWO

# THERMODYNAMICS AND MOLECULAR PHYSICS

---

## 2.1 EQUATION OF THE GAS STATE • PROCESSES

2.1 Let  $m_1$  and  $m_2$  be the masses of the gas in the vessel before and after the gas is released.

Hence mass of the gas released,

$$\Delta m = m_1 - m_2$$

Now from ideal gas equation

$$p_1 V = m_1 \frac{R}{M} T_0 \text{ and } p_2 V = m_2 \frac{R}{M} T_0$$

as  $V$  and  $T$  are same before and after the release of the gas.

so,

$$(p_1 - p_2) V = (m_1 - m_2) \frac{R}{M} T_0 = \Delta m \frac{R}{M} T_0$$

or,

$$\Delta m = \frac{(p_1 - p_2) V M}{R T_0} = \frac{\Delta p V M}{R T_0} \quad (1)$$

We also know  $p = \rho \frac{R}{M} T$  so,  $\frac{M}{R T_0} = \frac{\rho}{p_0}$  (2)

(where  $p_0$  = standard atmospheric pressure and  $T_0 = 273$  K)

From Eqs. (1) and (2) we get

$$\Delta m = \rho V \frac{\Delta p}{p_0} = 1.3 \times 30 \times \frac{0.78}{1} = 30 \text{ g}$$

2.2 Let  $m_1$  be the mass of the gas enclosed.

Then,

$$p_1 V = \nu_1 R T_1$$

When heated, some gas, passes into the evacuated vessel till pressure difference becomes  $\Delta p$ . Let  $p'_1$  and  $p'_2$  be the pressure on the two sides of the valve. Then

$$p'_1 V = \nu'_1 R T_2 \text{ and}$$

$$p'_2 V = \nu'_2 R T_2 = (\nu_1 - \nu'_1) R T_2$$

$$p'_2 V = \left( \frac{p_1 V}{R T_1} - \frac{p'_1 V}{R T_2} \right) \quad \text{or} \quad p'_2 = \left( \frac{p_1}{T_1} - \frac{p'_1}{T_2} \right) T_2$$

But,

$$p'_1 - p'_2 = \Delta p$$

So,

$$\begin{aligned} p'_2 &= \left( \frac{p_1}{T_1} - \frac{p'_2 + \Delta p}{T_2} \right) T_2 \\ &= \frac{p_1 T_2}{T_1} - p'_2 - \Delta p \end{aligned}$$

or,

$$p'_2 = \frac{1}{2} \left( \frac{p_1 T_2}{T_1} - \Delta p \right) = 0.08 \text{ atm}$$

**2.3** Let the mixture contain  $\nu_1$  and  $\nu_2$  moles of  $H_2$  and  $H_e$  respectively. If molecular weights of  $H_2$  and  $H_e$  are  $M_1$  and  $M_2$ , then respective masses in the mixture are equal to

$$m_1 = \nu_1 M_1 \quad \text{and} \quad m_2 = \nu_2 M_2$$

Therefore, for the total mass of the mixture we get,

$$m = m_1 + m_2 \quad \text{or} \quad m = \nu_1 M_1 + \nu_2 M_2 \quad (1)$$

Also, if  $\nu$  is the total number of moles of the mixture in the vessels, then we know,

$$\nu = \nu_1 + \nu_2 \quad (2)$$

Solving (1) and (2) for  $\nu_1$  and  $\nu_2$ , we get,

$$\nu_1 = \frac{(\nu M_2 - m)}{M_2 - M_1}, \quad \nu_2 = \frac{m - \nu M_1}{M_2 - M_1}$$

Therefore, we get  $m_1 = M_1 \cdot \frac{(\nu M_2 - m)}{M_2 - M_1}$  and  $m_2 = M_2 \frac{(m - \nu M_1)}{M_2 - M_1}$

or,

$$\frac{m_1}{m_2} = \frac{M_1 (\nu M_2 - m)}{M_2 (m - \nu M_1)}$$

One can also express the above result in terms of the effective molecular weight  $M$  of the mixture, defined as,

$$M = \frac{m}{\nu} = m \frac{RT}{pV}$$

Thus,

$$\frac{m_1}{m_2} = \frac{M_1}{M_2} \cdot \frac{M_2 - M}{M - M_1} = \frac{1 - M/M_2}{M/M_1 - 1}$$

Using the data and table, we get :

$$M = 3.0 \text{ g and, } \frac{m_1}{m_2} = 0.50$$

- 2.4 We know, for the mixture,  $N_2$  and  $CO_2$  (being regarded as ideal gases, their mixture too behaves like an ideal gas)

$$pV = \nu RT, \text{ so } p_0 V = \nu RT$$

where,  $\nu$  is the total number of moles of the gases (mixture) present and  $V$  is the volume of the vessel. If  $\nu_1$  and  $\nu_2$  are number of moles of  $N_2$  and  $CO_2$  respectively present in the mixture, then

$$\nu = \nu_1 + \nu_2$$

Now number of moles of  $N_2$  and  $CO_2$  is, by definition, given by

$$\nu_1 = \frac{m_1}{M_1} \text{ and, } \nu_2 = \frac{m_2}{M_2}$$

where,  $m_1$  is the mass of  $N_2$  (Molecular weight =  $M_1$ ) in the mixture and  $m_2$  is the mass of  $CO_2$  (Molecular weight =  $M_2$ ) in the mixture.

Therefore density of the mixture is given by

$$\begin{aligned} \rho &= \frac{m_1 + m_2}{V} = \frac{m_1 + m_2}{(\nu RT/p_0)} \\ &= \frac{p_0}{RT} \cdot \frac{m_1 + m_2}{\nu_1 + \nu_2} = \frac{p_0 (m_1 + m_2) M_1 M_2}{RT (m_1 M_2 + m_2 M_1)} \\ &= 1.5 \text{ kg/m}^3 \text{ on substitution} \end{aligned}$$

- 2.5 (a) The mixture contains  $\nu_1$ ,  $\nu_2$  and  $\nu_3$  moles of  $O_2$ ,  $N_2$  and  $CO_2$  respectively. Then the total number of moles of the mixture

$$\nu = \nu_1 + \nu_2 + \nu_3$$

We know, ideal gas equation for the mixture

$$pV = \nu RT \text{ or } p = \frac{\nu RT}{V}$$

$$\text{or, } p = \frac{(\nu_1 + \nu_2 + \nu_3) RT}{V} = 1.968 \text{ atm on substitution}$$

(b) Mass of oxygen ( $O_2$ ) present in the mixture :  $m_1 = \nu_1 M_1$

Mass of nitrogen ( $N_2$ ) present in the mixture :  $m_2 = \nu_2 M_2$

Mass of carbon dioxide ( $CO_2$ ) present in the mixture :  $m_3 = \nu_3 M_3$

So, mass of the mixture

$$m = m_1 + m_2 + m_3 = \nu_1 M_1 + \nu_2 M_2 + \nu_3 M_3$$

Molecular mass of the mixture :  $M = \frac{\text{mass of the mixture}}{\text{total number of moles}}$

$$= \frac{\nu_1 M_1 + \nu_2 M_2 + \nu_3 M_3}{\nu_1 + \nu_2 + \nu_3} = 36.7 \text{ g/mol. on substitution}$$

2.6 Let  $p_1$  and  $p_2$  be the pressure in the upper and lower part of the cylinder respectively at temperature  $T_0$ . At the equilibrium position for the piston :

$$p_1 S + mg = p_2 S \quad \text{or,} \quad p_1 + \frac{mg}{S} = p_2 \quad (m \text{ is the mass of the piston.})$$

But  $p_1 = \frac{RT_0}{\eta V_0}$  (where  $V_0$  is the initial volume of the lower part)

$$\text{So,} \quad \frac{RT_0}{\eta V_0} + \frac{mg}{S} = \frac{RT_0}{V_0} \quad \text{or,} \quad \frac{mg}{S} = \frac{RT_0}{V_0} \left(1 - \frac{1}{\eta}\right) \quad (1)$$

Let  $T'$  be the sought temperature and at this temperature the volume of the lower part becomes  $V'$ , then according to the problem the volume of the upper part becomes  $\eta' V'$

$$\text{Hence,} \quad \frac{mg}{S} = \frac{RT'}{V'} \left(1 - \frac{1}{\eta'}\right) \quad (2)$$

From (1) and (2).

$$\frac{RT_0}{V_0} \left(1 - \frac{1}{\eta}\right) = \frac{RT'}{V'} \left(1 - \frac{1}{\eta'}\right) \quad \text{or,} \quad T' = \frac{T_0 \left(1 - \frac{1}{\eta}\right) V'}{V_0 \left(1 - \frac{1}{\eta'}\right)}$$

As, the total volume must be constant,

$$V_0 (1 + \eta) = V' (1 + \eta') \quad \text{or,} \quad V' = \frac{V_0 (1 + \eta)}{(1 + \eta')}$$

Putting the value of  $V'$  in Eq. (3), we get

$$\begin{aligned} T &= \frac{T_0 \left(1 - \frac{1}{\eta}\right) V_0 \frac{(1 + \eta)}{(1 + \eta')}}{V_0 \left(1 - \frac{1}{\eta'}\right)} \\ &= \frac{T_0 (\eta^2 - 1) \eta'}{(\eta'^2 - 1) \eta} = 0.42 \text{ k K} \end{aligned}$$

2.7 Let  $\rho_1$  be the density after the first stroke. The the mass remains constant

$$V \rho = (V + \Delta V) \rho_1, \quad \text{or,} \quad \rho_1 = \frac{V \rho}{(V + \Delta V)}$$

Similarly, if  $\rho_2$  is the density after second stroke

$$V \rho_1 = (V + \Delta V) \rho_2 \quad \text{or,} \quad \rho_2 = \left(\frac{V}{V + \Delta V}\right) \rho_1 = \left(\frac{V}{V + \Delta V}\right)^2 \rho_0$$

In this way after  $n$ th stroke.

$$\rho_n = \left(\frac{V}{V + \Delta V}\right)^n \rho_0$$

Since pressure  $\propto$  density,

$$p_n = \left( \frac{V}{V + \Delta V} \right)^n p_0 \quad (\text{because temperature is constant})$$

It is required by  $\frac{p_n}{p_0}$  to be  $\frac{1}{\eta}$

$$\text{so,} \quad \frac{1}{\eta} = \left( \frac{V}{V + \Delta V} \right)^n \quad \text{or,} \quad \eta = \left( \frac{V + \Delta V}{V} \right)^n$$

$$\text{Hence} \quad n = \frac{\ln \eta}{\ln \left( 1 + \frac{\Delta V}{V} \right)}$$

2.8 From the ideal gas equation  $p = \frac{m}{M} \frac{RT}{V}$

$$\frac{dp}{dt} = \frac{RT}{MV} \frac{dm}{dt} \quad (1)$$

In each stroke, volume  $v$  of the gas is ejected, where  $v$  is given by

$$v = \frac{V}{m_N} [m_{N-1} - m_N]$$

In case of continuous ejection, if  $(m_{N-1})$  corresponds to mass of gas in the vessel at time  $t$ , then  $m_N$  is the mass at time  $t + \Delta t$ , where  $\Delta t$ , is the time in which volume  $v$  of the gas has come out. The rate of evacuation is therefore  $\frac{v}{\Delta t}$  i.e.

$$C = \frac{v}{\Delta t} = - \frac{V}{m(t + \Delta t)} \cdot \frac{m(t + \Delta t) - m(t)}{\Delta t}$$

In the limit  $\Delta t \rightarrow 0$ , we get

$$C = \frac{V}{m} \frac{dm}{dt} \quad (2)$$

From (1) and (2)

$$\frac{dp}{dt} = - \frac{C}{V} \frac{mRT}{MV} = - \frac{C}{V} p \quad \text{or} \quad \frac{dp}{p} = - \frac{C}{V} dt$$

$$\text{Integrating} \quad \int_p^{p_0} \frac{dp}{p} = - \frac{C}{V} \int_t^0 dt \quad \text{or} \quad \ln \frac{p}{p_0} = - \frac{C}{V} t$$

Thus

$$p = p_0 e^{-Ct/V}$$

2.9 Let  $\rho$  be the instantaneous density, then instantaneous mass =  $V\rho$ . In a short interval  $dt$  the volume is increased by  $Cdt$ .

$$\text{So,} \quad V\rho = (V + Cdt)(\rho + d\rho)$$

(because mass remains constant in a short interval  $dt$ )

so, 
$$\frac{dp}{\rho} = -\frac{C}{V} dt$$

Since pressure  $\propto$  density 
$$\frac{dp}{p} = -\frac{C}{V} dt$$

or 
$$\int_{p_1}^{p_2} -\frac{dp}{p} = \frac{C}{V} t,$$

or 
$$t = \frac{V}{C} \ln \frac{p_1}{p_2} = \frac{V}{C} \ln \frac{1}{\eta} \quad 1.0 \text{ min}$$

**2.10** The physical system consists of one mole of gas confined in the smooth vertical tube. Let  $m_1$  and  $m_2$  be the masses of upper and lower pistons and  $S_1$  and  $S_2$  are their respective areas.

For the lower piston

$$p S_2 + m_2 g = p_0 S_2 + T,$$

or, 
$$T = (p - p_0) S_2 + m_2 g \quad (1)$$

Similarly for the upper piston

$$p_0 S_1 + T + m_1 g = p S_1,$$

or, 
$$T = (p - p_0) S_1 - m_1 g \quad (2)$$

From (1) and (2)

$$(p - p_0) (S_1 - S_2) = (m_1 + m_2) g$$

or, 
$$(p - p_0) \Delta S = mg$$

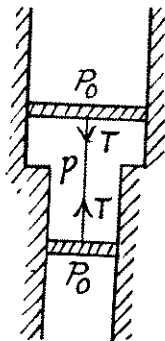
so, 
$$p = \frac{mg}{\Delta S} + p_0 = \text{constant}$$

From the gas law,  $pV = \nu RT$

$$p \Delta V = \nu R \Delta T \quad (\text{because } p \text{ is constant})$$

So, 
$$\left( p_0 + \frac{mg}{\Delta S} \right) \Delta S l = R \Delta T,$$

Hence, 
$$\Delta T = \frac{1}{R} (p_0 \Delta S + mg) l = 0.9 \text{ K}$$



**2.11** (a) 
$$p = p_0 - \alpha V^2 = p_0 - \alpha \left( \frac{RT}{p} \right)^2$$
  
(as,  $V = RT/p$  for one mole of gas)

Thus, 
$$T = \frac{1}{R \sqrt{\alpha}} p \sqrt{p_0 - p} = \frac{1}{R \sqrt{\alpha}} \sqrt{p_0 p^2 - p^3} \quad (1)$$

For  $T_{\max}$ , 
$$\frac{d}{dp} (p_0 p^2 - p^3) \text{ must be zero}$$



which yields, 
$$p = \frac{2}{3} p_0 \quad (2)$$

Hence, 
$$T_{\max} = \frac{1}{R\sqrt{\alpha}} \cdot \frac{2}{3} p_0 \sqrt{p_0 - \frac{2}{3} p_0} = \frac{2}{3} \left( \frac{p_0}{R} \right) \sqrt{\frac{p_0}{3\alpha}}$$

(b)  $p = p_0 e^{-\beta V} = p_0 e^{-\beta RT/p}$

so 
$$\frac{\beta RT}{p} = \ln \frac{p_0}{p}, \text{ and } T = \frac{p}{\beta R} \ln \frac{p_0}{p} \quad (1)$$

For  $T_{\max}$  the condition is  $\frac{dT}{dp} = 0$ , which yields

$$p = \frac{p_0}{e}$$

Hence using this value of  $p$  in Eq. (1), we get

$$T_{\max} = \frac{p_0}{e \beta R}$$

2.12  $T = T_0 + \alpha V^2 = T_0 + \alpha \frac{R^2 T^2}{p^2}$   
(as,  $V = RT/p$  for one mole of gas)

So, 
$$p = \sqrt{\alpha} RT (T - T_0)^{1/2} \quad (1)$$

For  $p_{\min}$ ,  $\frac{dp}{dT} = 0$ , which gives

$$T = 2T_0 \quad (2)$$

From (1) and (2), we get,

$$p_{\min} = \sqrt{\alpha} R 2T_0 (2T_0 - T_0)^{-1/2} = 2R\sqrt{\alpha} T_0$$

2.13 Consider a thin layer at a height  $h$  and thickness  $dh$ . Let  $p$  and  $dp + p$  be the pressure on the two sides of the layer. The mass of the layer is  $Sdh\rho$ . Equating vertical downward force to the upward force acting on the layer.

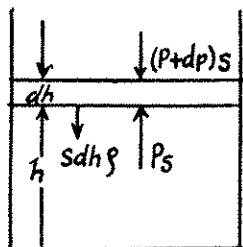
$$Sdh\rho g + (p + dp)S = pS$$

So, 
$$\frac{dp}{dh} = -\rho g \quad (1)$$

But,  $p = \frac{\rho}{M} RT$ , we have  $dp = \frac{\rho R}{M} dT$ ,

$$\text{or, } -\frac{\rho R}{M} dT = \rho g dh$$

So, 
$$\frac{dT}{dh} = -\frac{gM}{R} = -34 \text{ K/km}$$



That means, temperature of air drops by  $34^\circ\text{C}$  at a height of 1 km above bottom.

2.14 We have,  $\frac{dp}{dh} = -\rho g$  (See 2.13) (1)

But, from  $p = C\rho^n$  (where  $C$  is, a const)  $\frac{dp}{d\rho} = Cn\rho^{n-1}$  (2)

We have from gas law  $p = \rho \frac{R}{M} T$ , so using (2)

$$C\rho^n = \rho \frac{R}{M} \cdot T, \text{ or } T = \frac{M}{R} C\rho^{n-1}$$

Thus,  $\frac{dT}{d\rho} = \frac{M}{R} \cdot C(n-1)\rho^{n-2}$  (3)

But,  $\frac{dT}{dh} = \frac{dT}{d\rho} \cdot \frac{d\rho}{dp} \cdot \frac{dp}{dh}$

So,  $\frac{dT}{dh} = \frac{M}{R} C(n-1)\rho^{n-2} \frac{1}{Cn\rho^{n-1}} (-\rho g) = \frac{-Mg(n-1)}{nR}$

2.15 We have,  $dp = -\rho g dh$  and from gas law  $\rho = \frac{M}{RT} p$  (1)

Thus  $\frac{dp}{p} = -\frac{Mg}{RT} dh$

Integrating, we get

or,  $\int_{p_0}^p \frac{dp}{p} = -\frac{Mg}{RT} \int_0^h dh \text{ or, } \ln \frac{p}{p_0} = -\frac{Mg}{RT} h,$

(where  $p_0$  is the pressure at the surface of the Earth.)

$$p = p_0 e^{-Mgh/RT},$$

[Under standard condition,  $p_0 = 1$  atm,  $T = 273$  K

Pressure at a height of 5 atm  $= 1 \times e^{-28 \times 9.81 \times 5000/8314 \times 273} = 0.5$  atm.

Pressure in a mine at a depth of 5 km  $= 1 \times e^{-28 \times 9.81 \times (-5000)/8314 \times 273} = 2$  atm.]

2.16 We have  $dp = -\rho g dh$  but from gas law  $p = \frac{\rho}{M} RT$ ,

Thus  $dp = \frac{d\rho}{M} RT$  at const. temperature

So,  $\frac{d\rho}{\rho} = \frac{gM}{RT} dh$

Integrating within limits  $\int_{\rho_0}^{\rho} \frac{d\rho}{\rho} = \int_0^h \frac{gM}{RT} dh$

or, 
$$\ln \frac{\rho}{\rho_0} = -\frac{gM}{RT} h$$

So,  $\rho = \rho_0 e^{-Mgh/RT}$  and  $h = -\frac{RT}{Mg} \ln \frac{\rho}{\rho_0}$

(a) Given  $T = 273^\circ\text{K}$ ,  $\frac{\rho_0}{\rho} = e$

Thus 
$$h = -\frac{RT}{Mg} \ln e^{-1} = 8 \text{ km.}$$

(b)  $T = 273^\circ\text{K}$  and

$$\frac{\rho_0 - \rho}{\rho_0} = 0.01 \quad \text{or} \quad \frac{\rho}{\rho_0} = 0.99$$

Thus 
$$h = -\frac{RT}{Mg} \ln \frac{\rho}{\rho_0} = 0.09 \text{ km on substitution}$$

**2.17** From the Barometric formula, we have

$$p = p_0 e^{-Mgh/RT}$$

and from gas law 
$$\rho = \frac{pM}{RT}$$

So, at constant temperature from these two Eqs.

$$\rho = \frac{Mp_0}{RT} e^{-Mgh/RT} = \rho_0 e^{-Mgh/RT} \quad (1)$$

Eq. (1) shows that density varies with height in the same manner as pressure. Let us consider the mass element of the gas contained in the column.

$$dm = \rho (Sdh) = \frac{Mp_0}{RT} e^{-Mgh/RT} Sdh$$

Hence the sought mass,

$$m = \frac{Mp_0 S}{RT} \int_0^h e^{-Mgh/RT} dh = \frac{p_0 S}{g} (1 - e^{-Mgh/RT})$$

**2.18** As the gravitational field is constant the centre of gravity and the centre of mass are same. The location of C.M.

$$h = \frac{\int_0^\infty h dm}{\int_0^\infty dm} = \frac{\int_0^\infty h \rho dh}{\int_0^\infty \rho dh}$$

But from Barometric formula and gas law  $\rho = \rho_0 e^{-Mgh/RT}$

So,

$$h = \frac{\int_0^\alpha h \left( e^{-Mg h/RT} \right) dh}{\int_0^\alpha \left( e^{-Mg h/RT} \right) dh} = \frac{RT}{Mg}$$

**2.19** (a) We know that the variation of pressure with height of a fluid is given by :

$$dp = -\rho g dh$$

But from gas law  $p = \frac{\rho}{M} RT$  or,  $\rho = \frac{pM}{RT}$

From these two Eqs.

$$dp = -\frac{pMg}{RT} dh \quad (1)$$

or,  $\frac{dp}{p} = \frac{-Mg dh}{RT_0(1 - ah)}$

Integrating,  $\int_{p_0}^p \frac{dp}{p} = \frac{-Mg}{RT_0} \int_0^h \frac{dh}{(1 - ah)}$ , we get

$$\ln \frac{p}{p_0} = \ln (1 - ah)^{Mg/aRT_0}$$

Hence,  $p = p_0 (1 - ah)^{Mg/aRT_0}$ . Obviously  $h < \frac{1}{a}$

(b) Proceed up to Eq. (1) of part (a), and then put  $T = T_0 (1 + ah)$  and proceed further in the same fashion to get

$$p = \frac{p_0}{(1 + ah)^{Mg/aRT_0}}$$

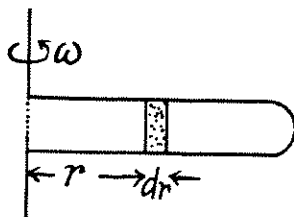
**2.20** Let us consider the mass element of the gas (thin layer) in the cylinder at a distance  $r$  from its open end as shown in the figure.

Using Newton's second law for the element

$$F_n = m\omega_n^2$$

$$(p + dp)S - pS = (\rho S dr) \omega^2 r$$

or,  $dp = \rho \omega^2 r dr = \frac{pM}{RT} \omega^2 r dr$



So, 
$$\frac{dp}{p} = \frac{M \omega^2}{RT} r dr \quad \text{or,} \quad \int_{p_0}^p \frac{dp}{p} = \frac{M \omega^2}{RT} \int_0^r r dr,$$

Thus, 
$$\ln \frac{p}{p_0} = \frac{M \omega^2}{2RT} r^2 \quad \text{or,} \quad p = p_0 e^{M \omega^2 r^2 / 2RT}$$

2.21 For an ideal gas law

$$p = \frac{\rho}{M} R T$$

So, 
$$p = 0.082 \times 300 \times \frac{500}{44} \text{ atms} = 279.5 \text{ atmosphere}$$

For Vander Waal gas Eq.

$$\left(p + \frac{v^2 a}{V^2}\right)(V - v b) = v R T, \quad \text{where } V = v V_M$$

or, 
$$p = \frac{v R T}{V - v b} - \frac{a v^2}{V^2} = \frac{m R T / M}{V - \frac{m b}{M}} - \frac{a m^2}{V^2 M^2}$$

$$= \frac{\rho R T}{M - \rho b} - \frac{a \rho^2}{M^2} = 79.2 \text{ atm}$$

2.22 (a) 
$$p = \left[ \frac{R T}{V_M - b} - \frac{a}{V_M^2} \right] (1 + \eta) = \frac{R T}{V_M}$$

(The pressure is less for a Vander Waal gas than for an ideal gas)

or, 
$$\frac{a(1 + \eta)}{V_M^2} = R T \left[ \frac{-1}{V_M} + \frac{1 + \eta}{V_M - b} \right] = R T \frac{\eta V_M + b}{V_M (V_M - b)}$$

or, 
$$T = \frac{a(1 + \eta)(V_M - b)}{R V_M (\eta V_M + b)}, \quad (\text{here } V_M \text{ is the molar volume.})$$

$$= \frac{1.35 \times 1.1 \times (1 - 0.039)}{0.082 \times (0.139)} \approx 125 \text{ K}$$

(b) The corresponding pressure is

$$p = \frac{R T}{V_M - b} - \frac{a}{V_M^2} = \frac{a(1 + \eta)}{V_M (\eta V_M + b)} - \frac{a}{V_M^2}$$

$$= \frac{a}{V_M^2} \frac{(V_M + \eta V_M - \eta V_M - b)}{(\eta V_M + b)} = \frac{a}{V_M^2} \frac{(V_M - b)}{(V_M + b)}$$

$$= \frac{1.35}{1} \times \frac{0.961}{0.139} \approx 9.3 \text{ atm}$$

$$2.23 \quad p_1 = RT_1 \frac{1}{V-b} - \frac{a}{V^2}, \quad p_2 = RT_2 \frac{1}{V-b} - \frac{a}{V^2}$$

$$\text{So,} \quad p_2 - p_1 = \frac{R(T_2 - T_1)}{V-b}$$

$$\text{or,} \quad V-b = \frac{R(T_2 - T_1)}{p_2 - p_1} \quad \text{or,} \quad b = V - \frac{R(T_2 - T_1)}{p_2 - p_1}$$

$$\text{Also,} \quad p_1 = T_1 \frac{p_2 - p_1}{T_2 - T_1} - \frac{a}{V^2},$$

$$\frac{a}{V^2} = \frac{T_1(p_2 - p_1)}{T_2 - T_1} - p_1 = \frac{T_1 p_2 - p_1 T_2}{T_2 - T_1}$$

$$\text{or,} \quad a = V^2 \frac{T_1 p_2 - p_1 T_2}{T_2 - T_1}$$

Using  $T_1 = 300 \text{ K}$ ,  $p_1 = 90 \text{ atm}$ ,  $T_2 = 350 \text{ K}$ ,  $p_2 = 110 \text{ atm}$ ,  $V = 0.250 \text{ litre}$

$$a = 1.87 \text{ atm. litre}^2/\text{mole}^2, \quad b = 0.045 \text{ litre/mole}$$

$$2.24 \quad p = \frac{RT}{V-b} - \frac{a}{V^2} - V \left( \frac{\partial p}{\partial V} \right)_T = \frac{RTV}{(V-b)^2} - \frac{2a}{V^2}$$

$$\text{or,} \quad \kappa = -\frac{1}{V} \left( \frac{\partial V}{\partial p} \right)_T$$

$$= \left[ \frac{RTV^3 - 2a(V-b)^2}{V^2(V-b)^2} \right]^{-1} = \frac{V^2(V-b)}{[RTV^3 - 2a(V-b)^2]}$$

$$2.25 \quad \text{For an ideal gas } \kappa_0 = \frac{V}{RT}$$

$$\begin{aligned} \text{Now } \kappa &= \frac{(V-b)^2}{RTV} \left\{ 1 - \frac{2a(V-b)^2}{RTV^3} \right\}^{-1} = \kappa_0 \left( 1 - \frac{b}{V} \right)^2 \left\{ 1 - \frac{2a}{RTV} \left( 1 - \frac{b}{V} \right)^2 \right\}^{-1} \\ &= \kappa_0 \left\{ 1 - \frac{2b}{V} + \frac{2a}{RTV} \right\}, \text{ to leading order in } a, b \end{aligned}$$

$$\text{Now} \quad \kappa > \kappa_0 \quad \text{if} \quad \frac{2a}{RTV} > \frac{2b}{V} \quad \text{or} \quad T < \frac{a}{bR}$$

If  $a$ ,  $b$  do not vary much with temperature, then the effect at high temperature is clearly determined by  $b$  and its effect is repulsive so compressibility is less.

## 2.2 THE FIRST LAW OF THERMODYNAMICS. HEAT CAPACITY

2.26 Internal energy of air, treating as an ideal gas

$$U = \frac{m}{M} C_V T = \frac{m}{M} \frac{R}{\gamma - 1} T = \frac{pV}{\gamma - 1} \quad (1)$$

Using  $C_V = \frac{R}{\gamma - 1}$ , since  $C_p - C_V = R$  and  $\frac{C_p}{C_V} = \gamma$

Thus at constant pressure  $U = \text{constant}$ , because the volume of the room is a constant.

Putting the value of  $p = p_{atm}$  and  $V$  in Eq. (1), we get  $U = 10 \text{ MJ}$ .

2.27 From energy conservation

$$U_i + \frac{1}{2} (\nu M) v^2 = U_f$$

or, 
$$\Delta U = \frac{1}{2} \nu M v^2 \quad (1)$$

But from  $U = \nu \frac{RT}{\gamma - 1}$ ,  $\Delta U = \frac{\nu R}{\gamma - 1} \Delta T$  (from the previous problem) (2)

Hence from Eqs. (1) and (2).

$$\Delta T = \frac{M v^2 (\gamma - 1)}{2R}$$

2.28 On opening the valve, the air will flow from the vessel at higher pressure to the vessel at lower pressure till both vessels have the same air pressure. If this air pressure is  $p$ , the total volume of the air in the two vessels will be  $(V_1 + V_2)$ . Also if  $\nu_1$  and  $\nu_2$  be the number of moles of air initially in the two vessels, we have

$$p_1 V_1 = \nu_1 R T_1 \text{ and } p_2 V_2 = \nu_2 R T_2 \quad (1)$$

After the air is mixed up, the total number of moles are  $(\nu_1 + \nu_2)$  and the mixture is at temperature  $T$ .

Hence 
$$p (V_1 + V_2) = (\nu_1 + \nu_2) R T \quad (2)$$

Let us look at the two portions of air as one single system. Since this system is contained in a thermally insulated vessel, no heat exchange is involved in the process. That is, total heat transfer for the combined system  $Q = 0$

Moreover, this combined system does not perform mechanical work either. The walls of the containers are rigid and there are no pistons etc to be pushed, looking at the total system, we know  $A = 0$ .

Hence, internal energy of the combined system does not change in the process. Initially energy of the combined system is equal to the sum of internal energies of the two portions of air :

$$U_i = U_1 + U_2 = \frac{\nu_1 R T_1}{\gamma - 1} + \frac{\nu_2 R T_2}{\gamma - 1} \quad (3)$$

Final internal energy of  $(n_1 + n_2)$  moles of air at temperature  $T$  is given by

$$U_f = \frac{(\nu_1 + \nu_2)RT}{\gamma - 1} \quad (4)$$

Therefore,  $U_i = U_f$  implies :

$$T = \frac{\nu_1 T_1 + \nu_2 T_2}{\nu_1 + \nu_2} = \frac{p_1 V_1 + p_2 V_2}{(p_1 V_1/T_1) + (p_2 V_2/T_2)} = T_1 T_2 \frac{p_1 V_1 + p_2 V_2}{p_1 V_1 T_2 + p_2 V_2 T_1}$$

From (2), therefore, final pressure is given by :

$$p = \frac{\nu_1 + \nu_2}{V_1 + V_2} RT = \frac{R}{V_1 + V_2} (\nu_1 T_1 + \nu_2 T_2) = \frac{p_1 V_1 + p_2 V_2}{V_1 + V_2}$$

This process is an example of free adiabatic expansion of ideal gas.

**2.29** By the first law of thermodynamics,

$$Q = \Delta U + A$$

Here  $A = 0$ , as the volume remains constant,

$$\text{So,} \quad Q = \Delta U = \frac{\nu R}{\gamma - 1} \Delta T$$

$$\text{From gas law,} \quad p_0 V = \nu R T_0$$

$$\text{So,} \quad \Delta U = \frac{p_0 V \Delta T}{T_0(\gamma - 1)} = -0.25 \text{ kJ}$$

$$\text{Hence amount of heat lost} = -\Delta U = 0.25 \text{ kJ}$$

**2.30** By the first law of thermodynamics  $Q = \Delta U + A$

$$\text{But} \quad \Delta U = \frac{p \Delta V}{\gamma - 1} = \frac{A}{\gamma - 1} \quad (\text{as } p \text{ is constant})$$

$$Q = \frac{A}{\gamma - 1} + A = \frac{\gamma \cdot A}{\gamma - 1} = \frac{1.4}{1.4 - 1} \times 2 = 7 \text{ J}$$

**2.31** Under isobaric process  $A = p \Delta V = R \Delta T$  (as  $\nu = 1$ ) = 0.6 kJ

From the first law of thermodynamics

$$\Delta U = Q - A = Q - R \Delta T = 1 \text{ kJ}$$

$$\text{Again increment in internal energy } \Delta U = \frac{R \Delta T}{\gamma - 1}, \text{ for } \nu = 1$$

$$\text{Thus} \quad Q - R \Delta T = \frac{R \Delta T}{\gamma - 1} \quad \text{or} \quad \gamma = \frac{Q}{Q - R \Delta T} = 1.6$$

**2.32** Let  $\nu = 2$  moles of the gas. In the first phase, under isochoric process,  $A_1 = 0$ , therefore from gas law if pressure is reduced  $n$  times so that temperature i.e. new temperature becomes  $T_0/n$ .

Now from first law of thermodynamics

$$Q_1 = \Delta U_1 = \frac{\nu R \Delta T}{\gamma - 1}$$



$$= \frac{\nu R}{\gamma - 1} \left( \frac{T_0}{n} - T_0 \right) = \frac{\nu R T_0 (1 - n)}{n (\gamma - 1)}$$

During the second phase (under isobaric process),

$$A_2 = p \Delta V = \nu R \Delta T$$

Thus from first law of thermodynamics :

$$\begin{aligned} Q_2 &= \Delta U_2 + A_2 = \frac{\nu R \Delta T}{\gamma - 1} + \nu R \Delta T \\ &= \frac{\nu R \left( T_0 - \frac{T_0}{n} \right) \gamma}{\gamma - 1} = \frac{\nu R T_0 (n - 1) \gamma}{n (\gamma - 1)} \end{aligned}$$

Hence the total amount of heat absorbed

$$\begin{aligned} Q &= Q_1 + Q_2 = \frac{\nu R T_0 (1 - n)}{n (\gamma - 1)} + \frac{\nu R T_0 (n - 1) \gamma}{n (\gamma - 1)} \\ &= \frac{\nu R T_0 (n - 1) \gamma}{n (\gamma - 1)} (-1 + \gamma) = \nu R T_0 \left( 1 - \frac{1}{n} \right) \end{aligned}$$

### 2.33 Total no. of moles of the mixture $\nu = \nu_1 + \nu_2$

At a certain temperature,  $U = U_1 + U_2$  or  $\nu C_V = \nu_1 C_{V_1} + \nu_2 C_{V_2}$

$$\text{Thus } C_V = \frac{\nu_1 C_{V_1} + \nu_2 C_{V_2}}{\nu} = \frac{\left( \nu_1 \frac{R}{\gamma_1 - 1} + \nu_2 \frac{R}{\gamma_2 - 1} \right)}{\nu}$$

$$\begin{aligned} \text{Similarly } C_P &= \frac{\nu_1 C_{P_1} + \nu_2 C_{P_2}}{\nu} \\ &= \frac{\nu_1 \gamma_1 C_{V_1} + \nu_2 \gamma_2 C_{V_2}}{\nu} = \frac{\left( \nu_1 \frac{\gamma_1 R}{\gamma_1 - 1} + \nu_2 \frac{\gamma_2 R}{\gamma_2 - 1} \right)}{\nu} \end{aligned}$$

$$\begin{aligned} \text{Thus } \gamma &= \frac{C_P}{C_V} = \frac{\nu_1 \frac{\gamma_1}{\gamma_1 - 1} R + \nu_2 \frac{\gamma_2}{\gamma_2 - 1} R}{\nu_1 \frac{R}{\gamma_1 - 1} + \nu_2 \frac{R}{\gamma_2 - 1}} \\ &= \frac{\nu_1 \gamma_1 (\gamma_2 - 1) + \nu_2 \gamma_2 (\gamma_1 - 1)}{\nu_1 (\gamma_2 - 1) + \nu_2 (\gamma_1 - 1)} \end{aligned}$$

### 2.34 From the previous problem

$$C_V = \frac{\nu_1 \frac{R}{\gamma_1 - 1} + \nu_2 \frac{R}{\gamma_2 - 1}}{\nu_1 + \nu_2} = 15.2 \text{ J/mole. K}$$

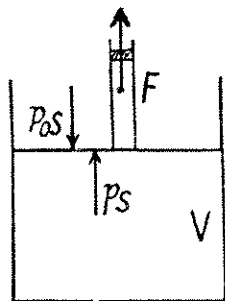
and 
$$C_p = \frac{v_1 \frac{\gamma_1 R}{\gamma_1 - 1} + v_2 \frac{\gamma_2 R}{\gamma_2 - 1}}{v_1 + v_2} = 23.85 \text{ J/mole} \cdot \text{K}$$

Now molar mass of the mixture ( $M$ ) =  $\frac{\text{Total mass}}{\text{Total number of moles}} = \frac{20 + 7}{\frac{1}{2} + \frac{1}{4}} = 36$

Hence  $c_v = \frac{C_v}{M} = 0.42 \text{ J/g} \cdot \text{K}$  and  $c_p = \frac{C_p}{M} = 0.66 \text{ J/g} \cdot \text{K}$

- 2.35 Let  $S$  be the area of the piston and  $F$  be the force exerted by the external agent. Then,  $F + pS = p_0 S$  (Fig.) at an arbitrary instant of time. Here  $p$  is the pressure at the instant the volume is  $V$ . (Initially the pressure inside is  $p_0$ )

$$\begin{aligned} A \quad (\text{Work done by the agent}) &= \int_{V_0}^{\eta V_0} F dx \\ &= \int_{V_0}^{\eta V_0} (p_0 - p) S \cdot dx = \int_{V_0}^{\eta V_0} (p_0 - p) dV \\ &= p_0 (\eta - 1) V_0 - \int_{V_0}^{\eta V_0} p dV = p_0 (\eta - 1) V_0 - \int_{V_0}^{\eta V_0} \nu RT \cdot \frac{dV}{V} \\ &= (\eta - 1) p_0 V_0 - \nu RT \ln \eta = (\eta - 1) \nu RT - \nu RT \ln \eta \\ &= \nu RT (\eta - 1 - \ln \eta) = RT (\eta - 1 - \ln \eta) \quad (\text{For } \nu = 1 \text{ mole}) \end{aligned}$$



- 2.36 Let the agent move the piston to the right by  $x$ . In equilibrium position,

$$p_1 S + F_{\text{agent}} = p_2 S, \quad \text{or,} \quad F_{\text{agent}} = (p_2 - p_1) S$$

Work done by the agent in an infinitesimal change  $dx$  is

$$F_{\text{agent}} \cdot dx = (p_2 - p_1) S dx = (p_2 - p_1) dV$$

By applying  $pV = \text{constant}$ , for the two parts,

$$p_1 (V_0 + Sx) = p_0 V_0 \quad \text{and} \quad p_2 (V_0 - Sx) = p_0 V_0$$

So, 
$$p_2 - p_1 = \frac{p_0 V_0 2Sx}{V_0^2 - S^2 x^2} = \frac{2p_0 V_0 V}{V_0^2 - V^2} \quad (\text{where } Sx = V)$$

When the volume of the left end is  $\eta$  times the volume of the right end

$$(V_0 + V) = \eta (V_0 - V), \quad \text{or,} \quad V = \frac{\eta - 1}{\eta + 1} V_0$$

$$\begin{aligned}
 A &= \int_0^V (p_2 - p_1) dV = \int_0^V \frac{2p_0 V_0 V}{V_0^2 - V^2} dV = -p_0 V_0 \left[ \ln (V_0^2 - V^2) \right]_0^V \\
 &= -p_0 V_0 \left[ \ln (V_0^2 - V^2) - \ln V_0^2 \right] \\
 &= -p_0 V_0 \left[ \ln \left\{ V_0^2 - \left( \frac{\eta - 1}{\eta + 1} \right)^2 V_0^2 \right\} - \ln V_0^2 \right] \\
 &= -p_0 V_0 \left( \ln \frac{4\eta}{(\eta + 1)^2} \right) = p_0 V_0 \ln \frac{(\eta + 1)^2}{4\eta}
 \end{aligned}$$

**2.37** In the isothermal process, heat transfer to the gas is given by

$$Q_1 = \nu RT_0 \ln \frac{V_2}{V_1} = \nu RT_0 \ln \eta \quad \left( \text{For } \eta = \frac{V_2}{V_1} = \frac{p_1}{p_2} \right)$$

In the isochoric process,  $A = 0$

Thus heat transfer to the gas is given by

$$Q_2 = \Delta U = \nu C_V \Delta T = \frac{\nu R}{\gamma - 1} \Delta T \quad \left( \text{for } C_V = \frac{R}{\gamma - 1} \right)$$

$$\text{But } \frac{p_2}{p_1} = \frac{T_0}{T}, \quad \text{or, } T = T_0 \frac{p_1}{p_2} = \eta T_0 \quad \left( \text{for } \eta = \frac{p_1}{p_2} \right)$$

$$\text{or, } \Delta T = \eta T_0 - T_0 = (\eta - 1) T_0 \quad \text{so, } Q_2 = \frac{\nu R}{\gamma - 1} \cdot (\eta - 1) T_0$$

Thus, net heat transfer to the gas

$$Q = \nu RT_0 \ln \eta + \frac{\nu R}{\gamma - 1} \cdot (\eta - 1) T_0$$

$$\text{or, } \frac{Q}{\nu RT_0} = \ln \eta + \frac{\eta - 1}{\gamma - 1}, \quad \text{or, } \frac{Q}{\nu RT_0} - \ln \eta = \frac{\eta - 1}{\gamma - 1}$$

$$\text{or, } \gamma = 1 + \frac{\eta - 1}{\frac{Q}{\nu RT_0} - \ln \eta} = 1 + \frac{6 - 1}{\left( \frac{80 \times 10^3}{3 \times 8.314 \times 273} \right) - \ln 6} = 1.4$$

**2.38** (a) From ideal gas law  $p = \left( \frac{\nu R}{V} \right) T = kT$  (where  $k = \frac{\nu R}{V}$ )

For isochoric process, obviously  $k = \text{constant}$ , thus  $p = kT$ , represents a straight line passing through the origin and its slope becomes  $k$ .

For isobaric process  $p = \text{constant}$ , thus on  $p - T$  curve, it is a horizontal straight line parallel to  $T$ -axis, if  $T$  is along horizontal (or  $x$ -axis)

For isothermal process,  $T = \text{constant}$ , thus on  $p - T$  curve, it represents a vertical straight line if  $T$  is taken along horizontal (or  $x$ -axis)

For adiabatic process  $T^\gamma p^{1-\gamma} = \text{constant}$

After differentiating, we get  $(1 - \gamma) p^{-\gamma} dp \cdot T^\gamma + \gamma p^{1-\gamma} \cdot T^{\gamma-1} \cdot dT = 0$

$$\frac{dp}{dT} = \left( \frac{\gamma}{1-\gamma} \right) \left( \frac{p^{1-\gamma}}{p^{-\gamma}} \right) \left( \frac{T^{\gamma-1}}{T^{\gamma}} \right) = \left( \frac{\gamma}{\gamma-1} \right) \frac{p}{T}$$

The approximate plots of isochoric, isobaric, isothermal, and adiabatic processes are drawn in the answersheet.

(b) As  $p$  is not considered as variable, we have from ideal gas law

$$V = \frac{\nu R}{p} T = k' T \left( \text{where } k' = \frac{\nu R}{p} \right)$$

On  $V-T$  co-ordinate system let us, take  $T$  along  $x$ -axis.

For isochoric process  $V = \text{constant}$ , thus  $k' = \text{constant}$  and  $V = k'T$  obviously represents a straight line passing through the origin of the co-ordinate system and  $k'$  is its slope.

For isothermal process  $T = \text{constant}$ . Thus on the stated co-ordinate system it represents a straight line parallel to the  $V$ -axis.

For adiabatic process  $TV^{\gamma-1} = \text{constant}$

After differentiating, we get  $(\gamma-1) V^{\gamma-2} dV \cdot T + V^{\gamma-1} dT = 0$

$$\frac{dV}{dT} = - \left( \frac{1}{\gamma-1} \right) \cdot \frac{V}{T}$$

The approximate plots of isochoric, isobaric, isothermal and adiabatic processes are drawn in the answer sheet.

**2.39** According to  $T-p$  relation in adiabatic process,  $T^{\gamma} = kp^{\gamma-1}$  (where  $k = \text{constant}$ )

$$\text{and} \quad \left( \frac{T_2}{T_1} \right)^{\gamma} = \left( \frac{p_2}{p_1} \right)^{\gamma-1} \quad \text{So,} \quad \frac{T^{\gamma}}{T_0^{\gamma}} = \eta^{\gamma-1} \left( \text{for } \eta = \frac{p_2}{p_1} \right)$$

$$\text{Hence} \quad T = T_0 \cdot \eta^{\frac{\gamma-1}{\gamma}} = 290 \times 10^{(1.4-1)/1.4} = 0.56 \text{ kK}$$

(b) Using the solution of part (a), sought work done

$$A = \frac{\nu R \Delta T}{\gamma-1} = \frac{\nu R T_0}{\gamma-1} (\eta^{(\gamma-1)/\gamma} - 1) = 5.61 \text{ kJ (on substitution)}$$

**2.40** Let  $(p_0, V_0, T_0)$  be the initial state of the gas.

$$\text{We know } A_{\text{adia}} = \frac{-\nu R \Delta T}{\gamma-1} \text{ (work done by the gas)}$$

$$\text{But from the equation } TV^{\gamma-1} = \text{constant, we get } \Delta T = T_0 (\eta^{\gamma-1} - 1)$$

$$\text{Thus} \quad A_{\text{adia}} = \frac{-\nu R T_0 (\eta^{\gamma-1} - 1)}{\gamma-1}$$

$$\text{On the other hand, we know } A_{\text{iso}} = \nu R T_0 \ln \left( \frac{1}{\eta} \right) = -\nu R T_0 \ln \eta \text{ (work done by the gas)}$$

$$\text{Thus} \quad \frac{A_{\text{adia}}}{A_{\text{iso}}} = \frac{\eta^{\gamma-1} - 1}{(\gamma-1) \ln \eta} = \frac{5^{0.4} - 1}{0.4 \times \ln 5} = 1.4$$

**2.41** Since here the piston is conducting and it is moved slowly the temperature on the two sides increases and maintained at the same value.

Elementary work done by the agent = Work done in compression - Work done in expansion

$$\text{i.e. } dA = p_2 dV - p_1 dV = (p_2 - p_1) dV$$

where  $p_1$  and  $p_2$  are pressures at any instant of the gas on expansion and compression side respectively.

From the gas law  $p_1 (V_0 + Sx) = \nu RT$  and  $p_2 (V_0 - Sx) = \nu RT$ , for each section ( $x$  is the displacement of the piston towards section 2)

$$\text{So, } p_2 - p_1 = \nu RT \frac{2Sx}{V_0^2 - S^2 x^2} = \nu RT \cdot \frac{2V}{V_0^2 - V^2} \text{ (as } Sx = V)$$

$$\text{So } dA = \nu RT \frac{2V}{V_0^2 - V^2} dV$$

Also, from the first law of thermodynamics

$$dA = -dU = -2\nu \frac{R}{\gamma - 1} dT \text{ (as } dQ = 0)$$

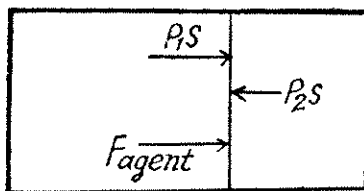
$$\text{So, work done on the gas} = -dA = 2\nu \cdot \frac{R}{\gamma - 1} dT$$

$$\text{Thus } 2\nu \frac{R}{\gamma - 1} dT = \nu RT \frac{2V \cdot dV}{V_0^2 - V^2},$$

$$\text{or, } \frac{dT}{T} = \gamma - 1 \frac{V dV}{V_0^2 - V^2}$$

When the left end is  $\eta$  times the volume of the right end.

$$(V_0 + V) = \eta (V_0 - V) \text{ or } V = \frac{\eta - 1}{\eta + 1} V_0$$



$$\text{On integrating } \int_{T_0}^T \frac{dT}{T} = (\gamma - 1) \int_0^V \frac{V dV}{V_0^2 - V^2}$$

$$\begin{aligned} \text{or } \ln \frac{T}{T_0} &= (\gamma - 1) \left[ -\frac{1}{2} \ln (V_0^2 - V^2) \right]_0^V \\ &= -\frac{\gamma - 1}{2} \left[ \ln (V_0^2 - V^2) - \ln V_0^2 - \ln V_0^2 \right] \\ &= \frac{\gamma - 1}{2} \left[ \ln V_0^2 - \ln V_0^2 \left\{ 1 - \left( \frac{\eta - 1}{\eta + 1} \right)^2 \right\} \right] = \frac{\gamma - 1}{2} \ln \frac{(\eta + 1)^2}{4\eta} \\ \text{Hence } T &= T_0 \left( \frac{(\eta + 1)^2}{4\eta} \right)^{\frac{\gamma - 1}{2}} \end{aligned}$$

**2.42** From energy conservation as in the derivation of Bernoulli's theorem it reads

$$\frac{p}{\rho} + \frac{1}{2} v^2 + gz + u + Q_d = \text{constant} \quad (1)$$

In the Eq. (1)  $u$  is the internal energy per unit mass and in this case is the thermal energy per unit mass of the gas. As the gas vessel is thermally insulated  $Q_d = 0$ , also in our case.

Just inside the vessel  $u = \frac{C_v T}{M} = \frac{RT}{M(\gamma - 1)}$  also  $\frac{p}{\rho} = \frac{RT}{M}$ . Inside the vessel  $v = 0$  also. Just outside  $p = 0$ , and  $u = 0$ . In general  $gz$  is not very significant for gases.

Thus applying Eq. (1) just inside and outside the hole, we get

$$\begin{aligned} \frac{1}{2} v^2 &= \frac{p}{\rho} + u \\ &= \frac{RT}{M} + \frac{RT}{M(\gamma - 1)} = \frac{\gamma RT}{M(\gamma - 1)} \end{aligned}$$

Hence  $v^2 = \frac{2\gamma RT}{M(\gamma - 1)}$  or,  $v = \sqrt{\frac{2\gamma RT}{M(\gamma - 1)}} = 3.22 \text{ km/s.}$

Note : The velocity here is the velocity of hydrodynamic flow of the gas into vacuum. This requires that the diameter of the hole is not too small ( $D > \text{mean free path } \lambda$ ). In the opposite case ( $D < \lambda$ ) the flow is called effusion. Then the above result does not apply and kinetic theory methods are needed.

**2.43** The differential work done by the gas

$$\begin{aligned} dA &= p dV = \frac{\nu R T^2}{a} \left( -\frac{a}{T^2} \right) dT = -\nu R dT \\ &\left( \text{as } pV = \nu RT \text{ and } V = \frac{a}{T} \right) \end{aligned}$$

So, 
$$A = - \int_T^{T+\Delta T} \nu R dT = -\nu R \Delta T$$

From the first law of thermodynamics

$$\begin{aligned} Q &= \Delta U + A = \frac{\nu R}{\gamma - 1} \Delta T - \nu R \Delta T \\ &= \nu R \Delta T \cdot \frac{2 - \gamma}{\gamma - 1} = R \Delta T \cdot \frac{2 - \gamma}{\gamma - 1} \quad (\text{for } \nu = 1 \text{ mole}) \end{aligned}$$

**2.44** According to the problem :  $A \propto U$  or  $dA = aU$  (where  $a$  is proportionality constant)

or, 
$$p dV = \frac{a \nu R dT}{\gamma - 1} \quad (1)$$

From ideal gas law,  $pV = \nu R T$ , on differentiating

$$p dV + V dp = \nu R dT \quad (2)$$

Thus from (1) and (2)

$$pdV = \frac{a}{\gamma - 1} (pdV + Vdp)$$

$$\text{or, } pdV \left( \frac{a}{\gamma - 1} - 1 \right) + \frac{a}{\gamma - 1} V dp = 0$$

$$\text{or, } pdV(k - 1) + kVdp = 0 \quad (\text{where } k = \frac{a}{\gamma - 1} = \text{another constant})$$

$$\text{or, } pdV \frac{k - 1}{k} + Vdp = 0$$

$$\text{or, } pdVn + Vdp = 0 \quad (\text{where } \frac{k - 1}{k} = n = \text{ratio})$$

Dividing both the sides by  $pV$

$$n \frac{dV}{V} + \frac{dp}{p} = 0$$

On integrating  $n \ln V + \ln p = \ln C$  (where  $C$  is constant)

$$\text{or, } \ln(pV^n) = \ln C \quad \text{or, } pV^n = C \quad (\text{const.})$$

**2.45** In the polytropic process work done by the gas

$$A = \frac{\nu R [T_i - T_f]}{n - 1}$$

(where  $T_i$  and  $T_f$  are initial and final temperature of the gas like in adiabatic process)

$$\text{and} \quad \Delta U = \frac{\nu R}{\gamma - 1} (T_f - T_i)$$

By the first law of thermodynamics  $Q = \Delta U + A$

$$\begin{aligned} &= \frac{\nu R}{\gamma - 1} (T_f - T_i) + \frac{\nu R}{n - 1} (T_i - T_f) \\ &= (T_f - T_i) \nu R \left[ \frac{1}{\gamma - 1} - \frac{1}{n - 1} \right] = \frac{\nu R [n - \gamma]}{(n - 1)(\gamma - 1)} \Delta T \end{aligned}$$

According to definition of molar heat capacity when number of moles  $\nu = 1$  and  $\Delta T = 1$  then  $Q = \text{Molar heat capacity}$ .

$$\text{Here, } C_n = \frac{R(n - \gamma)}{(n - 1)(\gamma - 1)} < 0 \quad \text{for } 1 < n < \gamma$$

**2.46** Let the process be polytropic according to the law  $pV^n = \text{constant}$

$$\text{Thus, } p_f V_f^n = p_i V_i^n \quad \text{or, } \left( \frac{p_i}{p_f} \right) = \beta$$

$$\text{So, } \alpha^n = \beta \quad \text{or } \ln \beta = n \ln \alpha \quad \text{or } n = \frac{\ln \beta}{\ln \alpha}$$

In the polytropic process molar heat capacity is given by

$$C_n = \frac{R(n-\gamma)}{(n-1)(\gamma-1)} = \frac{R}{\gamma-1} - \frac{R}{n-1}$$

$$= \frac{R}{\gamma-1} - \frac{R \ln \alpha}{\ln \beta - \ln \alpha}, \quad \text{where } n = \frac{\ln \beta}{\ln \alpha}$$

So,  $C_n = \frac{8.314}{1.66-1} - \frac{8.314 \ln 4}{\ln 8 - \ln 4} = -42 \text{ J/mol.K}$

2.47 (a) Increment of internal energy for  $\Delta T$ , becomes

$$\Delta U = \frac{\nu R \Delta T}{\gamma-1} = \frac{R \Delta T}{\gamma-1} = -324 \text{ J (as } \nu = 1 \text{ mole)}$$

From first law of thermodynamics

$$Q = \Delta U + A = \frac{R \Delta T}{\gamma-1} - \frac{R \Delta T}{n-1} = 0.11 \text{ kJ}$$

(b) Sought work done,  $A_n = \int_{V_i}^{V_f} p dV = \int_{V_i}^{V_f} \frac{k}{V^n} dV$

$$(\text{where } pV^n = k = p_i V_i^n = p_f V_f^n)$$

$$= \frac{k}{1-n} (V_f^{1-n} - V_i^{1-n}) = \frac{(p_f V_f^n V_f^{1-n} - p_i V_i^n V_i^{1-n})}{1-n}$$

$$= \frac{p_f V_f - p_i V_i}{1-n} = \frac{\nu R (T_f - T_i)}{1-n}$$

$$= \frac{\nu R \Delta T}{n-1} = -\frac{R \Delta T}{n-1} = 0.43 \text{ kJ (as } \nu = 1 \text{ mole)}$$

2.48 Law of the process is  $p = \alpha V$  or  $pV^{-1} = \alpha$

so the process is polytropic of index  $n = -1$

As  $p = \alpha V$  so,  $p_i = \alpha V_0$  and  $p_f = \alpha \eta V_0$

(a) Increment of the internal energy is given by

$$\Delta U = \frac{\nu R}{\gamma-1} [T_f - T_i] = \frac{p_f V_f - p_i V_i}{\gamma-1}$$

(b) Work done by the gas is given by

$$A = \frac{p_i V_i - p_f V_f}{n-1} = \frac{\alpha V_0^2 - \alpha \eta V_0 \cdot \eta V_0}{-1-1}$$

$$= \frac{\alpha V_0^2 (1 - \eta^2)}{-2} = \frac{1}{2} \alpha V_0^2 (\eta^2 - 1)$$

(c) Molar heat capacity is given by

$$C_n = \frac{R(n-\gamma)}{(n-1)(\gamma-1)} = \frac{R(-1-\gamma)}{(-1-1)(\gamma-1)} = \frac{R \gamma + 1}{2 \gamma - 1}$$



2.49 (a)  $\Delta U = \frac{\nu R}{\gamma - 1} \Delta T$  and  $Q = \nu C_n \Delta T$

where  $C_n$  is the molar heat capacity in the process. It is given that  $Q = -\Delta U$

So,  $C_n \Delta T = \frac{R}{\gamma - 1} \Delta T$ , or  $C_n = -\frac{R}{\gamma - 1}$

(b) By the first law of thermodynamics,  $dQ = dU + dA$ ,

or,  $2 dQ = dA$  (as  $dQ = -dU$ )

$$2\nu C_n dT = pdV, \text{ or, } \frac{2R\nu}{\gamma - 1} dT + pdV = 0$$

So,  $\frac{2RV}{\gamma - 1} dT + \frac{\nu RT}{V} dV = 0$ , or,  $\frac{2}{(\gamma - 1)} \frac{dT}{T} + \frac{dV}{V} = 0$

or,  $\frac{dT}{T} + \frac{\gamma - 1}{2} \frac{dV}{V} = 0$ , or,  $TV^{(\gamma - 1)/2} = \text{constant}$ .

(c) We know  $C_n = \frac{(n - \gamma)R}{(n - 1)(\gamma - 1)}$

But from part (a), we have  $C_n = -\frac{R}{\gamma - 1}$

Thus  $-\frac{R}{\gamma - 1} = \frac{(n - \gamma)R}{(n - 1)(\gamma - 1)}$  which yields

$$n = \frac{1 + \gamma}{2}$$

From part (b); we know  $TV^{(\gamma - 1)/2} = \text{constant}$

So,  $\frac{T_o}{T} = \left(\frac{V}{V_o}\right)^{(\gamma - 1)/2} = \eta^{(\gamma - 1)/2}$  (where  $T$  is the final temperature)

Work done by the gas for one mole is given by

$$A = R \frac{(T_o - T)}{n - 1} = \frac{2RT_o [1 - \eta^{(1 - \gamma)/2}]}{\gamma - 1}$$

2.50 Given  $p = a T^\alpha$  (for one mole of gas)

So,  $pT^{-\alpha} = a$  or,  $p \left(\frac{pV}{R}\right)^{-\alpha} = a$ ,

or,  $p^{1 - \alpha} V^{-\alpha} = aR^{-\alpha}$  or,  $pV^{\alpha/(\alpha - 1)} = \text{constant}$

Here polytropic exponent  $n = \frac{\alpha}{\alpha - 1}$

(a) In the polytropic process for one mole of gas :

$$A = \frac{R\Delta T}{1 - n} = \frac{R\Delta T}{\left(1 - \frac{\alpha}{\alpha - 1}\right)} = R\Delta T(1 - \alpha)$$

(b) Molar heat capacity is given by

$$C = \frac{R}{\gamma - 1} - \frac{R}{n - 1} = \frac{R}{\gamma - 1} - \frac{R}{\frac{\alpha}{\alpha - 1} - 1} = \frac{R}{\gamma - 1} + R(1 - \alpha)$$

**2.51** Given  $U = aV^\alpha$

$$\text{or, } \quad \nu C_V T = a V^\alpha, \quad \text{or, } \quad \nu C_V \frac{pV}{\nu R} = a V^\alpha$$

$$\text{or, } \quad a V^\alpha \cdot \frac{R}{C_V} \cdot \frac{1}{pV} = 1, \quad \text{or, } \quad V^{\alpha-1} \cdot p^{-1} = \frac{C_V}{Ra}$$

$$\text{or } \quad pV^{1-\alpha} = \frac{Ra}{C_V} = \text{constant} = a(\gamma-1) \left[ \text{as } C_V = \frac{R}{\gamma-1} \right]$$

So polytropic index  $n = 1 - \alpha$ .

(a) Work done by the gas is given by

$$A = \frac{-\nu R \Delta T}{n-1} \quad \text{and} \quad \Delta U = \frac{\nu R \Delta T}{\gamma-1}$$

$$\text{Hence } \quad A = \frac{-\Delta U(\gamma-1)}{n-1} = \frac{\Delta U(\gamma-1)}{\alpha} \quad (\text{as } n = 1 - \alpha)$$

By the first law of thermodynamics,  $Q = \Delta U + A$

$$= \Delta U + \frac{\Delta U(\gamma-1)}{\alpha} = \Delta U \left[ 1 + \frac{\gamma-1}{\alpha} \right]$$

(b) Molar heat capacity is given by

$$\begin{aligned} C &= \frac{R}{\gamma-1} - \frac{R}{n-1} = \frac{R}{\gamma-1} - \frac{R}{1-\alpha-1} \\ &= \frac{R}{\gamma-1} + \frac{R}{\alpha} \quad (\text{as } n = 1 - \alpha) \end{aligned}$$

**2.52** (a) By the first law of thermodynamics

$$dQ = dU + dA = \nu C_V dT + p dV$$

Molar specific heat according to definition

$$\begin{aligned} C &= \frac{dQ}{\nu dT} = \frac{C_V dT + p dV}{\nu dT} \\ &= \frac{\nu C_V dT + \frac{\nu RT}{V} dV}{\nu dT} = C_V + \frac{RT}{V} \frac{dV}{dT}, \end{aligned}$$

We have

$$T = T_0 e^{\alpha V}$$

After differentiating, we get  $dT = \alpha T_0 e^{\alpha V} \cdot dV$

$$\text{So, } \quad \frac{dV}{dT} = \frac{1}{\alpha T_0 e^{\alpha V}},$$

$$\text{Hence } \quad C = C_V + \frac{RT}{V} \cdot \frac{1}{\alpha T_0 e^{\alpha V}} = C_V + \frac{RT_0 e^{\alpha V}}{\alpha VT_0 e^{\alpha V}} = C_V + \frac{R}{\alpha V}$$

(b) Process is  $p = p_0 e^{\alpha V}$

$$p = \frac{RT}{V} = p_0 e^{\alpha V}$$

$$\text{or, } T = \frac{P_0}{R} e^{\alpha V} V$$

$$\text{So, } C = C_V + \frac{RT}{V} \frac{dV}{dT} = C_V + P_0 e^{\alpha V} \cdot \frac{R}{P_0 e^{\alpha V} (1 + \alpha V)} = C_V + \frac{R}{1 + \alpha V}$$

2.53 Using 2.52

$$(a) \quad C = C_V + \frac{RT}{V} \frac{dV}{dT} = C_V + \frac{pdV}{dT} \quad (\text{for one mole of gas})$$

$$\text{We have } p = p_0 + \frac{\alpha}{V} \quad \text{or, } \frac{RT}{V} = p_0 + \frac{\alpha}{V}, \quad \text{or, } RT = p_0 V + \alpha$$

$$\text{Therefore} \quad RdT = p_0 dV, \quad \text{So, } \frac{dV}{dT} = \frac{R}{p_0}$$

$$\begin{aligned} \text{Hence} \quad C &= C_V + \left( p_0 + \frac{\alpha}{V} \right) \cdot \frac{R}{p_0} = \frac{R}{\gamma - 1} + \left( 1 + \frac{\alpha}{p_0 V} \right) R \\ &= \left( R + \frac{R}{\gamma - 1} \right) + \frac{\alpha R}{p_0 V} = \frac{\gamma R}{\gamma - 1} + \frac{\alpha R}{p_0 V} \end{aligned}$$

(b) Work done is given by

$$A = \int_{V_1}^{V_2} \left( p_0 + \frac{\alpha}{V} \right) dV = p_0 (V_2 - V_1) + \alpha \ln \frac{V_2}{V_1}$$

$$\begin{aligned} \Delta U &= C_V (T_2 - T_1) = C_V \left( \frac{p_2 V_2}{R} - \frac{p_1 V_1}{R} \right) \quad (\text{for one mole}) \\ &= \frac{R}{(\gamma - 1) R} (p_2 V_2 - p_1 V_1) \\ &= \frac{1}{\gamma - 1} \left[ \left( p_0 + \alpha V_2 \right) V_2 - \left( p_0 + \frac{\alpha}{V_1} \right) V_1 \right] = \frac{p_0 (V_2 - V_1)}{\gamma - 1} \end{aligned}$$

By the first law of thermodynamics  $Q = \Delta U + A$

$$\begin{aligned} &= p_0 (V_2 - V_1) + \alpha \ln \frac{V_2}{V_1} + \frac{p_0 (V_2 - V_1)}{(\gamma - 1)} \\ &= \frac{\gamma p_0 (V_2 - V_1)}{\gamma - 1} + \alpha \ln \frac{V_2}{V_1} \end{aligned}$$

2.54 (a) Heat capacity is given by

$$C = C_V + \frac{RT}{V} \frac{dV}{dT} \quad (\text{see solution of 2.52})$$

$$\text{We have} \quad T = T_0 + \alpha V \quad \text{or, } V = \frac{T - T_0}{\alpha}$$

$$\text{After differentiating, we get, } \frac{dV}{dT} = \frac{1}{\alpha}$$

Hence 
$$C = C_V + \frac{RT}{V} \cdot \frac{1}{\alpha} = \frac{R}{\gamma - 1} + \frac{R(T_0 + \alpha V)}{V} \cdot \frac{1}{\alpha}$$

$$= \frac{R}{\gamma - 1} + R \left( \frac{T_0}{\alpha V} + 1 \right) = \frac{\gamma R}{\gamma - 1} + \frac{RT_0}{\alpha V} = C_V + \frac{RT}{\alpha V} = C_P + \frac{RT_0}{\alpha V}$$

(b) Given  $T = T_0 + \alpha V$

As  $T = \frac{pV}{R}$  for one mole of gas

$$p = \frac{R}{V}(T_0 + \alpha V) = \frac{RT}{V} = \alpha R$$

Now 
$$A = \int_{V_1}^{V_2} p dV = \int_{V_1}^{V_2} \left( \frac{RT_0}{V} + \alpha R \right) dV \text{ (for one mole)}$$

$$= RT_0 \ln \frac{V_2}{V_1} + \alpha (V_2 - V_1)$$

$$\Delta U = C_V(T_2 - T_1)$$

$$= C_V[T_0 + \alpha V_2 - T_0 + \alpha V_1] = \alpha C_V(V_2 - V_1)$$

By the first law of thermodynamics  $Q = \Delta U + A$

$$= \frac{\alpha R}{\gamma - 1}(V_2 - V_1) + RT_0 \ln \frac{V_2}{V_1} + \alpha R(V_2 - V_1)$$

$$= \alpha R(V_2 - V_1) \left[ 1 + \frac{1}{\gamma - 1} \right] + RT_0 \ln \frac{V_2}{V_1}$$

$$= \alpha C_P(V_2 - V_1) + RT_0 \ln \frac{V_2}{V_1}$$

$$= \alpha C_P(V_2 - V_1) + RT_0 \ln \frac{V_2}{V_1}$$

**2.55** Heat capacity is given by  $C = C_V + \frac{RT}{V} \frac{dV}{dT}$

(a) Given  $C = C_V + \alpha T$

So,  $C_V + \alpha T = C_V + \frac{RT}{V} \frac{dV}{dT}$  or,  $\frac{\alpha}{R} dT = \frac{dV}{V}$

Integrating both sides, we get  $\frac{\alpha}{R} T = \ln V + \ln C_0 = \ln VC_0$ ,  $C_0$  is a constant.

Or,  $V \cdot C_0 = e^{\alpha T/R}$  or  $V \cdot e^{\alpha T/R} = \frac{1}{C_0} = \text{constant}$

(b)  $C = C_V + \beta V$

and  $C = C_v + \frac{RT}{V} \frac{dV}{dT}$  so,  $C_v \frac{RT}{V} \frac{dV}{dT} = C_v + \beta V$

or,  $\frac{RT}{V} \frac{dV}{dT} = \beta V$  or,  $\frac{dV}{V^2} = \frac{\beta}{R} \frac{dT}{T}$  or,  $V^{-2} = \frac{dT}{T}$

Integrating both sides, we get  $\frac{R}{\beta} V^{-1} = \ln T + \ln C_0 = \ln T \cdot C_0$

So,  $\ln T \cdot C_0 = -\frac{R}{\beta V}$   $T \cdot C_0 = e^{-R/\beta V}$  or,  $T e^{-R/\beta V} = \frac{1}{C_0} = \text{constant}$

(c)  $C = C_v + ap$  and  $C = C_v + \frac{RT}{V} \frac{dV}{dT}$

So,  $C_v + ap = C_v + \frac{RT}{V} \frac{dV}{dT}$  so,  $ap = \frac{RT}{V} \frac{dV}{dT}$

or,  $a \frac{RT}{V} = \frac{RT}{V} \frac{dV}{dT}$  (as  $p = \frac{RT}{V}$  for one mole of gas)

or,  $\frac{dV}{dT} = a$  or,  $dV = a dT$  or,  $dT = \frac{dV}{a}$

So,  $T = \frac{V}{a} + \text{constant}$  or  $V - aT = \text{constant}$

**2.56** (a) By the first law of thermodynamics  $A = Q - \Delta U$

or,  $= C dT - C_v dT = (C - C_v) dT$  (for one mole)

Given  $C = \frac{\alpha}{T}$

So, 
$$A = \int_{T_0}^{\eta T_0} \left( \frac{\alpha}{T} - C_v \right) dT = \alpha \ln \frac{\eta T_0}{T_0} - C_v (\eta T_0 - T_0)$$

$$= \alpha \ln \eta - C_v T_0 (\eta - 1) = \alpha \ln \eta + \frac{RT}{\gamma - 1} (\eta - 1)$$

(b)  $C = + \frac{dQ}{dT} = \frac{RT}{V} \frac{dV}{dT} + C_v$

Given  $C = \frac{\alpha}{T}$ , so  $C_v + \frac{RT}{V} \frac{dV}{dT} = \frac{\alpha}{T}$

or,  $\frac{R}{\gamma - 1} \frac{1}{RT} + \frac{dV}{V} = \frac{\alpha}{RT^2} dT$

or,  $\frac{dV}{V} = \frac{\alpha}{RT^2} dT - \frac{1}{\gamma - 1} \cdot \frac{dT}{T}$

or,  $(\gamma - 1) \frac{dV}{V} = \frac{\alpha (\gamma - 1)}{RT^2} dT - \frac{dT}{T}$

Integrating both sides, we get

or, 
$$(\gamma - 1) \ln V = - \frac{\alpha (\gamma - 1)}{RT} - \ln T + \ln K$$

or, 
$$\ln V^{\gamma-1} \frac{T}{K} = \frac{-\alpha(\gamma-1)}{RT}$$

$$\ln V^{\gamma-1} \cdot \frac{pV}{RK} = \frac{-\alpha(\gamma-1)}{pV}$$

or, 
$$\frac{pV^\gamma}{RK} = e^{-\alpha(\gamma-1)/pV}$$

or, 
$$pV^\gamma e^{\alpha(\gamma-1)/pV} = RK = \text{constant}$$

**2.57** The work done is

$$\begin{aligned} A &= \int_{V_1}^{V_2} p \, dV = \int_{V_1}^{V_2} \left( \frac{RT}{v-b} - \frac{a}{V^2} \right) dV \\ &= RT \ln \frac{V_2-b}{V_1-b} + a \left( \frac{1}{V_2} - \frac{1}{V_1} \right) \end{aligned}$$

**2.58** (a) The increment in the internal energy is

$$\Delta U = \int_{V_1}^{V_2} \left( \frac{\partial U}{\partial V} \right)_T dV$$

But from second law

$$\left( \frac{\partial U}{\partial V} \right)_T = T \left( \frac{\partial S}{\partial V} \right)_T - p = T \left( \frac{\partial p}{\partial T} \right)_V - p$$

On the other hand

$$p = \frac{RT}{V-b} - \frac{a}{V^2}$$

or, 
$$T \left( \frac{\partial p}{\partial T} \right)_V = \frac{RT}{V-b} \text{ and } \left( \frac{\partial U}{\partial V} \right)_T = \frac{a}{V^2}$$

So, 
$$\Delta U = a \left( \frac{1}{V_1} - \frac{1}{V_2} \right)$$

(b) From the first law

$$Q = A + \Delta U = RT \ln \frac{V_2-b}{V_1-b}$$

**2.59** (a) From the first law for an adiabatic

$$dQ = dU + p \, dV = 0$$

From the previous problem

$$dU = \left( \frac{\partial U}{\partial T} \right)_V dT + \left( \frac{\partial U}{\partial V} \right)_T dV = C_V dT + \frac{a}{V^2} dV$$

So, 
$$0 = C_V dT + \frac{RT \, dV}{V-b}$$

This equation can be integrated if we assume that  $C_V$  and  $b$  are constant then

$$\frac{R}{C_V} \frac{dV}{V-b} + \frac{dT}{T} = 0, \quad \text{or,} \quad \ln T + \frac{R}{C_V} \ln (V-b) = \text{constant}$$

$$\text{or,} \quad T(V-b)^{R/C_V} = \text{constant}$$

(b) We use

$$dU = C_V dT + \frac{a}{V^2} dV$$

$$\text{Now,} \quad dQ = C_V dT + \frac{RT}{V-b} dV$$

$$\text{So along constant } p, \quad C_p = C_V + \frac{RT}{V-b} \left( \frac{\partial V}{\partial T} \right)_p$$

$$\text{Thus} \quad C_p - C_V = \frac{RT}{V-b} \left( \frac{\partial V}{\partial T} \right)_p, \quad \text{But } p = \frac{RT}{V-b} - \frac{a}{V^2}$$

$$\text{On differentiating, } 0 = \left( -\frac{RT}{(V-b)^2} + \frac{2a}{V^3} \right) \left( \frac{\partial V}{\partial T} \right)_p + \frac{R}{V-b}$$

$$\text{or,} \quad T \left( \frac{\partial V}{\partial T} \right)_p = \frac{RT/V-b}{\frac{RT}{(V-b)^2} - \frac{2a}{V^3}} = \frac{V-b}{1 - \frac{2a(V-b)^2}{RTV^3}}$$

$$\text{and} \quad C_p - C_V = \frac{R}{1 - \frac{2a(V-b)^2}{RTV^3}}$$

## 2.60 From the first law

$$Q = U_f - U_i + A = 0, \quad \text{as the vessels are themally insulated.}$$

$$\text{As this is free expansion, } A = 0, \quad \text{so, } U_f = U_i$$

$$\text{But} \quad U = \nu C_V T - \frac{a\nu^2}{V}$$

$$\text{So,} \quad C_V(T_f - T_i) = \left( \frac{a}{V_1 + V_2} - \frac{a}{V_1} \right) \nu = \frac{-aV_2\nu}{V_1(V_1 + V_2)}$$

$$\text{or,} \quad \Delta T = \frac{-a(\gamma - 1)V_2\nu}{RV_1(V_1 + V_2)}$$

Substitution gives  $\Delta T = -3 \text{ K}$

## 2.61 $Q = U_f - U_i + A = U_f - U_i$ , (as $A = 0$ in free expansion).

So at constant temperature.

$$Q = \frac{-a\nu^2}{V_2} - \left( -\frac{a\nu^2}{V_1} \right) = a\nu^2 \frac{V_2 - V_1}{V_1 \cdot V_2}$$

$$= 0.33 \text{ kJ from the given data.}$$

## 2.3 KINETIC THEORY OF GASES. BOLTZMANN'S LAW AND MAXWELL'S DISTRIBUTION

**2.62** From the formula  $p = nkT$

$$n = \frac{p}{kT} = \frac{4 \times 10^{-15} \times 1.01 \times 10^5}{1.38 \times 10^{-23} \times 300} \text{ per m}^3$$

$$= 1 \times 10^{11} \text{ per m}^3 = 10^5 \text{ per c.c.}$$

Mean distance between molecules

$$(10^{-5} \text{ c.c.})^{1/3} = 10^{1/3} \times 10^{-2} \text{ cm} = 0.2 \text{ mm.}$$

**2.63** After dissociation each  $N_2$  molecule becomes two  $N$ -atoms and so contributes,  $2 \times 3$  degrees of freedom. Thus the number of moles becomes

$$\frac{m}{M}(1 + \eta) \text{ and } p = \frac{mRT}{MV}(1 + \eta)$$

Here  $M$  is the molecular weight in grams of  $N_2$ .

**2.64** Let  $n_1$  = number density of  $He$  atoms,  $n_2$  = number density of  $N_2$  molecules

Then

$$\rho = n_1 m_1 + n_2 m_2$$

where  $m_1$  = mass of  $He$  atom,  $m_2$  = mass of  $N_2$  molecule also  $p = (n_1 + n_2) kT$

From these two equations we get

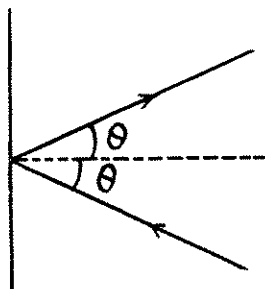
$$n_1 = \left( \frac{p}{kT} - \frac{\rho}{m_2} \right) / \left( 1 - \frac{m_1}{m_2} \right)$$

**2.65** 
$$p = \frac{nv \times 2mv \cos \theta \times dA \cos \theta}{dA}$$

$$= 2mnv^2 \cos^2 \theta$$

**2.66** From the formula

$$v = \sqrt{\frac{\gamma p}{\rho}}, \quad \gamma = \frac{\rho v^2}{p}$$



If  $i$  = number of degrees of freedom of the gas then

$$C_p = C_v + RT \text{ and } C_v = \frac{i}{2} RT$$

$$\gamma = \frac{C_p}{C_v} = 1 + \frac{2}{i} \text{ or } i = \frac{2}{\gamma - 1} = \frac{2}{\frac{\rho v^2}{p} - 1}$$

**2.67** 
$$v_{\text{sound}} = \sqrt{\frac{\gamma p}{\rho}} = \sqrt{\frac{\gamma RT}{M}}, \text{ and } v_{\text{rms}} = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3RT}{M}}$$

so,

$$\frac{v_{\text{sound}}}{v_{\text{rms}}} = \sqrt{\frac{\gamma}{3}} = \sqrt{\frac{i+2}{3i}}$$



(a) For monoatomic gases  $i = 3$

$$\frac{v_{\text{sound}}}{v_{\text{rms}}} = \sqrt{\frac{5}{9}} = 0.75$$

(b) For rigid diatomic molecules  $i = 5$

$$\frac{v_{\text{sound}}}{v_{\text{rms}}} = \sqrt{\frac{7}{15}} = 0.68$$

**2.68** For a general noncollinear, nonplanar molecule

$$\begin{aligned} \text{mean energy} &= \frac{3}{2} kT \text{ (translational)} + \frac{3}{2} kT \text{ (rotational)} + (3N - 6) kT \text{ (vibrational)} \\ &= (3N - 3) kT \text{ per molecule} \end{aligned}$$

$$\text{For linear molecules, mean energy} = \frac{3}{2} kT \text{ (translational)}$$

$$+ kT \text{ (rotational)} + (3N - 5) kT \text{ (vibrational)}$$

$$= \left(3N - \frac{5}{2}\right) kT \text{ per molecule}$$

Translational energy is a fraction  $\frac{1}{2(N-1)}$  and  $\frac{1}{2N - \frac{5}{2}}$  in the two cases.

**2.69** (a) A diatomic molecule has 3 translational, 2 rotational and one vibrational degrees of freedom. The corresponding energy per mole is

$$\frac{3}{2} RT, \text{ (for translational)} + 2 \times \frac{1}{2} RT, \text{ (for rotational)}$$

$$+ 1 \times RT, \text{ (for vibrational)} = \frac{7}{2} RT$$

$$\text{Thus, } C_V = \frac{7}{2} R, \text{ and } \gamma = \frac{C_P}{C_V} = \frac{9}{7}$$

(b) For linear  $N$ -atomic molecules energy per mole

$$= \left(3N - \frac{5}{2}\right) RT \text{ as before}$$

$$\text{So, } C_V = \left(3N - \frac{5}{2}\right) R \text{ and } \gamma = \frac{6N - 3}{6N - 5}$$

(c) For noncollinear  $N$ -atomic molecules

$$C_V = 3(N - 1) R \text{ as before (2.68)} \quad \gamma = \frac{3N - 2}{3N - 3} = \frac{N - 2/3}{N - 1}$$

**2.70** In the isobaric process, work done is

$$A = pdv = RdT \text{ per mole.}$$

On the other hand heat transferred  $Q = C_P dT$

Now  $C_P = (3N - 2) R$  for non-collinear molecules and  $C_P = \left(3N - \frac{3}{2}\right) R$  for linear molecules



Thus 
$$\frac{A}{Q} = \begin{cases} \frac{1}{3N-2} & \text{non collinear} \\ \frac{1}{3N-\frac{3}{2}} & \text{linear} \end{cases}$$

For monoatomic gases,  $c_p = \frac{5}{2}$  and  $\frac{A}{Q} = \frac{2}{5}$

2.71 Given specific heats  $c_p$ ,  $c_v$  (per unit mass)

$$M(c_p - c_v) = R \quad \text{or,} \quad M = \frac{R}{c_p - c_v}$$

Also 
$$\gamma = \frac{c_p}{c_v} = \frac{2}{i} + 1, \quad \text{os,} \quad i = \frac{2}{\frac{c_p}{c_v} - 1} = \frac{2c_v}{c_p - c_v}$$

2.72 (a)  $C_p = 29 \frac{J}{^\circ\text{K mole}} = \frac{29}{8.3} R$

$$C_v = \frac{20.7}{8.3} R, \quad \gamma = \frac{29}{20.7} = 1.4 = \frac{7}{5}$$

$$i = 5$$

(b) In the process  $pT = \text{const.}$

$$\frac{T^2}{V} = \text{const,} \quad \text{So} \quad 2 \frac{dT}{T} - \frac{dV}{V} = 0$$

Thus 
$$CdT = C_v dT + p dV = C_v dT + \frac{RT'}{V} dV = C_v dT + \frac{2RT}{T} dT$$

or 
$$C = C_v + 2R = \left(\frac{29}{8.3}\right) R \quad \text{So} \quad C_v = \frac{12.4}{8.3} R = \frac{3}{2} R$$

Hence  $i = 3$  (monoatomic)

2.73 Obviously

$$\frac{1}{R} C_v = \frac{3}{2} \gamma_1 + \frac{5}{2} \gamma_2$$

(Since a monoatomic gas has  $C_v = \frac{3}{2} R$  and a diatomic gas has  $C_v = \frac{5}{2} R$ . [The diatomic molecule is rigid so no vibration])

$$\frac{1}{R} C_p = \frac{3}{2} \gamma_1 + \frac{5}{2} \gamma_2 + \gamma_1 + \gamma_2$$

Hence 
$$\gamma = \frac{C_p}{C_v} = \frac{5\gamma_1 + 7\gamma_2}{3\gamma_1 + 5\gamma_2}$$

2.74 The internal energy of the molecules are

$$U = \frac{1}{2} m N \langle (\vec{u} - \vec{v})^2 \rangle = \frac{1}{2} m N \langle u^2 - v^2 \rangle$$

where  $\vec{v}$  = velocity of the vessel,  $N$  = number of molecules, each of mass  $m$ . When the vessel is stopped, internal energy becomes  $\frac{1}{2} mN \langle u^2 \rangle$

So there is an increase in internal energy of  $\Delta U = \frac{1}{2} mN v^2$ . This will give rise to a rise in temperature of

$$\Delta T = \frac{\frac{1}{2} mN v^2}{\frac{i}{2} R} = \frac{mN v^2}{iR}$$

there being no flow of heat. This change of temperature will lead to an excess pressure

$$\Delta p = \frac{R \Delta T}{V} = \frac{mN v^2}{iV}$$

and finally 
$$\frac{\Delta p}{p} = \frac{M v^2}{i R T} = 2.2 \%$$

where  $M$  = molecular weight of  $N_2$ ,  $i$  = number of degrees of freedom of  $N_2$

**2.75 (a)** From the equipartition theorem

$$\bar{\epsilon} = \frac{3}{2} k T = 6 \times 10^{-21} \text{ J}; \text{ and } v_{rms} = \sqrt{\frac{3 k T}{m}} = \sqrt{\frac{3 R T}{M}} = 0.47 \text{ km/s}$$

(b) In equilibrium the mean kinetic energy of the droplet will be equal to that of a molecule.

$$\frac{1}{2} \frac{\pi}{6} d^3 \rho v_{rms}^2 = \frac{3}{2} k T \quad \text{or} \quad v_{rms} = 3 \sqrt{\frac{2 k T}{\pi d^3 \rho}} = 0.15 \text{ m/s}$$

**2.76** Here  $i = 5$ ,  $C_V = \frac{5}{2} R$ ,  $\gamma = \frac{7}{5}$  given

$$v'_{rms} = \sqrt{\frac{3 R T}{M}} = \frac{1}{\eta} v_{rms} = \frac{1}{\eta} \sqrt{\frac{3 R T}{M}} \quad \text{or} \quad T = \frac{1}{\eta^2} T$$

Now in an adiabatic process

$$T V^{\gamma-1} = T V^{2/i} = \text{constant} \quad \text{or} \quad V T^{i/2} = \text{constant}$$

$$V' \left( \frac{1}{\eta^2} T \right)^{i/2} = V T^{i/2} \quad \text{or} \quad V' \eta^{-i} = V \quad \text{or} \quad V' = \eta^i V$$

The gas must be expanded  $\eta^i$  times, i.e. 7.6 times.

**2.77** Here  $C_V = \frac{5}{2} \frac{m}{M} R$  ( $i = 5$  here)

$m$  = mass of the gas,  $M$  = molecular weight. If  $v_{rms}$  increases  $\eta$  times, the temperature will have increased  $\eta^2$  times. This will require (neglecting expansion of the vessels) a heat flow of amount

$$\frac{5}{2} \frac{m}{M} R (\eta^2 - 1) T = 10 \text{ kJ.}$$

2.78 The root mean square angular velocity is given by

$$\frac{1}{2} I \omega^2 = 2 \times \frac{1}{2} k T \quad (2 \text{ degrees of rotations})$$

$$\text{or} \quad \omega = \sqrt{\frac{2kT}{I}} = 6.3 \times 10^{12} \text{ rad/s}$$

2.79 Under compression, the temperature will rise

$$TV^{\gamma-1} = \text{constant}, \quad TV^{2/i} = \text{constant}$$

$$\text{or,} \quad T (\eta^{-1} V_0)^{2/i} = T_0 V_0^{2/i} \quad \text{or,} \quad T = \eta^{+2/i} T_0$$

So mean kinetic energy of rotation per molecule in the compressed state

$$= kT = kT_0 \eta^{2/i} = 0.72 \times 10^{-20} \text{ J}$$

2.80 No. of collisions =  $\frac{1}{4} n \langle v \rangle = \nu$

$$\text{Now,} \quad \frac{\nu'}{\nu} = \frac{n' \langle v' \rangle}{n \langle v \rangle} = \frac{1}{\eta} \sqrt{\frac{T'}{T}}$$

(When the gas is expanded  $\eta$  times,  $n$  decreases by a factor  $\eta$ ). Also

$$T' (\eta V)^{2/i} = TV^{2/i} \quad \text{or} \quad T' = \eta^{2/i} T \quad \text{so,} \quad \frac{\nu'}{\nu} = \frac{1}{\eta} \eta^{-1/i} = \eta^{-\frac{i+1}{i}}$$

i.e. collisions decrease by a factor  $\eta^{-\frac{i+1}{i}}$ ,  $i = 5$  here.

2.81 In a polytropic process  $pV^n = \text{constant}$ , where  $n$  is called the polytropic index. For this process

$$pV^n = \text{constant or } TV^{n-1} = \text{constant}$$

$$\frac{dT}{T} + (n-1) \frac{dV}{V} = 0$$

$$\text{Then} \quad dQ = C dT = dU + p dV = C_v dT + p dV$$

$$= \frac{i}{2} R dT + \frac{RT}{V} dV = \frac{i}{2} R dT - \frac{1}{n-1} R dT = \left( \frac{i}{2} - \frac{1}{n-1} \right) R dT$$

$$\text{Now} \quad C = R \quad \text{so} \quad \frac{i}{2} - \frac{1}{n-1} = 1$$

$$\text{or,} \quad \frac{1}{n-1} = \frac{i}{2} - 1 = \frac{i-2}{2} \quad \text{or} \quad n = \frac{i}{i-2}$$

$$\text{Now} \quad \frac{\nu'}{\nu} = \frac{n' \langle v' \rangle}{n \langle v \rangle} = \frac{1}{\eta} \sqrt{\frac{T'}{T}} = \frac{1}{\eta} \left( \frac{V}{V'} \right)^{\frac{n-1}{2}}$$

$$= \frac{1}{\eta} \left( \frac{1}{\eta} \right)^{\frac{1}{i-2}} = \left( \frac{1}{\eta} \right)^{\frac{i-1}{i-2}} = \eta^{-\frac{i-1}{i-2}} \text{ times} = \frac{1}{2.52} \text{ times}$$

2.82 If  $\alpha$  is the polytropic index then

$$pV^\alpha = \text{constant}, TV^{\alpha-1} = \text{constant}.$$

$$\text{Now } \frac{v'}{v} = \frac{n'}{n} \frac{\langle v' \rangle}{\langle v \rangle} = \frac{V}{V'} \sqrt{\frac{T'}{T}} = \frac{VT^{-1/2}}{V' T'^{-1/2}} = 1$$

$$\text{Hence } \frac{1}{\alpha-1} = -\frac{1}{2} \quad \text{or} \quad \alpha = -1$$

$$\text{Then } C = \frac{iR}{2} + \frac{R}{2} = 3R$$

$$2.83 \quad v_p = \sqrt{\frac{2kT}{m}} = \sqrt{\frac{2RT}{M}} = \sqrt{\frac{2p}{\rho}} = 0.45 \text{ km/s},$$

$$v_{av} = \sqrt{\frac{8p}{\pi\rho}} = 0.51 \text{ km/s} \quad \text{and} \quad v_{rms} = \sqrt{\frac{3p}{\rho}} = 0.55 \text{ km/s}$$

2.84 (a) The formula is

$$df(u) = \frac{4}{\sqrt{\pi}} u^2 e^{-u^2} du, \quad \text{where } u = \frac{v}{v_p}$$

$$\begin{aligned} \text{Now Prob} \left( \left| \frac{v - v_p}{v_p} \right| < \delta \eta \right) &= \int_{1-\delta\eta}^{1+\delta\eta} df(u) \\ &= \frac{4}{\sqrt{\pi}} e^{-1} \times 2\delta\eta = \frac{8}{\sqrt{\pi} e} \delta\eta = 0.0166 \end{aligned}$$

$$\begin{aligned} \text{(b) Prob} \left( \left| \frac{v - v_{rms}}{v_{rms}} \right| < \delta \eta \right) &= \text{Prob} \left( \left| \frac{v}{v_p} - \frac{v_{rms}}{v_p} \right| < \delta \eta \frac{v_{rms}}{v_p} \right) \\ &= \text{Prob} \left( \left| u - \sqrt{\frac{3}{2}} \right| < \sqrt{\frac{3}{2}} \delta \eta \right) \\ &= \int_{\sqrt{\frac{3}{2}} - \sqrt{\frac{3}{2}} \delta \eta}^{\sqrt{\frac{3}{2}} + \sqrt{\frac{3}{2}} \delta \eta} \frac{4}{\sqrt{\pi}} u^2 e^{-u^2} du \\ &= \frac{4}{\sqrt{\pi}} \times \frac{3}{2} e^{-3/2} \times 2 \sqrt{\frac{3}{2}} \delta \eta = \frac{12\sqrt{3}}{\sqrt{2}\pi} e^{-3/2} \delta \eta = 0.0185 \end{aligned}$$

$$2.85 \quad (a) \quad v_{rms} - v_p = (\sqrt{3} - \sqrt{2}) \sqrt{\frac{kT}{m}} = \Delta v,$$

$$T = \frac{m}{k} \left( \frac{\Delta v}{(\sqrt{3} - \sqrt{2})} \right)^2 / K = 384 \text{ K}$$

(b) Clearly  $v$  is the most probable speed at this temperature. So

$$\sqrt{\frac{2kT}{m}} = v \quad \text{or} \quad T = \frac{mv^2}{2k} = 342 \text{ K}$$

2.86 (a) We have,

$$\frac{v_1^2}{v_p^2} e^{-v_1^2/v_p^2} = \frac{v_2^2}{v_p^2} e^{-v_2^2/v_p^2} \quad \text{or} \quad \left( \frac{v_1}{v_2} \right)^2 = e^{v_1^2 - v_2^2 / v_p^2} \quad \text{or} \quad v_p^2 = \frac{2kT}{m} = \frac{v_1^2 - v_2^2}{(\ln v_1^2 / v_2^2)}$$

$$\text{So} \quad T = \frac{m(v_1^2 - v_2^2)}{2k \ln \frac{v_1^2}{v_2^2}} = 330 \text{ K}$$

$$(b) \quad F(v) = \frac{4}{\sqrt{\pi}} \frac{v^2}{v_p^2} e^{-v^2/v_p^2} \times \frac{1}{v_p} \left( \frac{1}{v_p} \text{ comes from } F(v) dv = df(u), du = \frac{dv}{v_p} \right)$$

$$\text{Thus} \quad \frac{v^2}{v_p^3} e^{-v^2/v_p^2} = \frac{v^2/v_{p_2}}{v_p^2} e^{-v^2/v_{p_2}^2} \quad v_{p_1}^2 = \frac{2kT_0}{m}, \quad v_{p_2}^2 = \frac{2kT_0}{m} \eta \quad \text{now}$$

$$e^{-\frac{mv^2}{2kT_0} \left( 1 - \frac{1}{\eta} \right)} = \frac{1}{\eta^{3/2}} \quad \text{or} \quad \frac{mv^2}{2kT_0} \left( 1 - \frac{1}{\eta} \right) = \frac{3}{2} \ln \eta$$

$$\text{Thus} \quad v = \sqrt{\frac{3kT_0}{m}} \sqrt{\frac{\ln \eta}{1 - 1/\eta}}$$

$$2.87 \quad v_{pN} = \sqrt{\frac{2kT}{m_N}} = \sqrt{\frac{2RT}{M_N}}, \quad v_{pO} = \sqrt{\frac{2RT}{M_O}}$$

$$v_{pN} - v_{pO} = \Delta v = \sqrt{\frac{2RT}{M_N}} \left( 1 - \sqrt{\frac{M_N}{M_O}} \right)$$

$$T = \frac{M_N (\Delta v)^2}{2R \left( 1 - \sqrt{\frac{M_N}{M_O}} \right)^2} = \frac{m_N (\Delta v)^2}{2k \left( 1 - \sqrt{\frac{m_N}{M_O}} \right)^2} = 363 \text{ K}$$

$$2.88 \quad \frac{v^2}{v_{pH}^3} e^{-v^2/v_{pH}^2} = \frac{v^2}{v_{pHe}^3} e^{-v^2/v_{pHe}^2} \quad \text{or} \quad e^{v^2 \left( \frac{m_{He}}{2kT} - \frac{m_H}{2kT} \right)} = \left( \frac{m_{He}}{m_H} \right)^{3/2}$$

$$v^2 = 3kT \frac{\ln m_{He} / m_H}{m_{He} - m_H}, \quad \text{Putting the values we get } v = 1.60 \text{ km/s}$$

$$2.89 \quad dN(v) = \frac{N}{\sqrt{\pi}} \frac{v^2 dv}{v_p^3} e^{-v^2/v_p^2}$$

For a given range  $v$  to  $v + dv$  (i.e. given  $v$  and  $dv$ ) this is maximum when

$$\frac{\delta}{\delta v_p} \frac{dN(v)}{N v^2 dv} = 0 = \left( -3v_p^{-4} + \frac{2v^2}{v_p^6} \right) e^{-v^2/v_p^2}$$

or, 
$$v^2 = \frac{3}{2} v_p^2 = \frac{3kT}{m}. \quad \text{Thus } T = \frac{1}{3} \frac{mv^2}{k}$$

$$2.90 \quad d^3 v = 2\pi v_{\perp} dv_{\perp} dv_x$$

Thus 
$$dn(v) = N \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-\frac{m}{2kT} (v_x^2 + v_{\perp}^2)} dv_x 2\pi v_{\perp} dv_{\perp}$$

$$2.91 \quad \langle v_x \rangle = 0 \text{ by symmetry}$$

$$\begin{aligned} \langle |v_x| \rangle &= \int_{-\infty}^{\infty} |v_x| e^{-\frac{mv_x^2}{2kT}} dv_x / \int_0^{\infty} e^{-\frac{mv_x^2}{2kT}} dv_x = \int_0^{\infty} v_x e^{-\frac{mv_x^2}{2kT}} dv_x / \int_0^{\infty} e^{-\frac{mv_x^2}{2kT}} dv_x \\ &= \sqrt{\frac{2kT}{m}} \int_0^{\infty} u e^{-u^2} du / \int_0^{\infty} e^{-u^2} du \\ &= \sqrt{\frac{2kT}{m}} \int_0^{\infty} \frac{1}{2} e^{-x} dx / \int_0^{\infty} e^{-x} \frac{dx}{2\sqrt{x}} \\ &= \sqrt{\frac{2kT}{m}} \Gamma(1) / \Gamma\left(\frac{1}{2}\right) = \sqrt{\frac{2kT}{m\pi}} \end{aligned}$$

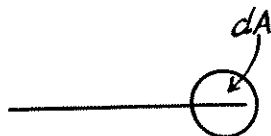
$$\begin{aligned} 2.92 \quad \langle v_x^2 \rangle &= \int_0^{\infty} v_x^2 e^{-\frac{mv_x^2}{2kT}} dv_x / \int_0^{\infty} e^{-\frac{mv_x^2}{2kT}} dv_x \\ &= \frac{2kT}{m} \int_0^{\infty} x e^{-x} \frac{dx}{2\sqrt{x}} / \int_0^{\infty} e^{-x} \frac{dx}{2\sqrt{x}} \\ &= \frac{2kT}{m} \Gamma\left(\frac{3}{2}\right) / \Gamma\left(\frac{1}{2}\right) = \frac{kT}{m} \end{aligned}$$

2.93 Here  $v dA$  = No. of molecules hitting an area  $dA$  of the wall per second

$$= \int_0^{\infty} dN(v_x) v_x dA$$

or,

$$\begin{aligned}
 v &= \int_0^{\infty} n \left( \frac{m}{2\pi kT} \right)^{1/2} e^{-\frac{mv_x^2}{2kT}} v_x dv_x \\
 &= \int_0^{\infty} \frac{n}{\sqrt{\pi}} \left( \frac{2kT}{m} \right)^{1/2} e^{-u^2} u du \\
 &= \frac{1}{2} n \sqrt{\frac{2kT}{m\pi}} = n \sqrt{\frac{kT}{2m\pi}} = \frac{1}{4} n \langle v \rangle, \\
 &\quad \left( \text{where } \langle v \rangle = \sqrt{\frac{8kT}{m\pi}} \right)
 \end{aligned}$$



2.94 Let,  $dn(v_x) = n \left( \frac{m}{2\pi kT} \right)^{1/2} e^{-mv_x^2/2kT} dv_x$

be the number of molecules per unit volume with  $x$  component of velocity in the range  $v_x$  to  $v_x + dv_x$

Then

$$\begin{aligned}
 p &= \int_0^{\infty} 2mv_x \cdot v_x dn(v_x) \\
 &= \int_0^{\infty} 2mv_x^2 n \left( \frac{m}{2\pi kT} \right)^{1/2} e^{-mv_x^2/2kT} dv_x \\
 &= 2mn \frac{1}{\sqrt{\pi}} \frac{2kT}{m} \int_0^{\infty} u^2 e^{-u^2} du \\
 &= \frac{4}{\sqrt{\pi}} nkT \cdot \int_0^{\infty} x e^{-x} \frac{dx}{2\sqrt{x}} = nkT
 \end{aligned}$$

2.95  $\langle \frac{1}{v} \rangle = \int_0^{\infty} \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-\frac{mv^2}{2kT}} 4\pi v^2 dv \frac{1}{v}$

$$\begin{aligned}
 &= \left( \frac{m}{2\pi kT} \right)^{3/2} 4\pi \frac{1}{2} \frac{2kT}{m} \int_0^{\infty} e^{-x} dx \\
 &= 2 \left( \frac{m}{2\pi kT} \right)^{1/2} = \left( \frac{2m}{\pi kT} \right)^{1/2} = \left( \frac{16}{\pi^2} \frac{m\pi}{8kT} \right)^{1/2} = \frac{4}{\pi \langle v \rangle}
 \end{aligned}$$



$$2.96 \quad dN(v) = N \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-mv^2/2kT} 4\pi v^2 dv = dN(\epsilon) = \frac{dN(\epsilon)}{d\epsilon} d\epsilon$$

$$\text{or,} \quad \frac{dN(\epsilon)}{d\epsilon} = N \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-mv^2/2kT} 4\pi v^2 \frac{dv}{d\epsilon}$$

$$\text{Now,} \quad \epsilon = \frac{1}{2}mv^2 \quad \text{so} \quad \frac{dv}{d\epsilon} = \frac{1}{mv}$$

$$\begin{aligned} \text{or,} \quad \frac{dN(\epsilon)}{d\epsilon} &= N \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-\epsilon/kT} 4\pi \sqrt{\frac{2\epsilon}{m}} \frac{1}{m} \\ &= N \frac{2}{\sqrt{\pi}} (kT)^{-3/2} e^{-\epsilon/kT} \epsilon^{1/2} \end{aligned}$$

$$\text{i.e.} \quad dN(\epsilon) = N \frac{2}{\sqrt{\pi}} (kT)^{-3/2} e^{-\epsilon/kT} \epsilon^{1/2} d\epsilon$$

The most probable kinetic energy is given from

$$\frac{d}{d\epsilon} \frac{dN(\epsilon)}{d\epsilon} = 0 \quad \text{or,} \quad \frac{1}{2} \epsilon^{-1/2} e^{-\epsilon/kT} - \frac{\epsilon^{1/2}}{kT} e^{-\epsilon/kT} = 0 \quad \text{or} \quad \epsilon = \frac{1}{2} kT = \epsilon_{pr}$$

The corresponding velocity is  $v = \sqrt{\frac{kT}{m}} = v_{pr}$

2.97 The mean kinetic energy is

$$\langle \epsilon \rangle = \frac{\int_0^{\infty} \epsilon^{3/2} e^{-\epsilon/kT} d\epsilon}{\int_0^{\infty} \epsilon^{1/2} e^{-\epsilon/kT} d\epsilon} = kT \frac{\Gamma(5/2)}{\Gamma(3/2)} = \frac{3}{2} kT$$

Thus

$$\begin{aligned} &\frac{3}{2} (1 + \delta\eta) kT \\ \frac{\delta N}{N} &= \frac{\int \frac{2}{\sqrt{\pi}} (kT)^{-3/2} e^{-\epsilon/kT} \epsilon^{1/2} d\epsilon}{\frac{3}{2} kT (1 - \delta\eta)} \\ &= \frac{2}{\sqrt{\pi}} e^{-3/2} \left( \frac{3}{2} \right)^{3/2} 2 \delta\eta = 3 \sqrt{\frac{6}{\pi}} e^{3/2} \delta\eta \end{aligned}$$

If  $\delta\eta = 1\%$  this gives  $0.9\%$

$$2.98 \quad \frac{\Delta N}{N} = \frac{2}{\sqrt{\pi}} (kT)^{-3/2} \int_{\epsilon_0}^{\infty} \sqrt{\epsilon} e^{-\epsilon/kT} d\epsilon$$

$$\approx \frac{2}{\sqrt{\pi}} (kT)^{-3/2} \sqrt{\epsilon_0} \int_{\epsilon_0}^{\infty} e^{-\epsilon/kT} d\epsilon \quad (\epsilon_0 \gg kT)$$

$$= \frac{2}{\sqrt{\pi}} (kT)^{-3/2} \sqrt{\epsilon_0} kT e^{-\epsilon_0/kT} = 2 \sqrt{\frac{\epsilon_0}{\pi kT}} e^{-\epsilon_0/kT}$$

(In evaluating the integral, we have taken out  $\sqrt{\epsilon}$  as  $\sqrt{\epsilon_0}$  since the integral is dominated by the lower limit.)

2.99 (a)  $F(v) = Av^3 e^{-mv^2/2kT}$

For the most probable value of the velocity

$$\frac{dF(v)}{dv} = 0 \quad \text{or} \quad 3Av^2 e^{-mv^2/2kT} - Av^3 \frac{2mv}{2kT} e^{-mv^2/2kT} = 0$$

So, 
$$v_{pr} = \sqrt{\frac{3kT}{m}}$$

This should be compared with the value  $v_{pr} = \sqrt{\frac{2kT}{m}}$  for the Maxwellian distribution.

(b) In terms of energy,  $\epsilon = \frac{1}{2}mv^2$

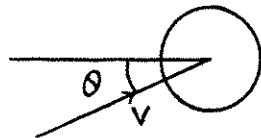
$$\begin{aligned} F(\epsilon) &= Av^3 e^{-mv^2/2kT} \frac{dv}{d\epsilon} \\ &= A \left( \frac{2\epsilon}{m} \right)^{3/2} e^{-\epsilon/kT} \frac{1}{\sqrt{2m\epsilon}} = A \frac{2\epsilon}{m^2} e^{-\epsilon/kT} \end{aligned}$$

From this the probable energy comes out as follows :  $F'(\epsilon) = 0$  implies

$$\frac{2A}{m^2} \left( e^{-\epsilon/kT} - \frac{\epsilon}{kT} e^{-\epsilon/kT} \right) = 0, \quad \text{or,} \quad \epsilon_{pr} = kT$$

2.100 The number of molecules reaching a unit area of wall at angle between  $\theta$  and  $\theta + d\theta$  to its normal per unit time is

$$\begin{aligned} dv &= \int_{v=0}^{v=\infty} dn(v) \frac{d\Omega}{4\pi} v \cos \theta \\ &= \int_0^\infty n \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-mv^2/2kT} v^3 dv \sin \theta \cos \theta d\theta \times 2\pi \\ &= n \left( \frac{2kT}{m\pi} \right)^{1/2} \int_0^\infty e^{-x} x dx \sin \theta \cos \theta d\theta = n \left( \frac{2kT}{m\pi} \right)^{1/2} \sin \theta \cos \theta d\theta \end{aligned}$$



2.101 Similarly the number of molecules reaching the wall (per unit area of the wall with velocities in the interval  $v$  to  $v + dv$  per unit time is

$$\begin{aligned} dv &= \int_{\theta=0}^{\theta=\pi/2} dn(v) \frac{d\Omega}{4\pi} v \cos \theta \end{aligned}$$

$$\begin{aligned}
 \theta = \pi/2 \\
 &= \int_{\theta=0}^{\pi/2} n \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-mv^2/2kT} v^3 dv \sin\theta \cos\theta d\theta \times 2\pi \\
 &= n\pi \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-mv^2/2kT} v^3 dv
 \end{aligned}$$

**2.102** If the force exerted is  $F$  then the law of variation of concentration with height reads

$$n(Z) = n_0 e^{-FZ/kT} \quad \text{So, } \eta = e^{F\Delta h/kT} \quad \text{or } F = \frac{kT \ln \eta}{\Delta h} = 9 \times 10^{-20} \text{ N}$$

**2.103** Here  $F = \frac{\pi}{6} d^3 \Delta \rho g = \frac{RT \ln \eta}{N_a h}$  or  $N_a = \frac{6RT \ln \eta}{\pi d^3 g \Delta \rho h}$

In the problem,  $\frac{\eta}{\eta_0} = 1.39$  here

$T = 290\text{K}$ ,  $\eta = 2$ ,  $h = 4 \times 10^{-5} \text{ m}$ ,  $d = 4 \times 10^{-7} \text{ m}$ ,  $g = 9.8 \text{ m/s}^2$ ,  $\Delta \rho = 0.2 \times 10^3 \text{ kg/m}^3$  and  $R = 8.31 \text{ J/k}$

$$\text{Hence, } N_a = \frac{6 \times 8.31 \times 290 \times \ln 2}{\pi \times 64 \times 9.8 \times 200 \times 4} \times 10^{26} = 6.36 \times 10^{23} \text{ mole}^{-1}$$

**2.104**  $\eta = \frac{\text{concentration of } H_2}{\text{concentration of } N_2} = \eta_0 \frac{e^{-M_{H_2} gh/RT}}{e^{-M_{N_2} gh/RT}} = \eta_0 e^{(M_{N_2} - M_{H_2}) gh/RT}$

So more  $N_2$  at the bottom,  $\left( \frac{\eta}{\eta_0} = 1.39 \text{ here} \right)$

**2.105**  $n_1(h) = n_1 e^{-m_1 gh/kT}$ ,  $n_2(h) = n_2 e^{-m_2 gh/kT}$

They are equal at a height  $h$  where  $\frac{n_1}{n_2} = e^{gh(m_1 - m_2)/kT}$

$$\text{or } h = \frac{kT \ln n_1 - \ln n_2}{g(m_1 - m_2)}$$

**2.106** At a temperature  $T$  the concentration  $n(z)$  varies with height according to

$$n(z) = n_0 e^{-mgz/kT}$$

This means that the cylinder contains  $\int_0^\infty n(z) dz$

$$= \int_0^\infty n_0 e^{-mgz/kT} dz = \frac{n_0 kT}{mg}$$

particles per unit area of the base. Clearly this cannot change. Thus  $n_0 kT = p_0 =$  pressure at the bottom of the cylinder must not change with change of temperature.

$$2.107 \quad \langle U \rangle = \frac{\int_0^{\infty} mgz e^{-mgz/kT} dz}{\int_0^{\infty} e^{-mgz/kT} dz} = kT \frac{\int_0^{\infty} x e^{-x} dx}{\int_0^{\infty} e^{-x} dx} = kT \frac{\Gamma(2)}{\Gamma(1)} = kT$$

When there are many kinds of molecules, this formula holds for each kind and the average energy

$$\langle U \rangle = \frac{\sum f_i kT}{\sum f_i} = kT$$

where  $f_i \propto$  fractional concentration of each kind at the ground level.

2.108 The constant acceleration is equivalent to a pseudo force wherein a concentration gradient is set up. Then

$$e^{-M_A w l / RT} = 1 - \eta$$

or 
$$w = -\frac{RT \ln(1 - \eta)}{M_A l} = \frac{\eta RT}{M_A l} = 70 \text{ g}$$

2.109 In a centrifuge rotating with angular velocity  $\omega$  about an axis, there is a centrifugal acceleration  $\omega^2 r$  where  $r$  is the radial distance from the axis. In a fluid if there are suspended colloidal particles they experience an additional force. If  $m$  is the mass of each particle then its volume is  $\frac{m}{\rho}$  and the excess force on this particle is

$$\frac{m}{\rho} (\rho - \rho_0) \omega^2 r \text{ outward corresponding to a potential energy } -\frac{m}{2\rho} (\rho - \rho_0) \omega^2 r^2$$

This gives rise to a concentration variation

$$n(r) = n_0 \exp \left( + \frac{m}{2\rho kT} (\rho - \rho_0) \omega^2 r^2 \right)$$

Thus 
$$\frac{n(r_2)}{n(r_1)} = \eta = \exp \left( + \frac{M}{2\rho RT} (\rho - \rho_0) \omega^2 (r_2^2 - r_1^2) \right)$$

where 
$$\frac{m}{k} = \frac{M}{R}, \quad M = N_A m \text{ is the molecular weight}$$

Thus 
$$M = \frac{2\rho RT \ln \eta}{(\rho - \rho_0) \omega^2 (r_2^2 - r_1^2)}$$

2.110 The potential energy associated with each molecule is :  $-\frac{1}{2} m \omega^2 r^2$

and there is a concentration variation

$$n(r) = n_0 \exp \left( \frac{m \omega^2 r^2}{2kT} \right) = n_0 \exp \left( \frac{M \omega^2 r^2}{2RT} \right)$$

Thus 
$$\eta = \exp \left( \frac{M \omega^2 l^2}{2RT} \right) \quad \text{or} \quad \omega = \sqrt{\frac{2RT}{M l^2} \ln \eta}$$

Using  $M = 12 + 32 = 44$  gm,  $l = 100$  cm,  $R = 8.31 \times 10^7 \frac{\text{erg}}{^\circ\text{K}}$ ,  $T = 300$ , we get  $\omega = 280$  radians per second.

2.111 Here  $n(r) = n_0 \exp\left(-\frac{ar^2}{kT}\right)$

(a) The number of molecules located at the distance between  $r$  and  $r + dr$  is

$$4\pi r^2 dr n(r) = 4\pi n_0 \exp\left(-\frac{ar^2}{kT}\right) r^2 dr$$

(b)  $r_{pr}$  is given by  $\frac{d}{dr} r^2 n(r) = 0$  or,  $2r - \frac{2ar^3}{kT} = 0$  or  $r_{pr} = \sqrt{\frac{kT}{a}}$

(c) The fraction of molecules lying between  $r$  and  $r + dr$  is

$$\begin{aligned} \frac{dN}{N} &= \frac{4\pi r^2 dr n_0 \exp(-ar^2/kT)}{\int_0^\infty 4\pi r^2 dr n_0 \exp(-ar^2/kT)} \\ &= \frac{\int_0^\infty 4\pi r^2 dr \exp\left(-\frac{ar^2}{kT}\right)}{\int_0^\infty 4\pi r^2 dr \exp\left(-\frac{ar^2}{kT}\right)} = \left(\frac{kT}{a}\right)^{3/2} 4\pi \int_0^\infty x \frac{dx}{2\sqrt{x}} \exp(-x) \\ &= \left(\frac{kT}{a}\right)^{3/2} 2\pi \Gamma\left(\frac{3}{2}\right) = \left(\frac{\pi kT}{a}\right)^{3/2} \end{aligned}$$

Thus  $\frac{dN}{N} = \left(\frac{a}{\pi kT}\right)^{3/2} 4\pi r^2 dr \exp\left(-\frac{ar^2}{kT}\right)$

(d)  $dN = N \left(\frac{a}{\pi kT}\right)^{3/2} 4\pi r^2 dr \exp\left(-\frac{ar^2}{kT}\right)$

So  $n(r) = N \left(\frac{a}{\pi kT}\right)^{1/2} \exp\left(-\frac{ar^2}{kT}\right)$

When  $T$  decreases  $\eta$  times  $n(0) = n_0$  will increase  $\eta^{3/2}$  times.

2.112 Write  $U = ar^2$  or  $r = \sqrt{\frac{U}{a}}$ , so  $dr = \sqrt{\frac{1}{a}} \frac{dU}{2\sqrt{U}} = \frac{dU}{2\sqrt{aU}}$

so  $dN = n_0 4\pi \frac{U}{a} \frac{dU}{2\sqrt{aU}} \exp\left(\frac{U}{kT}\right)$

$= 2\pi n_0 a^{-3/2} U^{1/2} \exp\left(\frac{-U}{kT}\right) dU$

The most probable value of  $U$  is given by

$$\frac{d}{dU} \left( \frac{dN}{dU} \right) = 0 = \left( \frac{1}{2\sqrt{u}} - \frac{U^{1/2}}{kT} \right) \exp\left(\frac{-U}{kT}\right) \text{ or, } U_{pr} = \frac{1}{2} kT$$

From 2.111 (b), the potential energy at the most probable distance is  $kT$ .

## 2.4 THE SECOND LAW OF THERMODYNAMICS. ENTROPY

2.113 The efficiency is given by

$$\eta = \frac{T_1 - T_2}{T_1}, \quad T_1 > T_2$$

Now in the two cases the efficiencies are

$$\eta_h = \frac{T_1 + \Delta T - T_2}{T_1 + \Delta T}, \quad T_1 \text{ increased}$$

$$\eta_l = \frac{T_1 - T_2 + \Delta T}{T_1}, \quad T_2 \text{ decreased}$$

Thus

$$\eta_h < \eta_l$$

2.114 For  $H_2$ ,  $\gamma = \frac{7}{5}$

$$p_1 V_1 = p_2 V_2, \quad p_3 V_3 = p_4 V_4$$

$$p_2 V_2^\gamma = p_3 V_3^\gamma, \quad p_1 V_1^\gamma = p_4 V_4^\gamma$$

Define  $n$  by  $V_3 = n V_2$

Then  $p_3 = p_2 n^{-\gamma}$  so

$$p_4 V_4 = p_3 V_3 = p_2 V_2 n^{1-\gamma} = p_1 V_1 n^{1-\gamma}$$

$$p_4 V_4^\gamma = p_1 V_1^\gamma \text{ so } V_4^{1-\gamma} = V_1^{1-\gamma} n^{1-\gamma} \text{ or } V_4 = n V_1$$

$$\text{Also } Q_1 = p_2 V_2 \ln \frac{V_2}{V_1}, \quad Q'_2 = p_3 V_3 \ln \frac{V_3}{V_4} n^{1-\gamma} = p_2 V_2 \ln \frac{V_3}{V_4}$$

$$\text{Finally } \eta = 1 - \frac{Q_2}{Q_1} = 1 - n^{1-\gamma} = 0.242$$

(b) Define  $n$  by  $p_3 = \frac{p_2}{n}$

$$p_2 V_2^\gamma = \frac{p_2}{n} V_3^\gamma \text{ or } V_3 = n^{1/\gamma} V_2$$

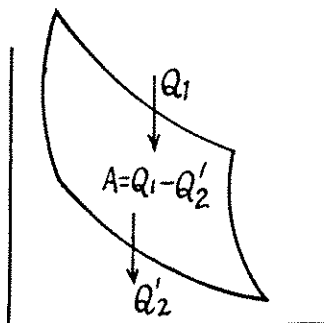
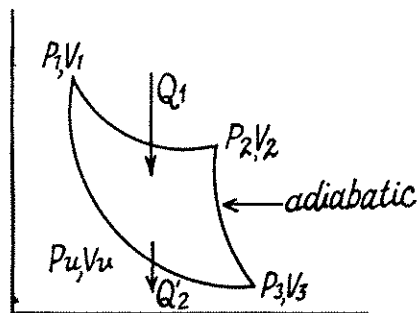
So we get the formulae here by  $n \rightarrow n^{1/\gamma}$  in the previous case.

$$\eta = 1 - n^{(1/\gamma)-1} = 1 - n^{-2/7} \approx 0.18$$

2.115 Used as a refrigerator, the refrigerating efficiency of a heat engine is given by

$$\epsilon = \frac{Q'_2}{A} = \frac{Q'_2}{Q_1 - Q'_2} = \frac{Q'_2/Q_1}{1 - Q'_2/Q_1} = \frac{1 - \eta}{\eta} = 9 \text{ here,}$$

where  $\eta$  is the efficiency of the heat engine.



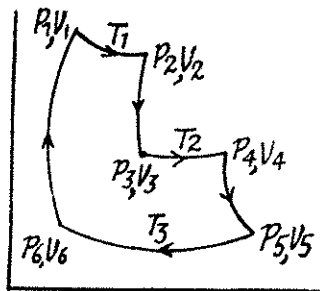
2.116 Given  $V_2 = n V_1$ ,  $V_4 = n V_3$

$Q_1 =$  Heat taken at the upper temperature

$$= RT_1 \ln n + R T_2 \ln n = R (T_1 + T_2) \ln n$$

Now  $T_1 V_2^{\gamma-1} = T_2 V_3^{\gamma-1}$  or  $V_3 = \left(\frac{T_1}{T_2}\right)^{\frac{1}{\gamma-1}} V_2$

Similarly  $V_5 = \left(\frac{T_2}{T_3}\right)^{\frac{1}{\gamma-1}} V_4$ ,  $V_6 = \left(\frac{T_1}{T_3}\right)^{\frac{1}{\gamma-1}} V_1$



Thus  $Q_2 =$  heat ejected at the lower temperature  $= -RT_3 \ln \frac{V_6}{V_5}$

$$= -R T_3 \ln \left(\frac{T_1}{T_2}\right)^{\frac{1}{\gamma-1}} \frac{V_1}{V_4} = -R T_3 \ln \left(\frac{T_1}{T_2}\right)^{\frac{1}{\gamma-1}} \frac{V_2}{n^2 V_3}$$

$$= -R T_3 \ln \left(\frac{T_1}{T_2}\right)^{\frac{1}{\gamma-1}} \frac{1}{n^2} \left(\frac{T_1}{T_2}\right)^{-\frac{1}{\gamma-1}} = 2 R T_3 \ln n$$

Thus  $\eta = 1 - \frac{2T_3}{T_1 + T_2}$

2.117  $Q'_2 = C_V (T_2 - T_3) = \frac{C_V}{R} V_2 (p_2 - p_3)$

$$Q_1 = \frac{C_V}{R} V_1 (p_1 - p_4)$$

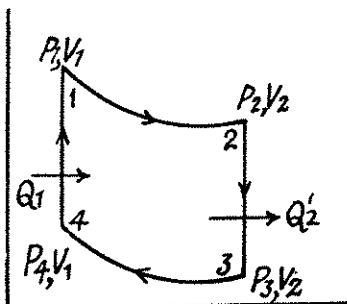
Thus  $\eta = 1 - \frac{V_2 (p_2 - p_3)}{V_1 (p_1 - p_4)}$

On the other hand,

$$6p_1 V_1^\gamma = p_2 V_2^\gamma, \quad p_3 V_2^\gamma = p_4 V_1^\gamma \text{ also } V_2 = n V_1$$

Thus  $p_1 = p_2 n^\gamma$ ,  $p_4 = p_3 n^\gamma$

and  $\eta = 1 - n^{1-\gamma}$ , with  $\gamma = \frac{7}{5}$  for  $N_2$  this is  $\eta = 0.602$



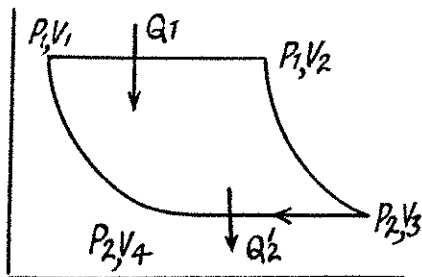
2.118  $Q_1 = \frac{C_p}{R} p_1 (V_2 - V_1)$ ,  $Q'_2 = \frac{C_p}{R} p_2 (V_3 - V_4)$

So  $\eta = 1 - \frac{p_2 (V_3 - V_4)}{p_1 (V_2 - V_1)}$

Now  $p_1 = n p_2$ ,  $p_1 V_2^\gamma = p_2 V_3^\gamma$  or  $V_3 = n^{\frac{1}{\gamma}} V_2$

$p_2 V_4^\gamma = p_1 V_1^\gamma$  or  $V_4 = n^{\frac{1}{\gamma}} V_1$

so  $\eta = 1 - \frac{1}{n} \cdot \frac{1}{n^{\frac{1}{\gamma}}} = 1 - n^{\frac{1}{\gamma}-1}$



- 2.119 Since the absolute temperature of the gas rises  $n$  times both in the isochoric heating and in the isobaric expansion

$$p_1 = np_2 \text{ and } V_2 = nV_1. \text{ Heat taken is}$$

$$Q_1 = Q_{11} + Q_{12}$$

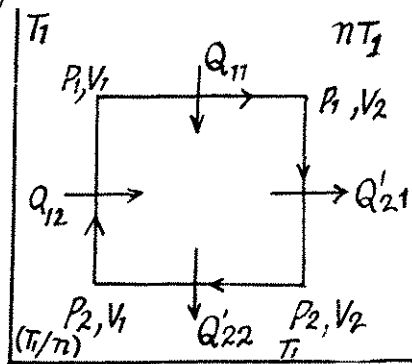
$$\text{where } Q_{11} = C_p(n-1)T_1 \text{ and } Q_{12} = C_v T_1 \left(1 - \frac{1}{n}\right)$$

Heat rejected is

$$Q'_2 = Q'_{21} + Q'_{22} \text{ where}$$

$$Q'_{21} = C_v T_1(n-1), \quad Q'_{22} = C_p T_1 \left(1 - \frac{1}{n}\right)$$

$$\begin{aligned} \text{Thus } \eta &= 1 - \frac{Q'_2}{Q_1} = 1 - \frac{C_v(n-1) + C_p \left(1 - \frac{1}{n}\right)}{C_p(n-1) + C_v \left(1 - \frac{1}{n}\right)} \\ &= 1 - \frac{n-1+\gamma \left(1 - \frac{1}{n}\right)}{\gamma(n-1) + \left(1 - \frac{1}{n}\right)} = 1 - \frac{1 + \frac{\gamma}{n}}{\gamma + \frac{1}{n}} = 1 - \frac{n+\gamma}{1+n\gamma} \end{aligned}$$



- 2.120 (a) Here  $p_2 = np_1$ ,  $p_1 V_1 = p_0 V_0$ ,

$$np_1 V_1^\gamma = p_0 V_0^\gamma$$

$$Q'_2 = RT_0 \ln \frac{V_0}{V_1}, \quad Q_1 = C_v T_0(n-1)$$

$$\text{But } nV_1^{\gamma-1} = V_0^{\gamma-1} \text{ or, } V_1 = V_0 n^{\frac{-1}{\gamma-1}}$$

$$Q'_2 = RT_0 \ln n^{\frac{1}{\gamma-1}} = \frac{RT_0}{\gamma-1} \ln n$$

$$\text{Thus } \eta = 1 - \frac{\ln n}{n-1}, \text{ on using } C_v = \frac{R}{\gamma-1}$$

- (b) Here  $V_2 = nV_1$ ,  $p_1 V_1 = p_0 V_0$

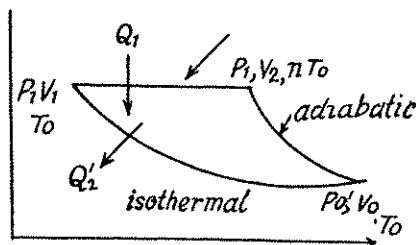
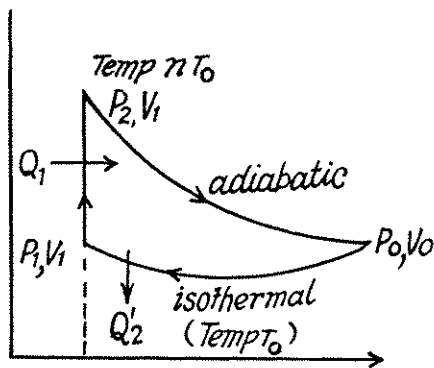
$$\text{and } p_1 (nV_1)^\gamma = p_0 V_0^\gamma$$

$$\text{i.e. } n^\gamma V_1^{\gamma-1} = V_0^{\gamma-1} \text{ or } V_1 = n^{-\frac{\gamma}{\gamma-1}} V_0$$

$$\text{Also } Q_1 = C_p T_0(n-1), \quad Q'_2 = RT_0 \ln \frac{V_0}{V_1}$$

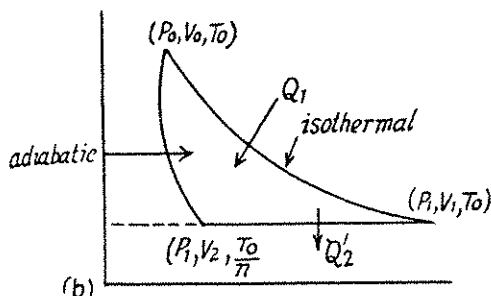
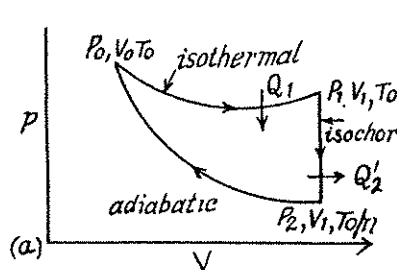
$$\text{or } Q'_2 = RT_0 \ln n^{\frac{\gamma}{\gamma-1}} = \frac{R\gamma}{\gamma-1} T_0 \ln n = C_p T_0 \ln n$$

$$\text{Thus } \eta = 1 - \frac{\ln n}{n-1}$$





**2.121** Here the isothermal process proceeds at the maximum temperature instead of at the minimum temperature of the cycle as in 2.120.



(a) Here  $p_1 V_1 = p_0 V_0$ ,  $p_2 = \frac{p_1}{n}$

$$p_2 V_1^\gamma = p_0 V_0^\gamma \quad \text{or} \quad p_1 V_1^\gamma = n p_0 V_0^\gamma$$

i.e.  $V_1^{\gamma-1} = n V_0^{\gamma-1} \quad \text{or} \quad V_1 = V_0 n^{\frac{1}{\gamma-1}}$

$$Q_2' = C_V T_0 \left(1 - \frac{1}{n}\right), \quad Q_1 = RT_0 \ln \frac{V_1}{V_0} = \frac{RT_0}{\gamma-1} \ln n = C_V T_0 \ln n.$$

Thus  $\eta = 1 - \frac{Q_2'}{Q_1} = 1 - \frac{n-1}{n \ln n}$

(b) Here  $V_2 = \frac{V_1}{n}$ ,  $p_0 V_0 = p_1 V_1$

$$p_0 V_0^\gamma = p_1 V_2^\gamma = p_1 n^{-\gamma} V_1^\gamma = V_0^{\gamma-1} n^{-\gamma} V_1^{\gamma-1} \quad \text{or} \quad V_1 = n^{(\gamma-1)} V_0$$

$$Q_2' = C_p T_0 \left(1 - \frac{1}{n}\right), \quad Q_1 = RT_0 \ln \frac{V_1}{V_0} = \frac{R\gamma}{\gamma-1} T_0 \ln n = C_p T_0 \ln n$$

Thus  $\eta = 1 - \frac{n-1}{n \ln n}$

**2.122** The section from  $(p_1, V_1, T_0)$  to  $(p_2, V_2, T_0/n)$  is a polytropic process of index  $\alpha$ . We shall assume that the corresponding specific heat  $C$  is +ve.

Here,  $dQ = CdT = C_V dT + p dV$

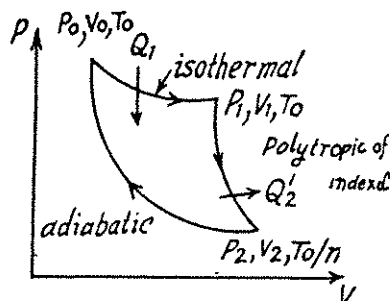
Now  $pV^\alpha = \text{constant}$  or  $TV^{\alpha-1} = \text{constant}$ .

$$\text{so } p dV = \frac{RT}{V} dV = -\frac{R}{\alpha-1} dT$$

$$\text{Then } C = C_V - \frac{R}{\alpha-1} = R \left( \frac{1}{\gamma-1} - \frac{1}{\alpha-1} \right)$$

We have  $p_1 V_1 = RT_0 = p_2 V_2 = \frac{RT_0}{n} = \frac{p_1 V_1}{n}$

$$p_0 V_0 = p_1 V_1 = n p_2 V_2, \quad p_0 V_0^\gamma = p_2 V_2^\gamma,$$



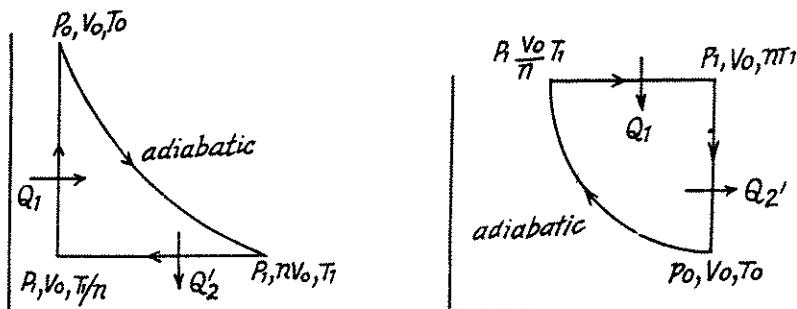
$$P_1 V_1^\alpha = P_2 V_2^\alpha \quad \text{or} \quad V_0^{\gamma-1} = \frac{1}{n} V_2^{\gamma-1} \quad \text{or} \quad V_2 = V_0 n^{\frac{1}{\gamma-1}}$$

$$V_1^{\alpha-1} = \frac{1}{n} V_2^{\alpha-1} \quad \text{or} \quad V_1 = n^{-\frac{1}{\alpha-1}} V_2 = n^{\frac{1}{\gamma-1} - \frac{1}{\alpha-1}} V_0$$

$$\text{Now } Q'_2 = CT_0 \left(1 - \frac{1}{n}\right), \quad Q_1 = RT_0 \ln \frac{V_1}{V_0} = RT_0 \left(\frac{1}{\gamma-1} - \frac{1}{\alpha-1}\right) \ln n = CT_0 \ln n$$

$$\text{Thus} \quad \eta = 1 - \frac{n-1}{n \ln n}$$

2.123



$$(a) \quad \text{Here } Q'_2 = C_p \left(T_1 - \frac{T_1}{n}\right) = C_p T_1 \left(1 - \frac{1}{n}\right), \quad Q_1 = C_v \left(T_0 - \frac{T_1}{n}\right)$$

Along the adiabatic line

$$T_0 V_0^{\gamma-1} = T_1 (n V_0)^{\gamma-1} \quad \text{or} \quad T_0 = T_1 n^{\gamma-1}$$

$$\text{so} \quad Q_1 = C_v \frac{T_1}{n} (n^\gamma - 1). \quad \text{Thus} \quad \eta = 1 - \frac{\gamma(n-1)}{n^{\gamma-1}}$$

$$(b) \quad \text{Here } Q'_2 = C_v (n T_1 - T_0), \quad Q_1 = C_p \cdot T_1 (n-1)$$

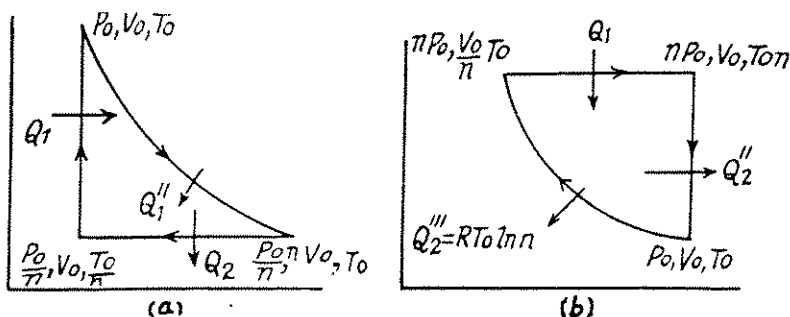
Along the adiabatic line  $TV^{\gamma-1} = \text{constant}$

$$T_0 V_0^{\gamma-1} = T_1 \left(\frac{V_0}{n}\right)^{\gamma-1} \quad \text{or} \quad T_1 = n^{\gamma-1} T_0$$

Thus

$$\eta = 1 - \frac{n^\gamma - 1}{\gamma n^{\gamma-1} (n-1)}$$

2.124



$$(a) \quad Q'_2 = C_p T_0 \left(1 - \frac{1}{n}\right), \quad Q''_1 = RT_0 \ln n, \quad Q'_1 = C_v T_0 \left(1 - \frac{1}{n}\right), \quad Q_1 = Q'_1 + Q''_1$$

$$\begin{aligned} \text{So} \quad \eta &= 1 - \frac{Q'_2}{Q_1} = 1 - \frac{C_p \left(1 - \frac{1}{n}\right)}{C_v \left(1 - \frac{1}{n}\right) + R \ln n} \\ &= 1 - \frac{\gamma}{1 + \frac{R}{C_v} \frac{n \ln n}{n-1}} = 1 - \frac{\gamma(n-1)}{n-1 + (\gamma-1)n \ln n} \end{aligned}$$

$$(b) \quad Q_1 = C_p T_0 (n-1), \quad Q''_2 = C_v T_0 (n-1), \quad Q'''_2 = RT_0 \ln n, \quad Q'_2 = Q''_2 + Q'''_2$$

$$\text{So} \quad \eta = 1 - \frac{Q'_2}{Q_1} = 1 - \frac{n-1 + (\gamma-1) \ln n}{\gamma(n-1)}$$

**2.125** We have

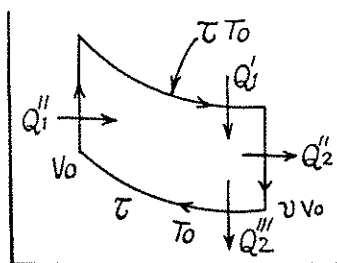
$$Q'_1 = \tau RT_0 \ln v, \quad Q''_2 = C_v T_0 (\tau - 1), \quad Q_1 = Q'_1 + Q''_1 \text{ and}$$

$$Q'''_2 = RT_0 \ln v, \quad Q''_1 = C_v T_0 (\tau - 1)$$

as well as  $Q_1 = Q'_1 + Q''_1$  and

$$Q'_2 = Q''_2 + Q'''_2$$

$$\begin{aligned} \text{So} \quad \eta &= 1 - \frac{Q'_2}{Q_1} + 1 = \frac{C_v (\tau - 1) + R \ln v}{C_v (\tau - 1) + \tau R \ln v} \\ &= 1 - \frac{\frac{\tau-1}{\gamma-1} + \ln v}{\frac{\tau-1}{\gamma-1} + \tau \ln v} = \frac{(\tau-1) \ln v}{\tau \ln v + \frac{\tau-1}{\gamma-1}} \end{aligned}$$



**2.126** Here  $Q_1'' = C_p T_0 (\tau - 1)$ ,  $Q_1' = \tau RT_0 \ln n$  and

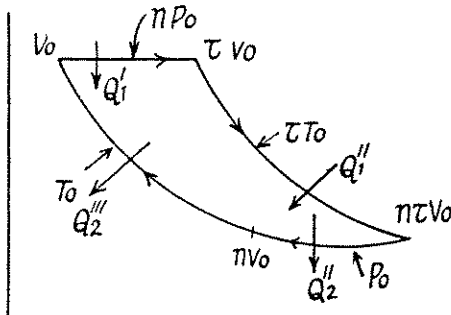
$$Q_2'' = C_p T_0 (\tau - 1), \quad Q_2''' = RT_0 \ln n$$

in addition to we have

$$Q_1 = Q_1' + Q_1'' \text{ and}$$

$$Q_2' = Q_2'' + Q_2'''$$

$$\begin{aligned} \text{So} \quad \eta &= 1 - \frac{Q'_2}{Q_1} = 1 - \frac{C_p (\tau - 1) + R \ln n}{C_p (\tau - 1) + \tau R \ln n} \\ &= 1 - \frac{\tau - 1 + \left(1 - \frac{1}{\gamma}\right) \ln n}{\tau - 1 + \left(1 - \frac{1}{\gamma}\right) \tau \ln n} \\ &= 1 - \frac{\tau - 1 + \left(1 - \frac{1}{\gamma}\right) \ln n}{\tau - 1 + \left(1 - \frac{1}{\gamma}\right) \tau \ln n} = \frac{(\tau - 1) \ln n}{\tau \ln n + \frac{\gamma(\tau - 1)}{\gamma - 1}} \end{aligned}$$



**2.127** Because of the linearity of the section

$BC$  whose equation is

$$\frac{P}{P_0} = \frac{vV}{V_0} \quad (= P = \alpha V)$$

We have  $\frac{\tau}{v} = v$  or  $v = \sqrt{\tau}$

Here  $Q''_2 = C_V T_0 (\sqrt{\tau} - 1)$ ,

$$Q'''_2 = C_P T_0 \left(1 - \frac{1}{\sqrt{\tau}}\right) = C_P \frac{T_0}{\sqrt{\tau}} (\sqrt{\tau} - 1)$$

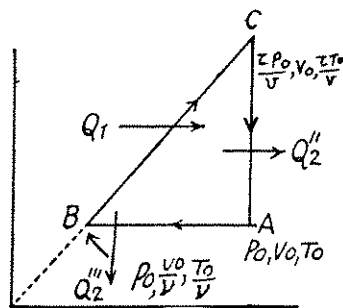
$$\text{Thus } Q'_2 = Q''_2 + Q'''_2 = \frac{RT_0}{\gamma - 1} (\sqrt{\tau} - 1) \left(1 + \frac{\gamma}{\sqrt{\tau}}\right)$$

Along  $BC$ , the specific heat  $C$  is given by

$$CdT = C_V dT + PdV = C_V dT + d\left(\frac{1}{2} \alpha V^2\right) = \left(C_V + \frac{1}{2} R\right) dT$$

$$\text{Thus } Q_1 = \frac{1}{2} R T_0 \frac{\gamma + 1}{\gamma - 1} \frac{\tau - 1}{\sqrt{\tau}}$$

$$\text{Finally } \eta = 1 - \frac{Q'_2}{Q_1} = 1 - 2 \frac{\sqrt{\tau} + \gamma}{\sqrt{\tau} + 1} \frac{1}{\gamma + 1} = \frac{(\gamma - 1)(\sqrt{\tau} - 1)}{(\gamma + 1)(\sqrt{\tau} + 1)}$$



**2.128** We write Clausius inequality in the form

$$\int \frac{\delta_1 Q}{T} - \int \frac{\delta_2 Q}{T} \leq 0$$

where  $\delta_1 Q$  is the heat transferred to the system but  $\delta_2 Q$  is heat rejected by the system, both are +ve and this explains the minus sign before  $\delta_2 Q$ ,

In this inequality  $T_{\max} > T > T_{\min}$  and we can write

$$\int \frac{\delta_1 Q}{T_{\max}} - \int \frac{\delta_2 Q}{T_{\min}} < 0$$

$$\text{Thus } \frac{Q_1}{T_{\max}} < \frac{Q'_2}{T_{\min}} \quad \text{or} \quad \frac{T_{\min}}{T_{\max}} < \frac{Q'_2}{Q_1}$$

$$\text{or } \eta = 1 - \frac{Q'_2}{Q_1} < 1 - \frac{T_{\min}}{T_{\max}} = \eta_{\text{carnot}}$$

**2.129** We consider an infinitesimal carnot cycle with isothermal process at temperatures  $T + dT$  and  $T$ .

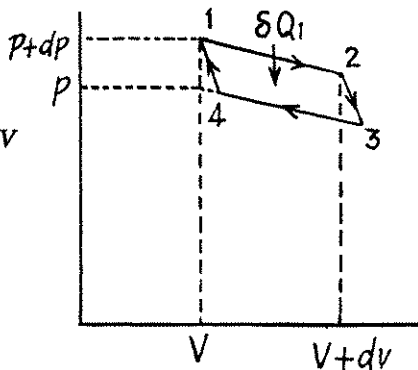
Let  $\delta A$  be the work done in the cycle and  $\delta Q$ , be the heat received at the higher temperature. Then by Carnot's theorem

$$\frac{\delta A}{\delta Q_1} = \frac{dT}{T}$$

On the other hand  $\delta A = dp dV = \left(\frac{\partial p}{\partial T}\right)_V dT dV$

while  $\delta Q_1 = dU_{12} + p dV = \left[\left(\frac{\partial U}{\partial V}\right)_T + p\right] dV$

Hence  $\left(\frac{\partial U}{\partial V}\right)_T + p = T \left(\frac{\partial p}{\partial T}\right)_V$



**2.130** (a) In an isochoric process the entropy change will be

$$\Delta S = \int_{T_i}^{T_f} \frac{C_V dT}{T} = C_V \ln \frac{T_f}{T_i} = C_V \ln n = \frac{R \ln n}{\gamma - 1}$$

For carbon dioxide  $\gamma = 1.30$

so,  $\Delta S = 19.2 \text{ Joule/}^\circ\text{K - mole}$

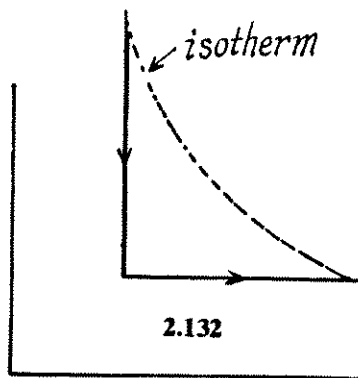
(b) For an isobaric process,

$$\begin{aligned} \Delta S &= C_p \ln \frac{T_f}{T_i} = C_p \ln n = \frac{\gamma R \ln n}{\gamma - 1} \\ &= 25 \text{ Joule/}^\circ\text{K - mole} \end{aligned}$$

**2.131** In an isothermal expansion

$$\Delta S = \nu R \ln \frac{V_f}{V_i}$$

so,  $\frac{V_f}{V_i} = e^{\Delta S/\nu R} = 2.0 \text{ times}$



**2.132** The entropy change depends on the final & initial states only, so we can calculate it directly along the isotherm, it is  $\Delta S = 2 R \ln n = 20 \text{ J/}^\circ\text{K}$

(assuming that the final volume is  $n$  times the initial volume)

**2.133** If the initial temperature is  $T_0$  and volume is  $V_0$  then in adiabatic expansion.

$$T V^{\gamma-1} = T_0 V_0^{\gamma-1}$$

so,  $T = T_0 n^{1-\gamma} = T_1 \text{ where } n = \frac{V_1}{V_0}$

$V_1$  being the volume at the end of the adiabatic process. There is no entropy change in this process. Next the gas is compressed isobarically and the net entropy change is

$$\Delta S = \left(\frac{m}{M} C_p\right) \ln \frac{T_f}{T_i}$$

But  $\frac{V_1}{T_1} = \frac{V_0}{T_f}$ , or  $T_f = T_1 \frac{V_0}{V_1} = T_0 n^{-\gamma}$

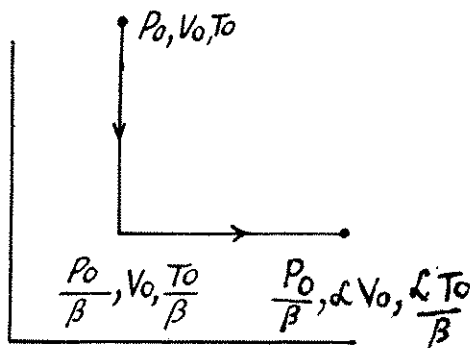
So  $\Delta S = \left( \frac{m}{M} C_p \right) \ln \frac{1}{n} = -\frac{m}{M} C_p \ln n = -\frac{m}{M} \frac{R\gamma}{\gamma-1} \ln n = -9.7 \text{ J/K}$

**2.134** The entropy change depends on the initial and final state only so can be calculated for any process whatsoever.

We choose to evaluate the entropy change along the pair of lines shown above. Then

$$\Delta S = \int_{T_0}^{\frac{T_0}{\beta}} \frac{\nu C_V dT}{T} + \int_{\frac{T_0}{\beta}}^{\frac{\alpha T_0}{\beta}} \nu C_p \frac{dT}{T}$$

$$= (-C_V \ln \beta + C_p \ln \alpha) \nu = \frac{\nu R}{\gamma-1} (\gamma \ln \alpha - \ln \beta) \approx -11 \frac{\text{Joule}}{^\circ\text{K}}$$



**2.135** To calculate the required entropy difference we only have to calculate the entropy difference for a process in which the state of the gas in vessel 1 is changed to that in vessel 2.

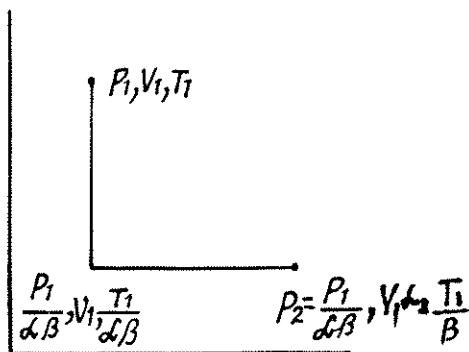
$$\Delta S = \nu \left( \int_{T_1}^{\frac{T_1}{\alpha\beta}} C_V \frac{dT}{T} + \int_{\frac{T_1}{\alpha\beta}}^{\frac{T_1}{\beta}} C_p \frac{dT}{T} \right)$$

$$= \nu (C_p \ln \alpha - C_V \ln \alpha\beta)$$

$$= \nu \left( R \ln \alpha - \frac{R}{\gamma-1} \ln \beta \right) = \nu R \left( \ln \alpha - \frac{\ln \beta}{\gamma-1} \right)$$

With  $\gamma = \frac{5}{3}$ ,  $\alpha = 2$  and  $\beta = 1.5$ ,  $\nu = 1.2$ ,

this gives  $\Delta S = 0.85 \text{ Joule/}^\circ\text{K}$



**2.136** For the polytropic process with index  $n$

$$p V^n = \text{constant}$$

Along this process (See 2.122)

$$C = R \left( \frac{1}{\gamma-1} - \frac{1}{n-1} \right) = \frac{n-\gamma}{(\gamma-1)(n-1)} \cdot R$$

So 
$$\Delta S = \int_{T_0}^{\tau T_0} C \frac{dT}{T} = \frac{n-\gamma}{(\gamma-1)(n-1)} R \ln \tau$$

2.137 The process in question may be written as

$$\frac{p}{p_0} = \alpha \frac{V}{V_0}$$

where  $\alpha$  is a constant and  $p_0, V_0$  are some reference values. For this process (see 2.127) the specific heat is

$$C = C_V + \frac{1}{2}R = R \left( \frac{1}{\gamma - 1} + \frac{1}{2} \right) = \frac{1}{2}R \frac{\gamma + 1}{\gamma - 1}$$

Along the line volume increases  $\alpha$  times then so does the pressure. The temperature must then increase  $\alpha^2$  times. Thus

$$\Delta S = \int_{T_0}^{\alpha^2 T_0} \frac{C_V dT}{T} = \frac{C_V}{T_0} \ln \alpha^2 = 2 C_V \ln \alpha$$

if  $\gamma = \frac{5}{3}, \alpha = 2, \Delta S = 46.1 \text{ Joule/}^\circ\text{K}$

2.138 Let  $(p_1, V_1)$  be a reference point on the line

$$p = p_0 - \alpha V$$

and let  $(p, V)$  be any other point.

The entropy difference

$$\Delta S = S(p, V) - S(p_1, V_1)$$

$$= C_V \ln \frac{p}{p_1} + C_P \ln \frac{V}{V_1} = C_V \ln \frac{p_0 - \alpha V}{p_0 - \alpha V_1} + C_P \ln \frac{V}{V_1}$$

For an extremum of  $\Delta S$

$$\frac{\partial \Delta S}{\partial V} = \frac{-\alpha C_V}{p_0 - \alpha V} + \frac{C_P}{V} = 0$$

$$\text{or } C_P(p_0 - \alpha V) - \alpha V C_V = 0$$

$$\text{or } \gamma(p_0 - \alpha V) - \alpha V = 0 \quad \text{or } V = V_m = \frac{\gamma p_0}{\alpha(\gamma + 1)}$$

This gives a maximum of  $\Delta S$  because  $\frac{\partial^2 \Delta S}{\partial V^2} < 0$

(Note :- a maximum of  $\Delta S$  is a maximum of  $S(p, V)$ )

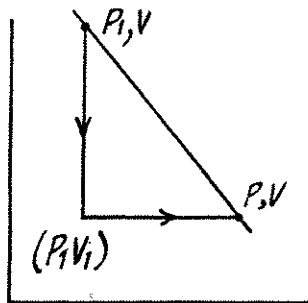
2.139 Along the process line :  $S = aT + C_V \ln T$

$$\text{or the specific heat is : } C = T \frac{dS}{dT} = aT + C_V$$

On the other hand :  $dQ = CdT = C_V dT + pdV$  for an ideal gas.

Thus,

$$pdV = \frac{RT}{V} dV = aT dT$$



or 
$$\frac{R}{a} \frac{dV}{V} = dT \quad \text{or,} \quad \frac{R}{a} \ln V + \text{constant} = T$$

Using  $T = T_0$  when  $V = V_0$ , we get,  $T = T_0 + \frac{R}{a} \ln \frac{V}{V_0}$

**2.140** For a Vander Waal gas

$$\left(p + \frac{a}{V^2}\right)(V - b) = RT$$

The entropy change along an isotherm can be calculated from

$$\Delta S = \int_{V_1}^{V_2} \left(\frac{\partial S}{\partial V}\right)_T dV$$

It follows from (2.129) that

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial p}{\partial T}\right)_V = \frac{R}{V - b}$$

assuming  $a, b$  to be known constants.

Thus 
$$\Delta S = R \ln \frac{V_2 - b}{V_1 - b}$$

**2.141** We use, 
$$\Delta S = \int_{V_1, T_1}^{V_2, T_2} dS(V, T) = \int_{T_1}^{T_2} \left(\frac{\partial S}{\partial T}\right)_{V_1} dT + \int_{V_1}^{V_2} \left(\frac{\partial S}{\partial V}\right)_{T=T_2} dV$$

$$= \int_{T_1}^{T_2} \frac{C_V dT}{T} + \int_{V_1}^{V_2} \frac{R}{V - b} dV = C_V \ln \frac{T_2}{T_1} + R \ln \frac{V_2 - b}{V_1 - b}$$

assuming  $C_V, a, b$  to be known constants.

**2.142** We can take  $S \rightarrow 0$  as  $T \rightarrow 0$  Then

$$S = \int_0^T C \frac{dT}{T} = \int_0^T aT^2 dT = \frac{1}{3} aT^3$$

**2.143** 
$$\Delta S = \int_{T_1}^{T_2} \frac{CdT}{T} = \int_{T_1}^{T_2} \frac{m(a + bT)}{T} dT = mb(T_2 - T_1) + ma \ln \frac{T_2}{T_1}$$



2.144 Here  $T = a S^n$  or  $S = \left(\frac{T}{a}\right)^{\frac{1}{n}}$

Then 
$$C = T \frac{1}{n} \frac{T^{\frac{1}{n}-1}}{a^{1/n}} = \frac{S}{n}$$

Clearly  $C < 0$  if  $n < 0$ .

2.145 We know,

$$S - S_0 = \int_{T_0}^T \frac{C dT}{T} = C \ln \frac{T}{T_0}$$

assuming  $C$  to be a known constant.

Then  $T = T_0 \exp \left( \frac{S - S_0}{C} \right)$

2.146 (a)  $C = T \frac{dS}{dT} = -\frac{\alpha}{T}$

(b)  $Q = \int_{T_1}^{T_2} C dT = \alpha \ln \frac{T_1}{T_2}$

(c)  $W = \Delta Q - \Delta U = \alpha \ln \frac{T_1}{T_2} + C_V (T_1 - T_2)$

Since for an ideal gas  $C_V$  is constant and  $\Delta U = C_V (T_2 - T_1)$

( $U$  does not depend on  $V$ )

2.147 (a) We have from the definition

$$Q = \int T dS = \text{area under the curve}$$

$$Q_1 = T_0 (S_1 - S_0)$$

$$Q'_2 = \frac{1}{2} (T_0 + T_1) (S_1 - S_0)$$

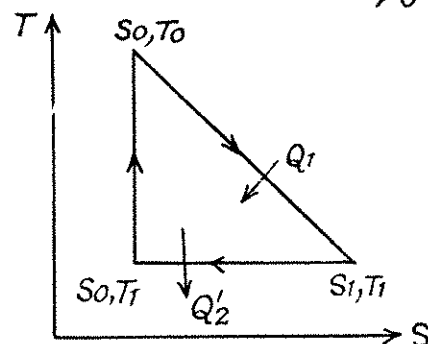
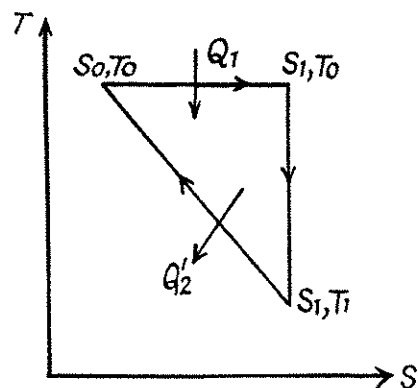
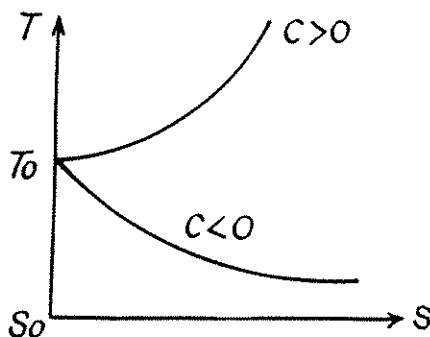
Thus, using  $T_1 = \frac{T_0}{n}$ ,

$$\eta = 1 - \frac{T_0 + T_1}{2 T_0} = 1 - \frac{1 + \frac{1}{n}}{2} = \frac{n-1}{2n}$$

(b) Here  $Q_1 = \frac{1}{2} (S_1 - S_0) (T_1 + T_0)$

$$Q'_2 = T_1 (S_1 - S_0)$$

$$\eta = 1 - \frac{2 T_1}{T_1 + T_0} = \frac{T_0 - T_1}{T_0 - T_1} = \frac{n-1}{n+1}$$



- 2.148** In this case, called free expansion no work is done and no heat is exchanged. So internal energy must remain unchanged  $U_f = U_i$ . For an ideal gas this implies constant temperature  $T_f = T_i$ . The process is irreversible but the entropy change can be calculated by considering a reversible isothermal process. Then, as before

$$\Delta S = \int_{T_i}^{T_f} \frac{dQ}{T} = \int_{V_i}^{V_f} \frac{pdV}{T} = \nu R \ln n = 20.1 \text{ J/K}$$

- 2.149** The process consists of two parts. The first part is free expansion in which  $U_f = U_i$ . The second part is adiabatic compression in which work done results in change of internal energy. Obviously,

$$0 = U_F - U_f + \int_{V_f}^{V_0} pdV, \quad V_f = 2V_0$$

Now in the first part  $p_f = \frac{1}{2}p_0$ ,  $V_f = 2V_0$ , because there is no change of temperature.

In the second part,  $pV^\gamma = \frac{1}{2}p_0(2V_0)^\gamma = 2^{\gamma-1}p_0V_0^\gamma$

$$\begin{aligned} \int_{2V_0}^{V_0} pdV &= \int_{2V_0}^{V_0} \frac{2^{\gamma-1}p_0V_0^\gamma}{V^\gamma} dV = \left[ \frac{2^{\gamma-1}p_0V_0^\gamma}{-\gamma+1} V^{1-\gamma} \right]_{2V_0}^{V_0} \\ &= 2^{\gamma-1}p_0V_0^\gamma V_0^{-\gamma+1} \frac{2^{-\gamma+1}-1}{\gamma-1} = -\frac{(2^{\gamma-1}-1)}{\gamma-1} RT \end{aligned}$$

Thus 
$$\Delta U = U_F - U_i = \frac{RT_0}{\gamma-1} (2^{\gamma-1} - 1)$$

The entropy change  $\Delta S = \Delta S_I + \Delta S_{II}$

$\Delta S_I = R \ln 2$  and  $\Delta S_{II} = 0$  as the process is reversible adiabatic. Thus  $\Delta S = R \ln 2$ .

- 2.150** In all adiabatic processes

$$Q = U_f - U_i + A = 0$$

by virtue of the first law of thermodynamics. Thus,

$$U_f = U_i - A$$

For a slow process,  $A' = \int_{V_0}^V pdV$  where for a quasistatic adiabatic process  $pV^\gamma = \text{constant}$ .

On the other hand for a fast process the external work done is  $A'' < A'$ . In fact  $A'' = 0$  for free expansion. Thus  $U'_f (\text{slow}) < U''_f (\text{fast})$

Since  $U$  depends on temperature only,  $T'_f < T''_f$

Consequently,  $p''_f > p'_f$

(From the ideal gas equation  $pV = RT$ )

2.151 Let  $V_1 = V_0$ ,  $V_2 = n V_0$

Since the temperature is the same, the required entropy change can be calculated by considering isothermal expansion of the gas in either parts into the whole vessel.

$$\begin{aligned}\text{Thus } \Delta S &= \Delta S_I + \Delta S_{II} = \nu_1 R \ln \frac{V_1 + V_2}{V_1} + \nu_2 R \ln \frac{V_1 + V_2}{V_2} \\ &= \nu_1 R \ln (1 + n) + \nu_2 R \ln \frac{1 + n}{n} = 5.1 \text{ J/K}\end{aligned}$$

2.152 Let  $c_1 =$  specific heat of copper specific heat of water  $= c_2$

$$\text{Then } \Delta S = \int_{T_0}^{97+273} \frac{c_2 m_2 dT}{T} - \int_{T_0}^{370} \frac{m_1 c_1 dT}{T} = m_2 c_2 \ln \frac{T_0}{280} - m_1 c_1 \ln \frac{370}{T_0}$$

$T_0$  is found from

$$c_2 m_2 (T_0 - 280) = m_1 c_1 (370 - T_0) \quad \text{or} \quad T_0 = \frac{280 m_2 c_2 + 370 m_1 c_1}{c_2 m_2 + m_1 c_1}$$

using  $c_1 = 0.39 \text{ J/g } ^\circ\text{K}$ ,  $c_2 = 4.18 \text{ J/g } ^\circ\text{K}$ ,

$$T_0 = 300^\circ\text{K} \text{ and } \Delta S = 28.4 - 24.5 = 3.9 \text{ J } ^\circ\text{K}$$

2.153 For an ideal gas the internal energy depends on temperature only. We can consider the process in question to be one of simultaneous free expansion. Then the total energy  $U = U_1 + U_2$ . Since

$U_1 = C_V T_1$ ,  $U_2 = C_V T_2$ ,  $U = 2C_V \frac{T_1 + T_2}{2}$  and  $(T_1 + T_2)/2$  is the final temperature. The entropy change is obtained by considering isochoric processes because in effect, the gas remains confined to its vessel.

$$\Delta S = \int_{T_1}^{(T_1+T_2)/2} \frac{C_V dT}{T} - \int_{T_2}^{(T_1+T_2)/2} \frac{C_V dT}{T} = C_V \ln \frac{(T_1 + T_2)^2}{4 T_1 T_2}$$

Since  $(T_1 + T_2)^2 = (T_1 - T_2)^2 + 4 T_1 T_2$ ,  $\Delta S > 0$

2.154 (a) Each atom has a probability  $\frac{1}{2}$  to be in either compartment. Thus

$$P = 2^{-N}$$

(b) Typical atomic velocity at room temperature is  $\sim 10^5 \text{ cm/s}$  so it takes an atom  $10^{-5} \text{ sec}$  to cross the vessel. This is the relevant time scale for our problem. Let  $T = 10^{-5} \text{ sec}$ , then in time  $t$  there will be  $t/T$  crossing or arrangements of the atoms. This will be large enough to produce the given arrangement if

$$\frac{t}{T} 2^{-N} \sim 1 \quad \text{or} \quad N \sim \frac{\ln t/T}{\ln 2} \sim 75$$

2.155 The statistical weight is

$$N_{C_{N/2}} = \frac{N!}{N/2! \frac{N}{2}!} = \frac{10 \times 9 \times 8 \times 7 \times 6}{8 \times 4 \times 3 \times 2} = 252$$

The probability distribution is

$$N_{C_{N/2}} 2^{-N} = 252 \times 2^{-10} = 24.6 \%$$

2.156 The probabilities that the half A contains  $n$  molecules is

$$N_{C_n} \times 2^{-N} = \frac{N!}{n! (N-n)!} 2^{-N}$$

2.157 The probability of one molecule being confined to the marked volume is

$$p = \frac{V}{V_0}$$

We can choose this molecule in many ( $N_{C_1}$ ) ways. The probability that  $n$  molecules get confined to the marked volume is clearly

$$N_{C_n} p^n (1-p)^{N-n} = \frac{N!}{n! (N-n)!} p^n (1-p)^{N-n}$$

2.158 In a sphere of diameter  $d$  there are

$$N = \frac{\pi d^3}{6} n_0 \quad \text{molecules}$$

where  $n_0$  = Loschmidt's number = No. of molecules per unit volume (1 cc) under NTP.

The relative fluctuation in this number is

$$\frac{\partial N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}} = \eta$$

$$\text{or } \frac{1}{\eta^2} = \frac{\pi}{6} d^3 n_0 \quad \text{or } d^3 = \frac{6}{\pi n_0 \eta^2} \quad \text{or } d = \left( \frac{6}{\pi \eta^2 n_0} \right)^{1/3} = 0.41 \mu\text{m}$$

The average number of molecules in this sphere is  $\frac{1}{\eta^2} = 10^6$

2.159 For a monoatomic gas  $C_V = \frac{3}{2} R$  per mole

The entropy change in the process is

$$\Delta S = S - S_0 = \int_{T_0}^{T_0 + \Delta T} C_V \frac{dT}{T} = \frac{3}{2} R \ln \left( 1 + \frac{\Delta T}{T_0} \right)$$

Now from the Boltzmann equation

$$S = k \ln \Omega$$

$$\frac{\Omega}{\Omega_0} = e^{(S-S_0)/k} = \left( 1 + \frac{\Delta T}{T_0} \right)^{\frac{3N_A}{2}} = \left( 1 + \frac{1}{300} \right)^{\frac{3 \times 6}{2} \times 10^{23}} = 10^{13} \times 10^{21}$$

Thus the statistical weight increases by this factor.

## 2.5 LIQUIDS. CAPILLARY EFFECTS

$$\begin{aligned}
 2.160 \quad (a) \quad \Delta p &= \alpha \left( \frac{1}{d/2} + \frac{1}{d/2} \right) = \frac{4\alpha}{d} \\
 &= \frac{4 \times 490 \times 10^{-3}}{1.5 \times 10^{-6}} \frac{\text{N}}{\text{m}^2} = 1.307 \times 10^6 \frac{\text{N}}{\text{m}^2} = 13 \text{ atmosphere}
 \end{aligned}$$

(b) The soap bubble has two surfaces

$$\begin{aligned}
 \text{so} \quad \Delta p &= 2 \alpha \left( \frac{1}{d/2} + \frac{1}{d/2} \right) = \frac{8\alpha}{d} \\
 &= \frac{8 \times 45}{3 \times 10^{-3}} \times 10^{-3} = 1.2 \times 10^{-3} \text{ atmosphere.}
 \end{aligned}$$

2.161 The pressure just inside the hole will be less than the outside pressure by  $4\alpha/d$ . This can support a height  $h$  of Hg where

$$\begin{aligned}
 \rho g h &= \frac{4\alpha}{d} \quad \text{or} \quad h = \frac{4\alpha}{\rho g d} \\
 &= \frac{4 \times 490 \times 10^{-3}}{13.6 \times 10^3 \times 9.8 \times 70 \times 10^{-6}} = \frac{200}{13.6 \times 70} = 21 \text{ m of Hg}
 \end{aligned}$$

2.162 By Boyle's law

$$\begin{aligned}
 \left( p_0 + \frac{8\alpha}{d} \right) \frac{4\pi}{3} \left( \frac{d}{2} \right)^3 &= \left( \frac{p_0}{n} + \frac{8\alpha}{\eta d} \right) \frac{4\pi}{3} \left( \frac{\eta d}{2} \right)^3 \\
 \text{or} \quad p_0 \left( 1 - \frac{\eta^3}{n} \right) &= \frac{8\alpha}{d} (\eta^2 - 1) \\
 \text{Thus} \quad \alpha &= \frac{1}{8} p_0 d \left( 1 - \frac{\eta^3}{n} \right) (\eta^2 - 1)
 \end{aligned}$$

2.163 The pressure has terms due to hydrostatic pressure and capillarity and they add

$$\begin{aligned}
 p &= p_0 + \rho g h + \frac{4\alpha}{d} \\
 &= \left( 1 + \frac{5 \times 9.8 \times 10^3}{10^5} + \frac{4 \times .73 \times 10^{-3}}{4 \times 10^{-6}} \times 10^{-5} \right) \text{atms} = 2.22 \text{ atm.}
 \end{aligned}$$

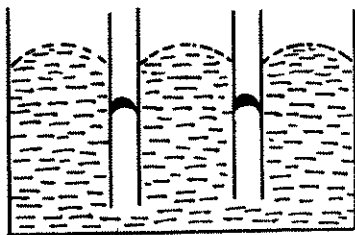
2.164 By Boyle's law

$$\begin{aligned}
 \left( p_0 + h g \rho + \frac{4\alpha}{d} \right) \frac{\pi}{6} d^3 &= \left( p_0 + \frac{4\alpha}{nd} \right) \frac{\pi}{6} n^3 d^3 \\
 \text{or} \quad [h g \rho - p_0 (n^3 - 1)] &= \frac{4\alpha}{d} (n^2 - 1) \\
 \text{or} \quad h &= \left[ p_0 (n^3 - 1) + \frac{4\alpha}{d} (n^2 - 1) \right] / g \rho = 4.98 \text{ meter of water}
 \end{aligned}$$

2.165 Clearly

$$\Delta h \rho g = 4 \alpha |\cos \theta| \left( \frac{1}{d_1} - \frac{1}{d_2} \right)$$

$$\Delta h = \frac{4 \alpha |\cos \theta| (d_2 - d_1)}{d_1 d_2 \rho g} = 11 \text{ mm}$$



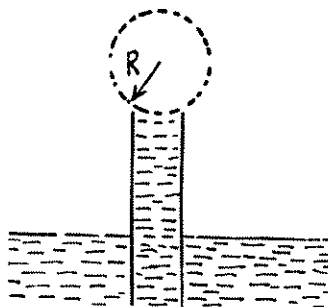
2.166 In a capillary with diameter  $d = 0.5 \text{ mm}$  water will rise to a height

$$\frac{2\alpha}{\rho g r} = \frac{4\alpha}{\rho g d}$$

$$= \frac{4 \times 73 \times 10^{-3}}{10^3 \times 9.8 \times 0.5 \times 10^{-3}} = 59.6 \text{ mm}$$

Since this is greater than the height ( $= 25 \text{ mm}$ ) of the tube, a meniscus of radius  $R$  will be formed at the top of the tube, where

$$R = \frac{2\alpha}{\rho g h} = \frac{2 \times 73 \times 10^{-3}}{10^3 \times 9.8 \times 25 \times 10^{-3}} \approx 0.6 \text{ mm}$$



2.167 Initially the pressure of air in the capillary is  $p_0$  and its length is  $l$ . When submerged under water, the pressure of air in the portion above water must be  $p_0 + 4\frac{\alpha}{d}$ , since the level of water inside the capillary is the same as the level outside. Thus by Boyle's law

$$\left( p_0 + \frac{4\alpha}{d} \right) (l - x) = p_0 l$$

or

$$\frac{4\alpha}{d} (l - x) = p_0 x \quad \text{or} \quad x = \frac{l}{1 + \frac{p_0 d}{4\alpha}}$$

2.168 We have by Boyle's law

$$\left( p_0 - \rho g h + \frac{4 \alpha \cos \theta}{d} \right) (l - h) = p_0 l$$

or,

$$\frac{4 \alpha \cos \theta}{d} = \rho g h + \frac{p_0 h}{l - h}$$

Hence,

$$\alpha = \left( \rho g h + \frac{p_0 h}{l - h} \right) \frac{d}{4 \cos \theta}$$

2.169 Suppose the liquid rises to a height  $h$ . Then the total energy of the liquid in the capillary is

$$E(h) = \frac{\pi}{4} (d_2^2 - d_1^2) h \times \rho g \times \frac{h}{2} - \pi (d_2 - d_1) \alpha h$$

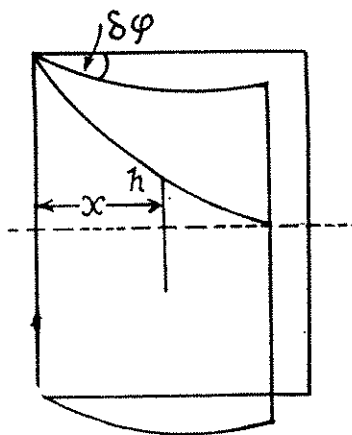
Minimising  $E$  we get

$$h = \frac{4\alpha}{\rho g (d_2 - d_1)} = 6 \text{ cm.}$$

- 2.170 Let  $h$  be the height of the water level at a distance  $x$  from the edge. Then the total energy of water in the wedge above the level outside is.

$$\begin{aligned}
 E &= \int x \delta \varphi \cdot dx \cdot h \cdot \rho g \frac{h}{2} - 2 \int dx \cdot h \cdot \alpha \cos \theta \\
 &= \int dx \frac{1}{2} x \rho g \delta \varphi \left( h^2 - 2 \frac{2 \alpha \cos \theta}{x \rho g \delta \varphi} h \right) \\
 &= \int dx \frac{1}{2} x \rho g \delta \varphi \left[ \left( h - \frac{2 \alpha \cos \theta}{x \rho g \delta \varphi} \right)^2 - \frac{4 \alpha^2 \cos^2 \theta}{x^2 \rho^2 g^2 \delta \varphi^2} \right]
 \end{aligned}$$

This is minimum when  $h = \frac{2 \alpha \cos \theta}{x \rho g \delta \varphi}$



- 2.171 From the equation of continuity

$$\frac{\pi}{4} d^2 \cdot v = \frac{\pi}{4} \left( \frac{d}{n} \right)^2 \cdot V \quad \text{or} \quad V = n^2 v.$$

We then apply Bernoulli's theorem

$$\frac{p}{\rho} + \frac{1}{2} v^2 + \Phi = \text{constant}$$

The pressure  $p$  differs from the atmospheric pressure by capillary effects. At the upper section

$$p = p_0 + \frac{2\alpha}{d}$$

neglecting the curvature in the vertical plane. Thus,

$$\frac{p_0 + \frac{2\alpha}{d}}{\rho} + \frac{1}{2} v^2 + gl = \frac{p_0 + \frac{2n\alpha}{d}}{\rho} + \frac{1}{2} n^4 v^2$$

or

$$v = \sqrt{\frac{2gl - \frac{4\alpha}{\rho d} (n-1)}{n^4 - 1}}$$

Finally, the liquid coming out per second is,

$$V = \frac{1}{4} \pi d^2 \sqrt{\frac{2gl - \frac{4\alpha}{\rho d} (n-1)}{n^4 - 1}}$$

- 2.172 The radius of curvature of the drop is  $R_1$  at the upper end of the drop and  $R_2$  at the lower end. Then the pressure inside the drop is  $p_0 + \frac{2\alpha}{R_1}$  at the top end and  $p_0 + \frac{2\alpha}{R_2}$  at the bottom end. Hence

$$p_0 + \frac{2\alpha}{R_1} = p_0 + \frac{2\alpha}{R_2} + \rho gh \quad \text{or} \quad \frac{2\alpha(R_2 - R_1)}{R_1 R_2} = \rho gh$$

To a first approximation  $R_1 \approx R_2 \approx \frac{h}{2}$  so  $R_2 - R_1 \approx \frac{1}{8} \rho gh^3 / \alpha \approx 0.20 \text{ mm}$

if

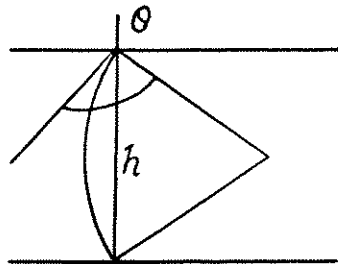
$$h = 2.3 \text{ mm}, \quad \alpha = 73 \text{ mN/m}$$

**2.173** We must first calculate the pressure difference inside the film from that outside. This is

$$p = \alpha \left( \frac{1}{r_1} + \frac{1}{r_2} \right).$$

Here  $2r_1 |\cos \theta| = h$  and  $r_2 \sim -R$  the radius of the tablet and can be neglected. Thus the total force exerted by mercury drop on the upper glass plate is

$$\frac{2\pi R^2 \alpha |\cos \theta|}{h} \text{ typically}$$



We should put  $h/n$  for  $h$  because the tablet is compressed  $n$  times. Then since  $Hg$  is nearly, incompressible,  $\pi R^2 h = \text{constants}$  so  $R \rightarrow R\sqrt{n}$ . Thus,

$$\text{total force} = \frac{2\pi R^2 \alpha |\cos \theta|}{h} n^2$$

Part of the force is needed to keep the  $Hg$  in the shape of a table rather than in the shape of infinitely thin sheet. This part can be calculated being putting  $n = 1$  above. Thus

$$mg + \frac{2\pi R^2 \alpha |\cos \theta|}{h} = \frac{2\pi R^2 \alpha |\cos \theta|}{h} n^2$$

or

$$m = \frac{2\pi R^2 \alpha |\cos \theta|}{hg} (n^2 - 1) = 0.7 \text{ kg}$$

**2.174** The pressure inside the film is less than that outside by an amount  $\alpha \left( \frac{1}{r_1} + \frac{1}{r_2} \right)$  where  $r_1$  and  $r_2$  are the principal radii of curvature of the meniscus. One of these is small being given by  $h = 2r_1 \cos \theta$  while the other is large and will be ignored. Then

$$F \approx \frac{2A \cos \theta}{h} \alpha \text{ where } A = \text{area of the water film between the plates.}$$

$$\text{Now } A = \frac{m}{\rho h} \text{ so } F = \frac{2m\alpha}{\rho h^2} \text{ when } \theta \text{ (the angle of contact)} = 0$$

**2.175** This is analogous to the previous problem except that :  $A = \pi R^2$

$$\text{So } F = \frac{2\pi R^2 \alpha}{h} = 0.6 \text{ kN}$$

**2.176** The energy of the liquid between the plates is

$$E = l d h \rho g \frac{h}{2} - 2\alpha l h = \frac{1}{2} \rho g l d h^2 - 2\alpha l h$$

$$= \frac{1}{2} \rho g l d \left( h - \frac{2\alpha}{\rho g d} \right)^2 - \frac{2\alpha^2 l}{\rho g d}$$

This energy is minimum when,  $h = \frac{2\alpha}{\rho g d}$  and

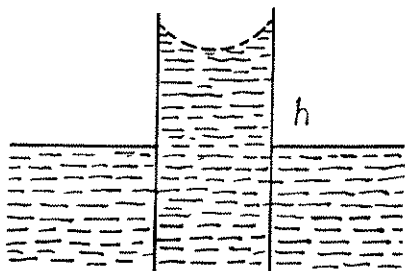
$$\text{the minimum potential energy is then } E_{\min} = -\frac{2\alpha^2 l}{\rho g d}$$

The force of attraction between the plates can be obtained from this as

$$F = -\frac{\partial E_{\min}}{\partial d} = -\frac{2\alpha^2 l}{\rho g d^2} \text{ (minus sign means the force is attractive.)}$$

Thus

$$F = -\frac{\alpha l h}{d} = 13 \text{ N}$$





- 2.177 Suppose the radius of the bubble is  $x$  at some instant. Then the pressure inside is  $p_0 + \frac{4\alpha}{x}$ . The flow through the capillary is by Poiseuille's equation,

$$Q = \frac{\pi r^4}{8 \eta l} \frac{4\alpha}{x} = -4\pi^2 \frac{dx}{dt}$$

Integrating  $\frac{\pi r^4 \alpha}{2 \eta l} t = \pi (R^4 - x^4)$  where we have used the fact that  $t = 0$  where  $x = R$ .

This gives  $t = \frac{2 \eta l R^4}{\alpha r^4}$  as the life time of the bubble corresponding to  $x = 0$

- 2.178 If the liquid rises to a height  $h$ , the energy of the liquid column becomes

$$E = \rho g \pi r^2 h \cdot \frac{h}{2} - 2 \pi r h \alpha = \frac{1}{2} \rho g \pi \left( r h - 2 \frac{\alpha}{\rho g} \right)^2 - \frac{2 \pi \alpha^2}{\rho g}$$

This is minimum when  $rh = \frac{2\alpha}{\rho g}$  and that is relevant height to which water must rise.

At this point,

$$E_{\min} = -\frac{2 \pi \alpha^2}{\rho g}$$

Since  $E = 0$  in the absence of surface tension a heat  $Q = \frac{2 \pi \alpha^2}{\rho g}$  must have been liberated.

- 2.179 (a) The free energy per unit area being  $\alpha$ ,

$$F = \pi \alpha d^2 = 3 \mu J$$

(b)  $F = 2 \pi \alpha d^2$  because the soap bubble has two surfaces. Substitution gives  $F = 10 \mu J$

- 2.180 When two mercury drops each of diameter  $d$  merge, the resulting drop has diameter  $d_1$

where  $\frac{\pi}{6} d_1^3 = \frac{\pi}{6} d^3 \times 2$  or,  $d_1 = 2^{1/3} d$

The increase in free energy is

$$\Delta F = \pi 2^{2/3} d^2 \alpha - 2 \pi d^2 \alpha = 2 \pi d^2 \alpha (2^{-1/3} - 1) = -1.43 \mu J$$

- 2.181 Work must be done to stretch the soap film and compress the air inside. The former is simply  $2 \alpha \times 4 \pi R^2 = 8 \pi R^2 \alpha$ , there being two sides of the film. To get the latter we note that the compression is isothermal and work done is

$$- \int_{V_1}^{V_0} p dV \quad \text{where} \quad V_0 p_0 = \left( p_0 + \frac{4\alpha}{R} \right) \cdot V, \quad V = \frac{4\pi}{3} R^3$$

$$\text{or} \quad V_0 = \frac{pV}{p_0}, \quad p = p_0 + \frac{4\alpha}{R}$$

and minus sign is needed because we are calculating work done on the system. Thus since  $pV$  remains constants, the work done is

$$pV \ln \frac{V_0}{V} = pV \ln \frac{p}{p_0}$$

$$\text{So} \quad A' = 8 \pi R^2 \alpha + pV \ln \frac{p}{p_0}$$

- 2.182** When heat is given to a soap bubble the temperature of the air inside rises and the bubble expands but unless the bubble bursts, the amount of air inside does not change. Further we shall neglect the variation of the surface tension with temperature. Then from the gas equations

$$\left(p_0 + \frac{4\alpha}{r}\right) \frac{4\pi}{3} r^3 = \nu R T, \quad \nu = \text{Constant}$$

Differentiating

$$\left(p_0 + \frac{8\alpha}{3r}\right) 4\pi r^2 dr = \nu R dT$$

or

$$dV = 4\pi r^2 dr = \frac{\nu R dT}{p_0 + \frac{8\alpha}{3r}}$$

Now from the first law

$$dQ = \nu C dT = \nu C_V dT + \frac{\nu R dT}{p_0 + \frac{8\alpha}{3r}} \cdot \left(p_0 + \frac{4\alpha}{r}\right)$$

or

$$C = C_V + R \frac{p_0 + \frac{4\alpha}{r}}{p_0 + \frac{8\alpha}{3r}}$$

using

$$C_p = C_V + R, \quad C = C_p + \frac{\frac{1}{2}R}{1 + \frac{8\alpha}{3p_0 r}}$$

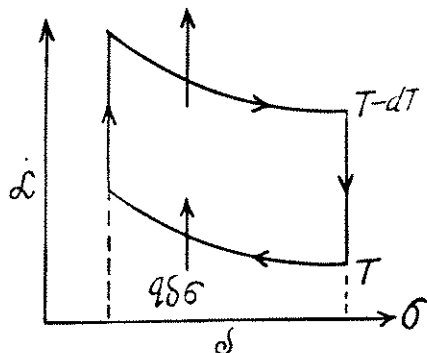
- 2.183** Consider an infinitesimal Carnot cycle with isotherms at  $T - dT$  and  $T$ . Let  $A$  be the work done during the cycle. Then

$$A = [\alpha(T - dT) - \alpha(T)] \delta\sigma = -\frac{d\alpha}{dT} dT \delta\sigma$$

Where  $\delta\sigma$  is the change in the area of film (we are considering only one surface).

Then  $\eta = \frac{A}{Q_1} = \frac{dT}{T}$  by Carnot theorem.

$$\text{or } \frac{-\frac{d\alpha}{dT} dT \delta\sigma}{q \delta\sigma} = \frac{dT}{T} \quad \text{or } q = -T \frac{d\alpha}{dT}$$



- 2.184** As before we can calculate the heat required. It, is taking into account two sides of the soap film

$$\delta q = -T \frac{d\alpha}{dT} \delta\sigma \times 2$$

Thus

$$\Delta S = \frac{\delta q}{T} = -2 \frac{d\alpha}{dT} \delta\sigma$$

Now  $\Delta F = 2\alpha \delta\sigma$  so,  $\Delta U = \Delta F + T \Delta S = 2 \left( \alpha - T \frac{d\alpha}{dT} \right) \delta\sigma$

## 2.6 PHASE TRANSFORMATIONS

**2.185** The condensation takes place at constant pressure and temperature and the work done is

$$p \Delta V$$

where  $\Delta V$  is the volume of the condensed vapour in the vapour phase. It is

$$p \Delta V = \frac{\Delta m}{M} RT = 120.6 \text{ J}$$

where  $M = 18 \text{ gm}$  is the molecular weight of water.

**2.186** The specific volume of water (the liquid) will be written as  $V_l$ . Since  $V'_v > V'_l$ , most of the weight is due to water. Thus if  $m_l$  is mass of the liquid and  $m_v$  that of the vapour then

$$m = m_l + m_v$$

$$V = m_l V'_l + m_v V'_v \quad \text{or} \quad V - m V'_l = m_v (V'_v - V'_l)$$

So  $m_v = \frac{V - m V'_l}{V'_v - V'_l} = 20 \text{ gm}$  in the present case. Its volume is  $m_v V'_v = 1.01$

**2.187** The volume of the condensed vapour was originally  $V_0 - V$  at temperature  $T = 373 \text{ K}$ . Its mass will be given by

$$p(V_0 - V) = \frac{m}{M} RT \quad \text{or} \quad m = \frac{Mp(V_0 - V)}{RT} = 2 \text{ gm where } p = \text{atmospheric pressure}$$

**2.188** We let  $V'_l$  = specific volume of liquid.  $V'_v = N V'_l$  = specific volume of vapour.

Let  $V$  = Original volume of the vapour. Then

$$M \frac{pV}{RT} = m_l + m_v = \frac{V}{N V'_l} \quad \text{or} \quad \frac{V}{n} = (m_l + N m_v) V'_l$$

$$\text{So} \quad (N-1) m_l V'_l = V \left(1 - \frac{1}{n}\right) = \frac{V}{n} (n-1) \quad \text{or} \quad \eta = \frac{m_l V'_l}{V/n} = \frac{n-1}{N-1}$$

In the case when the final volume of the substance corresponds to the midpoint of a horizontal portion of the isothermal line in the  $p, v$  diagram, the final volume must be

$(1+N) \frac{V'_l}{2}$  per unit mass of the substance. Of this the volume of the liquid is  $V'_l/2$  per unit total mass of the substance.

$$\text{Thus} \quad \eta = \frac{1}{1+N}$$

**2.189** From the first law of thermodynamics

$$\Delta U + A = Q = m q$$

where  $q$  is the specific latent heat of vaporization

$$\text{Now} \quad A = p(V'_v - V'_l) m = m \frac{RT}{M}$$

$$\text{Thus} \quad \Delta U = m \left( q - \frac{RT}{M} \right)$$

For water this gives  $\approx 2.08 \times 10^6 \text{ Joules}$ .

- 2.190 Some of the heat used in heating water to the boiling temperature

$$T = 100^\circ\text{C} = 373 \text{ K. The remaining heat}$$

$$= Q - mc \Delta T$$

( $c$  = specific heat of water,  $\Delta T = 100 \text{ K}$ ) is used to create vapour. If the piston rises to a height  $h$  then the volume of vapour will be  $\approx sh$  (neglecting water). Its mass will be  $\frac{p_0 sh}{RT} \times M$  and heat of vapourization will be  $\frac{p_0 sh M q}{RT}$ . To this must be added the work done in creating the saturated vapour  $\approx p_0 sh$ . Thus

$$Q - mc \Delta T \approx p_0 sh \left( 1 + \frac{qM}{RT} \right) \quad \text{or} \quad h = \frac{Q - mc \Delta T}{p_0 s \left( 1 + \frac{qM}{RT} \right)} = 20 \text{ cm}$$

- 2.191 A quantity  $\frac{mc(T - T_0)}{q}$  of saturated vapour must condense to heat the water to boiling point  $T = 373^\circ\text{K}$

(Here  $c$  = specific heat of water,  $T_0 = 295 \text{ K}$  = initial water temperature).

The work done in lowering the piston will then be

$$\frac{mc(T - T_0)}{q} \times \frac{RT}{M} = 25 \text{ J,}$$

since work done per unit mass of the condensed vapour is  $pV = \frac{RT}{M}$

- 2.192 Given  $\Delta P = \frac{\rho_v}{\rho_l} \frac{2\alpha}{r} = \frac{\rho_v}{\rho_l} \times \frac{4\alpha}{d} = \eta p_{\text{vap}} = \eta \frac{\frac{m}{M} RT}{V_{\text{vap}}} = \frac{\eta RT}{M} \rho_v$

$$\text{or} \quad d = \frac{4\alpha M}{\rho_l RT \eta}$$

For water  $\alpha = 73 \text{ dynes/cm}$ ,  $M = 18 \text{ gm}$ ,  $\rho_l = \text{gm/cc}$ ,  $T = 300 \text{ K}$ , and with  $\eta \approx 0.01$ , we get

$$d \approx 0.2 \mu\text{m}$$

- 2.193 In equilibrium the number of "liquid" molecules evaporating must equals the number of "vapour" molecules condensing. By kinetic theory, this number is

$$\eta \times \frac{1}{4} n \langle v \rangle = \eta \times \frac{1}{4} n \times \sqrt{\frac{8kT}{\pi m}}$$

Its mass is

$$\begin{aligned} \mu &= m \times \eta \times n \times \sqrt{\frac{kT}{2\pi m}} = \eta n k T \sqrt{\frac{m}{2\pi kT}} \\ &= \eta p_0 \sqrt{\frac{M}{2\pi RT}} = 0.35 \text{ g/cm}^2 \cdot \text{s.} \end{aligned}$$

where  $p_0$  is atmospheric pressure and  $T = 373 \text{ K}$  and  $M$  = molecular weight of water.

- 2.194 Here we must assume that  $\mu$  is also the rate at which the tungsten filament loses mass when in an atmosphere of its own vapour at this temperature and that  $\eta$  (of the previous problem)  $\approx 1$ . Then

$$p = \mu \sqrt{\frac{2 \pi RT}{M}} = 0.9 \text{ n Pa}$$

from the previous problem where  $p$  = pressure of the saturated vapour.

- 2.195 From the Vander Waals equation

$$p = \frac{RT}{V-b} - \frac{a}{V^2}$$

where  $V$  = Volume of one gm mole of the substances.

For water  $V$  = 18 c.c. per mole =  $1.8 \times 10^{-2}$  litre per mole

$$a = 5.47 \text{ atmos} \cdot \frac{\text{litre}^2}{\text{mole}^2}$$

If molecular attraction vanished the equation will be

$$p' = \frac{RT}{V-b}$$

for the same specific volume. Thus

$$\Delta p = \frac{a}{V^2} = \frac{5.47}{1.8 \times 1.8} \times 10^4 \text{ atmos} \approx 1.7 \times 10^4 \text{ atmos}$$

- 2.196 The internal pressure being  $\frac{a}{V^2}$ , the work done in condensation is

$$\int_{V_l}^{V_g} \frac{a}{V^2} dV = \frac{a}{V_l} - \frac{a}{V_g} \approx \frac{a}{V_l}$$

This by assumption is  $Mq$ ,  $M$  being the molecular weight and  $V_l$ ,  $V_g$  being the molar volumes of the liquid and gas.

Thus

$$p_l = \frac{a}{V_l^2} = \frac{Mq}{V_l} = \rho q$$

where  $\rho$  is the density of the liquid. For water  $p_l = 3.3 \times 10^{13} \text{ atm}$

- 2.197 The Vander Waal's equation can be written as (for one mole)

$$p(V) = \frac{RT}{V-b} - \frac{a}{V^2}$$

At the critical point  $\left(\frac{\partial p}{\partial V}\right)_T$  and  $\left(\frac{\partial^2 p}{\partial V^2}\right)_T$  vanish. Thus

$$0 = \frac{RT}{(V-b)^2} - \frac{2a}{V^3} \quad \text{or} \quad \frac{RT}{(V-b)^2} = \frac{2a}{V^3}$$

$$0 = \frac{2RT}{(V-b)^3} - \frac{6a}{V^4} \quad \text{or} \quad \frac{RT}{(V-b)^3} = \frac{3a}{V^4}$$

Solving these simultaneously we get on division

$$V - b = \frac{2}{3} V, \quad V = 3b = V_{MCr}$$

This is the critical molar volume. Putting this back

$$\frac{RT_{Cr}}{4b^2} = \frac{2a}{27b^3} \quad \text{or} \quad T_{Cr} = \frac{8a}{27bR}$$

Finally 
$$p_{Cr} = \frac{RT_{Cr}}{V_{MCr} - b} - \frac{a}{V_{MCr}^2} = \frac{4a}{27b^2} - \frac{a}{9b^2} = \frac{a}{27b^2}$$

From these we see that 
$$\frac{p_{Cr} V_{MCr}}{RT_{Cr}} = \frac{a/9b}{8a/27b} = \frac{3}{8}$$

2.198 
$$\frac{p_{Cr}}{RT_{Cr}} = \frac{a/27b^2}{8a/27b} = \frac{1}{8b}$$

Thus 
$$b = R \frac{T_{Cr}}{8p_{Cr}} = \frac{0.082 \times 304}{73 \times 8} = 0.043 \text{ litre/mol}$$

and 
$$\frac{(RT_{Cr})^2}{p_{Cr}} = \frac{64a}{27} \quad \text{or} \quad a = \frac{27}{64} (RT_{Cr})^2 / p_{Cr} = 3.59 \frac{\text{atm} \cdot \text{litre}^2}{(\text{mol})^2}$$

2.199 Specific volume is molar volume divided by molecular weight. Thus

$$V'_{Cr} = \frac{V_{MCr}}{M} = \frac{3RT_{Cr}}{8Mp_{Cr}} = \frac{3 \times 0.082 \times 562 \text{ litre}}{8 \times 78 \times 47} \frac{\text{g}}{\text{g}} = 4.71 \frac{\text{cc}}{\text{g}}$$

2.200 
$$\left(p + \frac{a}{V_m^2}\right)(V_m - b) = RT$$

or 
$$\frac{p + \frac{a}{V_m^2}}{p_{Cr}} \times \frac{V_m - b}{V_{MCr}} = \frac{8}{3} \frac{T}{T_{Cr}}$$

or 
$$\left(\pi + \frac{a}{p_{Cr} V_m^2}\right) \times \left(v - \frac{b}{V_{MCr}}\right) = \frac{8}{3} \tau,$$

where 
$$\pi = \frac{p}{p_{Cr}}, \quad v = \frac{V_m}{V_{MCr}}, \quad \tau = \frac{T}{T_{Cr}}$$

or 
$$\left(\pi + \frac{27b^2}{V_m^2}\right) \left(v - \frac{1}{3}\right) = \frac{8}{3} \tau, \quad \text{or} \quad \left(\pi + \frac{3}{v^2}\right) \left(v - \frac{1}{3}\right) = \frac{8}{3} \tau$$

When 
$$\pi = 12 \text{ and } v = \frac{1}{2}, \quad \tau = \frac{3}{8} \times 24 \times \frac{1}{6} = \frac{3}{2}$$

2.201 (a) The critical Volume  $V_{MCr}$  is the maximum volume in the liquid phase and the minimum volume in the gaseous. Thus

$$V_{\max} = \frac{1000}{18} \times 3 \times 0.030 \text{ litre} = 5 \text{ litre}$$

(b) The critical pressure is the maximum possible pressure in the vapour phase in equilibrium with liquid phase. Thus

$$p_{\max} = \frac{a}{27b^2} = \frac{5.47}{27 \times .03 \times .03} = 225 \text{ atmosphere}$$

$$2.202 \quad T_{Cr} = \frac{8}{27} \frac{a}{bR} = \frac{8}{27} \times \frac{3.62}{.043 \times .082} = 304 \text{ K}$$

$$\rho_{Cr} = \frac{M}{3b} = \frac{44}{3 \times 43} \text{ gm/c.c.} = 0.34 \text{ gm/c.c.}$$

2.203 The vessel is such that either vapour or liquid of mass  $m$  occupies it at critical point. Then its volume will be

$$v_{Cr} = \frac{m}{M} V_{MCr} = \frac{3}{8} \frac{RT_{Cr}}{p_{Cr}} \frac{m}{M}$$

The corresponding volume in liquid phase at room temperature is

$$V = \frac{m}{\rho}$$

where  $\rho$  = density of liquid ether at room temperature. Thus

$$\eta = \frac{V}{V_{Cr}} = \frac{8Mp_{Cr}}{3RT_{Cr}\rho} \approx 0.254$$

using the given data (and  $\rho = 720 \text{ gm per litre}$ )

2.204 We apply the relation ( $T = \text{constant}$ )

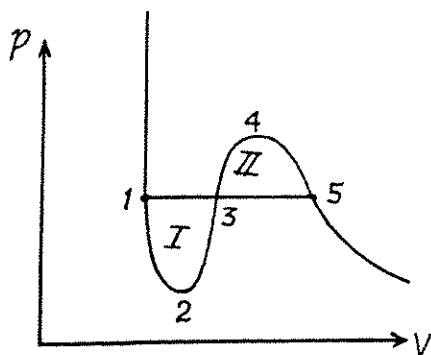
$$T \oint dS = \oint dU + \oint p dV$$

to the cycle 1234531.

$$\text{Here } \oint dS = \oint dU = 0$$

$$\text{So } \oint p dV = 0$$

This implies that the areas I and II are equal. This reasoning is inapplicable to the cycle 1231, for example. This cycle is irreversible because it involves the irreversible transition from a single phase to a two-phase state at the point 3.



2.205 When a portion of supercool water turns into ice some heat is liberated, which should heat it upto ice point. Neglecting the variation of specific heat of water, the fraction of water turning into ice is clearly

$$f = \frac{c|t|}{q} = 0.25$$

where  $c$  = specific heat of water and  $q$  = latent heat of fusion of ice, Clearly  $f = 1$  at  $t = -80^\circ\text{C}$

**2.206** From the Clausius-Clapeyron (C-C) equations

$$\frac{dT}{dp} = \frac{T(V_2 - V_1)}{q_{12}}$$

$q_{12}$  is the specific latent heat absorbed in  $1 \rightarrow 2$  ( $1 = \text{solid}, 2 = \text{liquid}$ )

$$\Delta T = \frac{T(V_w - V_{ice})}{q_{12}} \quad \Delta p = -\frac{273 \times 0.091}{333} \times 1 \frac{\text{atm} \times \text{cm}^3 \times \text{K}}{\text{joule}}$$

$$1 \frac{\text{atm} \times \text{cm}^3}{\text{Joule}} \approx \frac{10^5 \frac{\text{N}}{\text{m}^2} \times 10^{-6} \text{m}^3}{\text{Joule}} = 10^{-1}, \quad \Delta T = -0.0075 \text{ K}$$

**2.207** Here  $1 = \text{liquid}, 2 = \text{Steam}$

$$\Delta T = \frac{T(V_s - V_{liq})}{q_{12}} \Delta p$$

$$\text{or} \quad V_s \approx \frac{q_{12}}{T} \frac{\Delta T}{\Delta p} = \frac{2250}{373} \times \frac{0.9}{3.2} \times 10^{-3} \text{ m}^3/\text{g} = 1.7 \text{ m}^3/\text{kg}$$

**2.208** From C-C equations

$$\frac{dp}{dT} = \frac{q_{12}}{T(V_2 - V_1)} \approx \frac{q_{12}}{TV_2}$$

Assuming the saturated vapour to be ideal gas

$$\frac{1}{V_2} = \frac{mp}{RT}, \quad \text{Thus} \quad \Delta p = \frac{Mq}{RT^2} p \Delta T$$

$$\text{and} \quad p \approx p_0 \left( 1 + \frac{Mq}{RT^2} \Delta T \right) = 1.04 \text{ atmosphere}$$

**2.209** From C-C equation, neglecting the volume of the liquid

$$\frac{dp}{dT} = \frac{q_{12}}{TV_2} = \frac{Mq}{RT^2} p, \quad (q = q_{12})$$

$$\text{or} \quad \frac{dp}{p} = \frac{Mq}{RT} \frac{dT}{T}$$

$$\text{Now} \quad pV = \frac{m}{M} RT \quad \text{or} \quad m = \frac{MpV}{RT} \quad \text{for a perfect gas}$$

$$\text{So} \quad \frac{dm}{m} = \frac{dp}{p} - \frac{dT}{T} \quad (V \text{ is Const} = \text{specific volume})$$

$$= \left( \frac{Mq}{RT} - 1 \right) \frac{dT}{T} = \left( \frac{18 \times 2250}{8.3 \times 373} - 1 \right) \times \frac{1.5}{373} = 4.85 \%$$



## 2.210 From C-C equation

$$\frac{dp}{dT} = \frac{q}{TV_2} = \frac{Mq}{RT^2P}$$

Integrating  $\ln p = \text{constant} - \frac{Mq}{RT}$

So 
$$p = p_0 \exp \left[ \frac{Mq}{R} \left( \frac{1}{T_0} - \frac{1}{T} \right) \right]$$

This is reasonable for  $|T - T_0| \ll T_0$  and far below critical temperature.

## 2.211 As before (2.206) the lowering of melting point is given by

$$\Delta T = - \frac{T \Delta V'}{q} p$$

The superheated ice will then melt in part. The fraction that will melt is

$$\eta = \frac{C T \Delta V'}{q^2} p = .03$$

## 2.212 (a) The equations of the transition lines are

$$\log p = 9.05 - \frac{1800}{T} : \text{Solid gas}$$

$$= 6.78 - \frac{1310}{T} : \text{Liquid gas}$$

At the triple point they intersect. Thus

$$2.27 = \frac{490}{T_p} \text{ or } T_p = \frac{490}{2.27} = 216 \text{ K}$$

corresponding  $p_p$  is 5.14 atmosphere.

In the formula  $\log p = a - \frac{b}{T}$ , we compare  $b$  with the corresponding term in the equation in 2.210. Then

$$\ln p = a \times 2.303 - \frac{2.303 b}{T} \text{ So, } 2.303 = \frac{Mq}{R}$$

or, 
$$q_{\text{sublimation}} = \frac{2.303 \times 1800 \times 8.31}{44} = 783 \text{ J/gm}$$

$$q_{\text{liquid-gas}} = \frac{2.303 \times 1310 \times 8.31}{44} = 570 \text{ J/gm}$$

Finally  $q_{\text{solid-liquid}} = 213 \text{ J/gm}$  on subtraction

$$\begin{aligned} 2.213 \quad \Delta S &= \int_{T_1}^{T_2} mc \frac{dT}{T} + \frac{mq}{T_2} = m \left( c \ln \frac{T_2}{T_1} + \frac{q}{T_2} \right) \\ &= 10^3 \left( 4.18 \ln \frac{373}{283} + \frac{2250}{373} \right) = 7.2 \text{ kJ/K} \end{aligned}$$

$$\begin{aligned}
 2.214 \quad \Delta S &= \frac{q_m}{T_1} + c \ln \frac{T_2}{T} + \frac{q_v}{T_2} \\
 &= \frac{333}{273} + 4.18 \ln \frac{373}{283} = 8.56 \text{ J/}^\circ\text{K}
 \end{aligned}$$

2.215  $c$  = specific heat of copper =  $0.39 \frac{\text{J}}{\text{g} \cdot \text{K}}$  Suppose all ice does not melt, then

$$\text{heat rejected} = 90 \times 0.39 (90 - 0) = 3159 \text{ J}$$

$$\text{heat gained by ice} = 50 \times 2.09 \times 3 + x \times 333$$

$$\text{Thus} \quad x = 8.5 \text{ gm}$$

The hypothesis is correct and final temperature will be  $T = 273 \text{ K}$ .

Hence change in entropy of copper piece

$$= mc \ln \frac{273}{363} = -10 \text{ J/K.}$$

2.216 (a) Here  $t_2 = 60^\circ\text{C}$ . Suppose the final temperature is  $t^\circ\text{C}$ . Then

$$\text{heat lost by water} = m_2 c (t_2 - t)$$

$$\text{heat gained by ice} = m_1 q_m + m_1 c (t - t_1), \text{ if all ice melts}$$

$$\text{In this case } m_1 q_m = m_2 \times 4.18 (60 - t), \text{ for } m_1 = m_2$$

So the final temperature will be  $0^\circ\text{C}$  and only some ice will melt.

$$\text{Then} \quad 100 \times 4.18 (60) = m'_1 \times 333$$

$$m'_1 = 75.3 \text{ gm} = \text{amount of ice that will melt}$$

$$\text{Finally} \quad \Delta S = 75.3 \times \frac{333}{273} + 100 \times 4.18 \ln \frac{273}{333}$$

$$\Delta S = \frac{m'_1 q_m}{T_1} + m_2 c \ln \frac{T_1}{T_2}$$

$$= m_2 c \frac{(T_2 - T_1)}{T_1} - m_2 \ln \frac{T_2}{T_1}$$

$$= m_2 C \left[ \frac{T_2}{T_1} - 1 - \ln \frac{T_2}{T_1} \right] = 8.8 \text{ J/K}$$

(b) If  $m_2 c t_2 > m_1 q_m$  then all ice will melt as one can check and the final temperature can be obtained like this

$$m_2 c (T_2 - T) = m_1 q_m + m_1 c (T - T_1)$$

$$(m_2 T_2 + m_1 T_1) c - m_1 q_m = (m_1 + m_2) c T$$

$$\text{or} \quad T = \frac{m_2 T_2 + m_1 T_1 - \frac{m_1 q_m}{c}}{m_1 + m_2} = 280 \text{ K}$$

$$\text{and} \quad \Delta S = \frac{m_1 q}{T_1} + c \left( m_1 \ln \frac{T}{T_1} - m_2 \ln \frac{T_2}{T} \right) = 19 \text{ J/K}$$

$$2.217 \quad \Delta S = -\frac{m q_1}{T_2} - mc \ln \frac{T_2}{T_1} + \frac{M q_{ice}}{T_1}$$

where

$$\begin{aligned} M q_{ice} &= m (q_2 + c (T_2 - T_1)) \\ &= m q_2 \left( \frac{1}{T_1} - \frac{1}{T_2} \right) + mc \left( \frac{T_2}{T_1} - 1 - \frac{T_2}{T_1} \right) \\ &= 0.2245 + 0.2564 = 0.48 \text{ J/K} \end{aligned}$$

2.218 When heat  $dQ$  is given to the vapour its temperature will change by  $dT$ , pressure by  $dp$  and volume by  $dV$ , it being assumed that the vapour remains saturated.

Then by C-C equation

$$\frac{dp}{dT} = \frac{q}{TV'} (V'_{\text{vapour}} \gg V'_{\text{Liq}}), \text{ or } dp = \frac{q}{TV'} dT$$

on the other hand,  $pV' = \frac{RT}{M}$

So  $p dV' + V' dp = \frac{R dT}{M},$

Hence  $p dV' = \left( \frac{R}{M} - \frac{q}{T} \right) dT$

finally

$$\begin{aligned} dQ &= C dT = dU + p dV' \\ &= C_V dT + \left( \frac{T}{M} - \frac{q}{T} \right) dT = C_p dT - \frac{q}{T} dT \end{aligned}$$

( $C_p, C_V$  refer to unit mass here). Thus

$$C = C_p - \frac{q}{T}$$

For water  $C_p = \frac{R \gamma}{\gamma - 1} \cdot \frac{1}{M}$  with  $\gamma = 1.32$  and  $M = 18$

So  $C_p = 1.90 \text{ J/gm K}$

and  $C = -4.13 \text{ J/gm}^\circ\text{K} = -74 \text{ J/mole K}$

2.219 The required entropy change can be calculated along a process in which the water is heated from  $T_1$  to  $T_2$  and then allowed to evaporate. The entropy change for this is

$$\Delta S = C_p \ln \frac{T_2}{T_1} + \frac{qM}{T_2}$$

where  $q$  = specific latent heat of vaporization.

## 2.7 TRANSPORT PHENOMENA

- 2.220 (a) The fraction of gas molecules which traverses distances exceeding the mean free path without collision is just the probability to traverse the distance  $s = \lambda$  without collision.

Thus 
$$P = e^{-1} = \frac{1}{e} = 0.37$$

- (b) This probability is

$$P = e^{-1} - e^{-2} = 0.23$$

- 2.221 From the formula

$$\frac{1}{\eta} = e^{-\Delta l / \lambda} \quad \text{or} \quad \lambda = \frac{\Delta l}{\ln \eta}$$

- 2.222 (a) Let  $P(t)$  = probability of no collision in the interval  $(0, t)$ . Then

$$P(t + dt) = P(t)(1 - \alpha dt)$$

or 
$$\frac{dP}{dt} = -\alpha P(t) \quad \text{or} \quad P(t) = e^{-\alpha t}$$

where we have used  $P(0) = 1$

- (b) The mean interval between collision is also the mean interval of no collision. Then

$$\langle t \rangle = \frac{\int_0^{\infty} t e^{-\alpha t} dt}{\int_0^{\infty} e^{-\alpha t} dt} = \frac{1}{\alpha} \frac{\Gamma(2)}{\Gamma(1)} = \frac{1}{\alpha}$$

2.223 (a) 
$$\lambda = \frac{1}{\sqrt{2} \pi d^2 n} = \frac{kT}{\sqrt{2} \pi d^2 p}$$

$$= \frac{1.38 \times 10^{-23} \times 273}{\sqrt{2} \pi (0.37 \times 10^{-9})^2 \times 10^5} = 6.2 \times 10^{-8} \text{ m}$$

$$\tau = \frac{\lambda}{\langle v \rangle} = \frac{6.2 \times 10^{-8}}{454} \text{ s} = 0.136 \text{ ns}$$

$$\lambda = 6.2 \times 10^6 \text{ m}$$

(b)  $\eta = 1.36 \times 10^4 \text{ s} = 3.8 \text{ hours}$

- 2.224 The mean distance between molecules is of the order

$$\left( \frac{22.4 \times 10^{-3}}{6.0 \times 10^{23}} \right)^{1/3} = \left( \frac{224}{6} \right)^{1/3} \times 10^{-9} \text{ meters} \approx 3.34 \times 10^{-9} \text{ meters}$$

This is about 18.5 times smaller than the mean free path calculated in 2.223 (a) above.

- 2.225 We know that the Vander Waal's constant  $b$  is four times the molecular volume. Thus

$$b = 4 N_A \frac{\pi}{6} d^3 \quad \text{or} \quad d = \left( \frac{3b}{2 \pi N_A} \right)^{1/3}$$

Hence

$$\lambda = \left( \frac{kT_0}{\sqrt{2} \pi p_0} \right) \left( \frac{2 \pi N_A}{3b} \right)^{2/3}$$

2.226 The velocity of sound in  $N_2$  is

$$\sqrt{\frac{\gamma P}{\rho}} = \sqrt{\frac{\gamma RT}{M}}$$

so, 
$$\frac{1}{v} = \sqrt{\frac{\gamma RT_0}{M}} = \frac{RT_0}{\sqrt{2} \pi d^2 p_0 N_A}$$

or, 
$$v = \pi d^2 p_0 N_A \sqrt{\frac{2\gamma}{MRT_0}}$$

2.227 (a)  $\lambda > l$  if  $p < \frac{kT}{\sqrt{2} \pi d^2 l}$

Now 
$$\frac{kT}{\sqrt{2} \pi d^2 l} \text{ for } O_2 \text{ of } O \text{ is } 0.7 \text{ Pa.}$$

(b) The corresponding  $n$  is obtained by dividing by  $kT$  and is  $1.84 \times 10^{20}$  per  $m^3 = 1.84^{14}$  per c.c. and the corresponding mean distance is  $\frac{l}{n^{1/3}}$ .

$$= \frac{10^{-2}}{(0.184)^{1/3} \times 10^5} = 1.8 \times 10^{-7} \text{ m} \approx 0.18 \mu\text{m.}$$

2.228 (a) 
$$v = \frac{1}{\tau} = \frac{1}{\lambda / \langle v \rangle} = \frac{\langle v \rangle}{\lambda}$$

$$= \sqrt{2} \pi d^2 n \langle v \rangle = .74 \times 10^{10} \text{ s}^{-1} \text{ (see 2.223)}$$

(b) Total number of collisions is

$$\frac{1}{2} n v \approx 1.0 \times 10^{29} \text{ s cm}^{-3}$$

Note, the factor  $\frac{1}{2}$ . When two molecules collide we must not count it twice.

2.229 (a) 
$$\lambda = \frac{1}{\sqrt{2} \pi d^2 n}$$

$d$  is a constant and  $n$  is a constant for an isochoric process so  $\lambda$  is constant for an isochoric process.

$$v = \frac{\langle v \rangle}{\lambda} = \frac{\sqrt{\frac{8RT}{M\pi}}}{\lambda} \propto \sqrt{T}$$

(b) 
$$\lambda = \frac{1}{\sqrt{2} \pi d^2} \frac{kT}{p} \propto T \text{ for an isobaric process.}$$

$$v = \frac{\langle v \rangle}{\lambda} \propto \frac{\sqrt{T}}{T} = \frac{1}{\sqrt{T}} \text{ for an isobaric process.}$$

2.230 (a) In an isochoric process  $\lambda$  is constant and

$$v \propto \sqrt{T} \propto \sqrt{pV} \propto \sqrt{p} \propto \sqrt{n}$$

(b) 
$$\lambda = \frac{kT}{\sqrt{2} \pi d^2 p}$$
 must decrease  $n$  times in an isothermal process and  $v$  must increase  $n$  times because  $\langle v \rangle$  is constant in an isothermal process.

2.231 (a)  $\lambda \propto \frac{1}{n} \Rightarrow \frac{1}{N/V} = \frac{V}{N}$

Thus  $\lambda \propto V$  and  $v \propto \frac{T^{1/2}}{V}$

But in an adiabatic process ( $\gamma = \frac{7}{5}$  here)

$$TV^{\gamma-1} = \text{constant so } TV^{2/5} = \text{constant}$$

or  $T^{1/2} \propto V^{-1/5}$  Thus  $v \propto V^{-6/5}$

(b)  $\lambda \propto \frac{T}{p}$

But  $p \left( \frac{T}{p} \right)^{\gamma} = \text{constant}$  or  $\frac{T}{p} \propto p^{-1/\gamma}$  or  $T \propto p^{1-1/\gamma}$

Thus  $\lambda \propto p^{-1/\gamma} = p^{-5/7}$

$$v = \frac{\langle v \rangle}{\lambda} \propto \frac{p}{\sqrt{T}} \propto p^{1/2 + \frac{1}{2\gamma}} = p^{\frac{\gamma+1}{2\gamma}} = p^{6/7}$$

(c)  $\lambda \propto V$

But  $TV^{2/5} = \text{constant}$  or  $V \propto T^{-5/2}$

Thus  $\lambda \propto T^{-5/2}$

$$v \propto \frac{T^{1/2}}{V} \propto T^3$$

2.232 In the polytropic process of index  $n$

$$pV^n = \text{constant}, TV^{n-1} = \text{constant and } p^{1-n} T^n = \text{constant}$$

(a)  $\lambda \propto V$

$$v \propto \frac{T^{1/2}}{V} = V^{\frac{1-n}{2}} V^{-1} = V^{\frac{-n+1}{2}}$$

(b)  $\lambda \propto \frac{T}{p}$ ,  $T^n \propto p^{n-1}$  or  $T \propto p^{1-\frac{1}{n}}$

so  $\lambda \propto p^{-1/n}$

$$v = \frac{\langle v \rangle}{\lambda} \propto \frac{p}{\sqrt{T}} \propto p^{1-\frac{1}{2}+\frac{1}{2n}} = p^{\frac{n+1}{2n}}$$

(c)  $\lambda \propto \frac{T}{p}$ ,  $p \propto T^{\frac{n}{n-1}}$

$$\lambda \propto T^{1-\frac{n}{n-1}} = T^{-\frac{1}{n-1}} = T^{\frac{1}{1-n}}$$

$$v \propto \frac{p}{\sqrt{T}} \propto T^{\frac{n}{n-1}-\frac{1}{2}} = T^{\frac{n+1}{2(n-1)}}$$

2.233 (a) The number of collisions between the molecules in a unit volume is

$$\frac{1}{2} n v = \frac{1}{\sqrt{2}} \pi d^2 n^2 \langle v \rangle \propto \frac{\sqrt{T}}{V^2}$$

This remains constant in the poly process  $pV^{-3} = \text{constant}$

Using (2.122) the molar specific heat for the polytropic process

$$pV^\alpha = \text{constant},$$

is

$$C = R \left( \frac{1}{\gamma - 1} - \frac{1}{\alpha - 1} \right)$$

Thus

$$C = R \left( \frac{1}{\gamma - 1} + \frac{1}{4} \right) = R \left( \frac{5}{2} + \frac{1}{4} \right) = \frac{11}{4} R$$

It can also be written as  $\frac{1}{4} R (1 + 2i)$  where  $i = 5$

(b) In this case  $\frac{\sqrt{T}}{V} = \text{constant}$  and so  $pV^{-1} = \text{constant}$

so

$$C = R \left( \frac{1}{\gamma - 1} + \frac{1}{2} \right) = R \left( \frac{5}{2} + \frac{1}{2} \right) = 3R$$

It can also be written as  $\frac{R}{2} (i + 1)$

2.234 We can assume that all molecules, incident on the hole, leak out. Then,

$$-dN = -d(nV) = \frac{1}{4} n \langle v \rangle S dt$$

or

$$dn = -n \frac{dt}{4v/S \langle v \rangle} = -n \frac{dt}{\tau}$$

Integrating

$$n = n_0 e^{-t/\tau}. \text{ Hence } \langle v \rangle = \sqrt{\frac{8RT}{\pi M}}$$

2.235 If the temperature of the compartment 2 is  $\eta$  times more than that of compartment 1, it must contain  $\frac{1}{\eta}$  times less number of molecules since pressure must be the same when the big hole is open. If  $M$  = mass of the gas in 1 then the mass of the gas in 2 must be  $\frac{M}{\eta}$ . So immediately after the big hole is closed.

$$n_1^0 = \frac{M}{mV}, \quad n_2^0 = \frac{M}{mV\eta}$$

where  $m$  = mass of each molecule and  $n_1^0, n_2^0$  are concentrations in 1 and 2. After the big hole is closed the pressures will differ and concentration will become  $n_1$  and  $n_2$  where

$$n_1 + n_2 = \frac{M}{mV\eta} (1 + \eta)$$

On the other hand

$$n_1 \langle v_1 \rangle = n_2 \langle v_2 \rangle \quad \text{i.e. } n_1 = \sqrt{\eta} n_2$$

Thus 
$$n_2(1 + \sqrt{\eta}) = \frac{m}{mV\eta}(1 + \eta) = n_2^0(1 + \eta)$$

So 
$$n_2 = n_2^0 \frac{1 + \eta}{1 + \sqrt{\eta}}$$

**2.236** We know

$$\eta = \frac{1}{3} \langle v \rangle \lambda \rho = \frac{1}{3} \langle v \rangle \frac{1}{\sqrt{2} \pi d^2} m \alpha \sqrt{T}$$

Thus  $\eta$  changing  $\alpha$  times implies  $T$  changing  $\alpha^2$  times.

On the other hand

$$D = \frac{1}{3} \langle v \rangle \lambda = \frac{1}{3} \sqrt{\frac{8kT}{\pi m}} \frac{kT}{\sqrt{2} \pi d^2 p}$$

Thus  $D$  changing  $\beta$  times means  $\frac{T^{3/2}}{p}$  changing  $\beta$  times

So  $p$  must change  $\frac{\alpha^3}{\beta}$  times

**2.237**  $D \propto \frac{\sqrt{T}}{n} \propto V \sqrt{T}, \eta \propto \sqrt{T}$

(a)  $D$  will increase  $n$  times

$\eta$  will remain constant if  $T$  is constant

(b)  $D \propto \frac{T^{3/2}}{p} \propto \frac{(pV)^{3/2}}{p} = p^{1/2} V^{3/2}$

$$\eta \propto \sqrt{pV}$$

Thus  $D$  will increase  $n^{3/2}$  times,  $\eta$  will increase  $n^{1/2}$  times, if  $p$  is constant

**2.238**  $D \propto V \sqrt{T}, \eta \propto \sqrt{T}$

In an adiabatic process

$$TV^{\gamma-1} = \text{constant, or } T \propto V^{1-\gamma}$$

Now  $V$  is decreased  $\frac{1}{n}$  times. Thus

$$D \propto V^{\frac{3-\gamma}{2}} = \left(\frac{1}{n}\right)^{\frac{3-\gamma}{2}} = \left(\frac{1}{n}\right)^{4/5}$$

$$\eta \propto \text{of } V^{\frac{1-\gamma}{2}} = \left(\frac{1}{n}\right)^{-1/5} = n^{1/5}$$

So  $D$  decreases  $n^{4/5}$  times and  $\eta$  increase  $n^{1/5}$  times.

**2.239** (a)  $D \propto V \sqrt{T} \propto \sqrt{pV^3}$

Thus  $D$  remains constant in the process  $pV^3 = \text{constant}$

So polytropic index  $n = 3$

(b)  $\eta \propto \sqrt{T} \propto \sqrt{pV}$



So  $\eta$  remains constant in the isothermal process

$$pV = \text{constant}, n = 1, \text{ here}$$

(c) Heat conductivity  $\kappa = \eta C_v$

and  $C_v$  is a constant for the ideal gas

Thus  $n = 1$  here also,

$$2.240 \quad \eta = \frac{1}{3} \sqrt{\frac{8kT}{\pi m}} \frac{m}{\sqrt{2} \pi d^2} = \frac{2}{3} \sqrt{\frac{m kT}{\pi^3}} \frac{1}{d^2}$$

$$\begin{aligned} \text{or } d &= \left(\frac{2}{3\eta}\right)^{1/2} \left(\frac{m kT}{\pi^3}\right)^{1/4} = \left(\frac{2}{3 \times 18.9 \times 10^6}\right)^{1/2} \left(\frac{4 \times 8.31 \times 273 \times 10^{-3}}{\pi^3 \times 36 \times 10^{46}}\right)^{1/4} \\ &= 10^{-10} \left(\frac{2}{3 \times 18.9}\right)^{1/2} \left(\frac{4 \times 83.1 \times 273}{\pi^3 \times 36}\right)^{1/4} = 0.178 \text{ nm} \end{aligned}$$

$$2.241 \quad \kappa = \frac{1}{3} \langle v \rangle \lambda \rho c_v$$

$$= \frac{1}{3} \sqrt{\frac{8kT}{m\pi}} \frac{1}{\sqrt{2} \pi d^2 n} m n \frac{C_v}{M}$$

( $C_v$  is the specific heat capacity which is  $\frac{C_v}{M}$ ). Now  $C_v$  is the same for all monoatomic gases such as He and A. Thus

$$\kappa \propto \frac{1}{\sqrt{M} d^2}$$

$$\text{or } \frac{\kappa_{He}}{\kappa_A} = 8.7 = \frac{\sqrt{M_A} d_A^2}{\sqrt{M_{H_2}} d_{H_2}^2} = \sqrt{10} \frac{d_A^2}{d_{H_2}^2}$$

$$\frac{d_A}{d_{H_2}} = \sqrt{\frac{8.7}{\sqrt{10}}} = 1.658 \approx 1.7$$

2.242 In this case

$$N_1 \frac{r_2^2 - r_1^2}{r_1^2 r_2^2} = 4 \pi \eta \omega$$

$$\text{or } N_1 \frac{2R \Delta R}{R^4} = 4 \pi \eta \omega \quad \text{or } N_1 = \frac{2 \pi \eta \omega R^3}{\Delta R}$$

To decrease  $N_1$ ,  $n$  times  $\eta$  must be decreased  $n$  times. Now  $\eta$  does not depend on pressure until the pressure is so low that the mean free path equals, say,  $\frac{1}{2} \Delta R$ . Then the mean free path is fixed and  $\eta$  decreases with pressure. The mean free path equals  $\frac{1}{2} \Delta R$  when

$$\frac{1}{\sqrt{2} \pi d^2 n_0} = \Delta R \quad (n_0 = \text{concentration})$$

Corresponding pressure is  $p_0 = \frac{\sqrt{2} k T}{\pi d^2 \Delta R}$

The sought pressure is  $n$  times less

$$p = \frac{\sqrt{2} k T}{\pi d^2 n \Delta R} = 70.7 \times \frac{10^{-23}}{10^{-18} \times 10^{-3}} = 0.71 \text{ Pa}$$

The answer is qualitative and depends on the choice  $\frac{1}{2} \Delta R$  for the mean free path.

- 2.243** We neglect the moment of inertia of the gas in a shell. Then the moment of friction forces on a unit length of the cylinder must be a constant as a function of  $r$ .

$$\text{So,} \quad 2 \pi r^3 \eta \frac{d\omega}{dr} = N_1 \quad \text{or} \quad \omega(r) = \frac{N_1}{4 \pi \eta} \left( \frac{1}{r_1^2} - \frac{1}{r^2} \right)$$

$$\text{and} \quad \omega = \frac{N_1}{4 \pi \eta} \left( \frac{1}{r_1^2} - \frac{1}{r_2^2} \right) \quad \text{or} \quad \eta = \frac{N_1}{4 \pi \omega} \left( \frac{1}{r_1^2} - \frac{1}{r_2^2} \right)$$

- 2.244** We consider two adjoining layers. The angular velocity gradient is  $\frac{\omega}{h}$ . So the moment of the frictional force is

$$N = \int_0^a r \cdot 2 \pi r dr \cdot \eta r \frac{\omega}{h} = \frac{\pi \eta a^4 \omega}{2h}$$

- 2.245** In the ultrararefied gas we must determine  $\eta$  by taking  $\lambda = \frac{1}{2} h$ . Then

$$\eta = \frac{1}{3} \sqrt{\frac{8kT}{m\pi}} \times \frac{1}{2} h \times \frac{mp}{kT} = \frac{1}{3} \sqrt{\frac{2M}{\pi RT}} hp$$

$$\text{so,} \quad N = \frac{1}{3} \omega a^4 p \sqrt{\frac{\pi M}{2RT}}$$

- 2.246** Take an infinitesimal section of length  $dx$  and apply Poiseuille's equation to this. Then

$$\frac{dV}{dt} = \frac{-\pi a^4}{8\eta} \frac{\partial p}{\partial x}$$

From the formula

$$pV = RT \cdot \frac{m}{M}$$

$$pdV = \frac{RT}{M} dm$$

or

$$\frac{dm}{dt} = \mu = - \frac{\pi a^4 M}{8 \eta RT} \frac{dp}{dx}$$

This equation implies that if the flow is isothermal then  $p \frac{dp}{dx}$  must be a constant and so

equals  $\frac{|p_2^2 - p_1^2|}{2l}$  in magnitude.

$$\text{Thus,} \quad \mu = \frac{\pi a^4 M}{16 \eta R T} \frac{|p_2^2 - p_1^2|}{l}$$

**2.247** Let  $T$  = temperature of the interface.

Then heat flowing from left = heat flowing into right in equilibrium.

$$\text{Thus, } \kappa_1 \frac{T_1 - T}{l_1} = \kappa_2 \frac{T - T_2}{l_2} \text{ or } T = \frac{\left( \frac{\kappa_1 T_1}{l_1} + \frac{\kappa_2 T_2}{l_2} \right)}{\left( \frac{\kappa_1}{l_1} + \frac{\kappa_2}{l_2} \right)}$$

**2.248** We have

$$\kappa_1 \frac{T_1 - T}{l_1} = \kappa_2 \frac{T - T_2}{l_2} = \kappa \frac{T_1 - T_2}{l_1 + l_2}$$

or using the previous result

$$\frac{\kappa_1}{l_1} \left( T_1 - \frac{\frac{\kappa_1 T_1}{l_1} + \frac{\kappa_2 T_2}{l_2}}{\frac{\kappa_1}{l_1} + \frac{\kappa_2}{l_2}} \right) = \kappa \frac{T_1 - T_2}{l_1 + l_2}$$

$$\text{or } \frac{\kappa_1 \frac{\kappa_2}{l_2} (T_1 - T_2)}{\frac{\kappa_1}{l_1} + \frac{\kappa_2}{l_2}} = \kappa \frac{T_1 - T_2}{l_1 + l_2} \text{ or } \kappa = \frac{l_1 + l_2}{\frac{l_1}{\kappa_1} + \frac{l_2}{\kappa_2}}$$

**2.249** By definition the heat flux (per unit area) is

$$\dot{Q} = -K \frac{dT}{dx} = -\alpha \frac{d}{dx} \ln T = \text{constant} = +\alpha \frac{\ln T_1/T_2}{l}$$

$$\text{Integrating} \quad \ln T = \frac{x}{l} \ln \frac{T_2}{T_1} + \ln T_1$$

where  $T_1$  = temperature at the end  $x = 0$

$$\text{So } T = T_1 \left( \frac{T_2}{T_1} \right)^{x/l} \text{ and } \dot{Q} = \frac{\alpha \ln T_1/T_2}{l}$$

**2.250** Suppose the chunks have temperatures  $T_1, T_2$  at time  $t$  and  $T_1 - dT_1, T_2 + dT_2$  at time  $dt + t$ .

$$\text{Then } C_1 dT_1 = C_2 dT_2 = \frac{\kappa S}{l} (T_1 - T_2) dt$$

$$\text{Thus } d\Delta T = -\frac{\kappa S}{l} \left( \frac{1}{C_1} + \frac{1}{C_2} \right) \Delta T dt \text{ where } \Delta T = T_1 - T_2$$

$$\text{Hence } \Delta T = (\Delta T)_0 e^{-t/\tau} \text{ where } \frac{1}{\tau} = \frac{\kappa S}{l} \left( \frac{1}{C_1} + \frac{1}{C_2} \right)$$

$$\begin{aligned}
 2.251 \quad \dot{Q} &= \kappa \frac{\partial T}{\partial x} = -A \sqrt{T} \frac{\partial T}{\partial x} \\
 &= -\frac{2}{3} A \frac{\partial T^{3/2}}{\partial x}, \quad (A = \text{constant}) \\
 &= \frac{2}{3} A \frac{(T_1^{3/2} - T_2^{3/2})}{l}
 \end{aligned}$$

Thus  $T^{3/2} = \text{constant} - \frac{x}{l} (T_1^{3/2} - T_2^{3/2})$

or using  $T = T_1$  at  $x = 0$

$$\begin{aligned}
 T^{3/2} &= T_1^{3/2} + \frac{x}{l} (T_2^{3/2} - T_1^{3/2}) \quad \text{or} \quad \left( \frac{T}{T_1} \right)^{3/2} = 1 + \frac{x}{l} \left( \left( \frac{T_2}{T_1} \right)^{3/2} - 1 \right) \\
 T &= T_1 \left[ 1 + \frac{x}{l} \left\{ \left( \frac{T_2}{T_1} \right)^{3/2} - 1 \right\} \right]^{2/3}
 \end{aligned}$$

$$2.252 \quad \kappa = \frac{1}{3} \sqrt{\frac{8RT}{\pi M}} \frac{1}{\sqrt{2} \pi d^2 n} \frac{R}{M} \frac{i}{2} = \frac{R^{3/2} i T^{3/2}}{3\pi^{3/2} d^2 \sqrt{M} N_A}$$

Then from the previous problem

$$q = \frac{2i R^{3/2} (T_2^{3/2} - T_1^{3/2})}{9\pi^{3/2} d^2 \sqrt{M} N_A l}, \quad i = 3 \text{ here.}$$

2.253 At this pressure and average temperature  $= 27^\circ\text{C} = 300\text{K} = T = \frac{(T_1 + T_2)}{2}$

$$\lambda = \frac{1}{\sqrt{2} \pi d^2 p} \frac{\kappa T}{p} = 2330 \times 10^{-5} \text{ m} = 23.3 \text{ mm} > 5.0 \text{ mm} = l$$

The gas is ultrathin and we write  $\lambda = \frac{1}{2} l$  here

Then  $q = \kappa \frac{dT}{dx} = \kappa \frac{T_2 - T_1}{l}$

where  $\kappa = \frac{1}{3} \langle v \rangle \times \frac{1}{2} l \times \frac{MP}{RT} \times \frac{R}{\gamma - 1} \times \frac{1}{M} = \frac{p \langle v \rangle}{6T(\gamma - 1)} l$

and  $q = \frac{p \langle v \rangle}{6T(\gamma - 1)} (T_2 - T_1)$

where  $\langle v \rangle = \sqrt{\frac{8RT}{M\pi}}$ . We have used  $T_2 - T_1 \ll \frac{T_2 + T_1}{2}$  here.

**2.254** In equilibrium  $2\pi r \kappa \frac{dT}{dr} = -A = \text{constant}$ . So  $T = B - \frac{A}{2\pi\kappa} \ln r$

But  $T = T_1$  when  $r = R_1$  and  $T = T_2$  when  $r = R_2$ .

$$\text{From this we find } T = T_1 + \frac{T_2 - T_1}{\ln \frac{R_2}{R_1}} \ln \frac{r}{R_1}$$

**2.255** In equilibrium  $4\pi r^2 \kappa \frac{dT}{dr} = -A = \text{constant}$

$$T = B + \frac{A}{4\pi\kappa} \frac{1}{r}$$

Using  $T = T_1$  when  $r = R_1$  and  $T = T_2$  when  $r = R_2$ ,

$$T = T_1 + \frac{T_2 - T_1}{\frac{1}{R_2} - \frac{1}{R_1}} \left( \frac{1}{r} - \frac{1}{R_1} \right)$$

**2.256** The heat flux vector is  $-\kappa \text{ grad } T$  and its divergence equals  $w$ . Thus

$$\nabla^2 T = -\frac{w}{\kappa}$$

or 
$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) = -\frac{w}{\kappa} \text{ in cylindrical coordinates.}$$

or 
$$T = B + A \ln r - \frac{w}{2\kappa} r^2$$

Since  $T$  is finite at  $r = 0$ ,  $A = 0$ . Also  $T = T_0$  at  $r = R$

so 
$$B = T_0 + \frac{w}{4\kappa} R^2$$

Thus 
$$T = T_0 + \frac{w}{4\kappa} (R^2 - r^2)$$

$r$  here is the distance from the axis of wire (axial radius).

**2.257** Here again

$$\nabla^2 T = -\frac{w}{\kappa}$$

So in spherical polar coordinates,

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) = -\frac{w}{\kappa} \text{ or } r^2 \frac{\partial T}{\partial r} = -\frac{w}{3\kappa} r^3 + A$$

or 
$$T = B - \frac{A}{r} - \frac{w}{6\kappa} r^2$$

Again 
$$A = 0 \text{ and } B = T_0 + \frac{w}{6\kappa} R^2$$

so finally 
$$T = T_0 + \frac{w}{6\kappa} (R^2 - r^2)$$

## PART THREE

# ELECTRODYNAMICS

---

### 3.1 CONSTANT ELECTRIC FIELD IN VACUUM

$$3.1 \quad F_d \text{ (for electrons)} = \frac{q^2}{4 \pi \epsilon_0 r^2} \text{ and } F_{gr} = \frac{\gamma m^2}{r^2}$$

$$\begin{aligned} \text{Thus} \quad \frac{F_d}{F_{gr}} \text{ (for electrons)} &= \frac{q^2}{4 \pi \epsilon_0 \gamma m^2} \\ &= \frac{(1.602 \times 10^{-19} \text{ C})^2}{\left(\frac{1}{9 \times 10^9}\right) \times 6.67 \times 10^{-11} \text{ m}^3 / (\text{kg} \cdot \text{s}^2) \times (9.11 \times 10^{-31} \text{ kg})^2} = 4 \times 10^{42} \end{aligned}$$

$$\begin{aligned} \text{Similarly} \quad \frac{F_d}{F_{gr}} \text{ (for proton)} &= \frac{q^2}{4 \pi \epsilon_0 \gamma m^2} \\ &= \frac{(1.602 \times 10^{-19} \text{ C})^2}{\left(\frac{1}{9 \times 10^9}\right) \times 6.67 \times 10^{-11} \text{ m}^3 / (\text{kg} \cdot \text{s}^2) \times (1.672 \times 10^{-27} \text{ kg})^2} = 1 \times 10^{36} \end{aligned}$$

$$\text{For } F_d = F_{gr}$$

$$\begin{aligned} \frac{q^2}{4 \pi \epsilon_0 r^2} &= \frac{\gamma m^2}{r^2} \text{ or } \frac{q}{m} = \sqrt{4 \pi \epsilon_0 \gamma} \\ &= \sqrt{\frac{6.67 \times 10^{-11} \text{ m}^3 (\text{kg} \cdot \text{s}^2)}{9 \times 10^9}} = 0.86 \times 10^{-10} \text{ C/kg} \end{aligned}$$

$$3.2 \quad \text{Total number of atoms in the sphere of mass 1 gm} = \frac{1}{63.54} \times 6.023 \times 10^{23}$$

$$\text{So the total nuclear charge } \lambda = \frac{6.023 \times 10^{23}}{63.54} \times 1.6 \times 10^{-19} \times 29$$

Now the charge on the sphere = Total nuclear charge – Total electronic charge

$$= \frac{6.023 \times 10^{23}}{63.54} \times 1.6 \times 10^{-19} \times \frac{29 \times 1}{100} = 4.298 \times 10^2 \text{ C}$$

Hence force of interaction between these two spheres,

$$F = \frac{1}{4\pi\epsilon_0} \cdot \frac{[4.398 \times 10^2]^2}{1^2} \text{ N} = 9 \times 10^9 \times 10^4 \times 19.348 \text{ N} = 1.74 \times 10^{15} \text{ N}$$

**3.3** Let the balls be deviated by an angle  $\theta$ , from the vertical when separation between them equals  $x$ .

Applying Newton's second law of motion for any one of the sphere, we get,

$$T \cos \theta = mg \quad (1)$$

$$\text{and} \quad T \sin \theta = F_e \quad (2)$$

From the Eqs. (1) and (2)

$$\tan \theta = \frac{F_e}{mg} \quad (3)$$

But from the figure

$$\tan \theta = \frac{x}{2\sqrt{l^2 - \left(\frac{x}{2}\right)^2}} \approx \frac{x}{2l} \text{ as } x \ll l \quad (4)$$

From Eqs. (3) and (4)

$$F_e = \frac{mgx}{2l} \text{ or } \frac{q^2}{4\pi\epsilon_0 x^2} = \frac{mgx}{2l}$$

Thus

$$q^2 = \frac{2\pi\epsilon_0 mg x^3}{l} \quad (5)$$

Differentiating Eqn. (5) with respect to time

$$2q \frac{dq}{dt} = \frac{2\pi\epsilon_0 mg}{l} 3x^2 \frac{dx}{dt}$$

According to the problem  $\frac{dx}{dt} = v = a/\sqrt{x}$  (approach velocity is  $\frac{dx}{dt}$ )

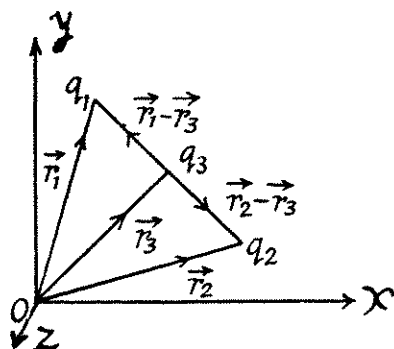
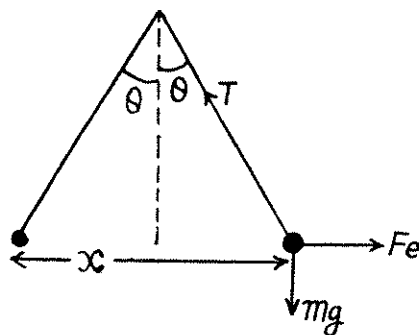
$$\text{so, } \left( \frac{2\pi\epsilon_0 mg}{l} x^3 \right)^{1/2} \frac{dq}{dt} = \frac{3\pi\epsilon_0 mg}{l} x^2 \frac{a}{\sqrt{x}}$$

$$\text{Hence, } \frac{dq}{dt} = \frac{3}{2} a \sqrt{\frac{2\pi\epsilon_0 mg}{l}}$$

**3.4** Let us choose coordinate axes as shown in the figure and fix three charges,  $q_1$ ,  $q_2$  and  $q_3$  having position vectors  $\vec{r}_1$ ,  $\vec{r}_2$  and  $\vec{r}_3$  respectively.

Now, for the equilibrium of  $q_3$

$$\frac{+q_2 q_3 (\vec{r}_2 - \vec{r}_3)}{|\vec{r}_2 - \vec{r}_3|^3} + \frac{q_1 q_3 (\vec{r}_1 - \vec{r}_3)}{|\vec{r}_1 - \vec{r}_3|^3} = 0$$



$$\text{or, } \frac{q_2}{|\vec{r}_2 - \vec{r}_3|^2} = \frac{q_1}{|\vec{r}_1 - \vec{r}_3|^2}$$

$$\text{because } \frac{\vec{r}_2 - \vec{r}_3}{|\vec{r}_2 - \vec{r}_3|} = - \frac{\vec{r}_1 - \vec{r}_3}{|\vec{r}_1 - \vec{r}_3|}$$

$$\text{or, } \sqrt{q_2} (\vec{r}_1 - \vec{r}_3) = \sqrt{q_1} (\vec{r}_3 - \vec{r}_2)$$

$$\text{or, } \vec{r}_3 = \frac{\sqrt{q_2} \vec{r}_1 + \sqrt{q_1} \vec{r}_2}{\sqrt{q_1} + \sqrt{q_2}}$$

Also for the equilibrium of  $q_1$ ,

$$\frac{q_3 (\vec{r}_3 - \vec{r}_1)}{|\vec{r}_3 - \vec{r}_1|^3} + \frac{q_2 (\vec{r}_2 - \vec{r}_1)}{|\vec{r}_2 - \vec{r}_1|^3} = 0$$

$$\text{or, } q_3 = \frac{-q_2}{|\vec{r}_2 - \vec{r}_1|^2} |\vec{r}_1 - \vec{r}_3|^2$$

Substituting the value of  $\vec{r}_3$ , we get,

$$q_3 = \frac{-q_1 q_2}{(\sqrt{q_1} + \sqrt{q_2})^2}$$

**3.5** When the charge  $q_0$  is placed at the centre of the ring, the wire get stretched and the extra tension, produced in the wire, will balance the electric force due to the charge  $q_0$ . Let the tension produced in the wire, after placing the charge  $q_0$ , be  $T$ . From Newton's second law in projection form  $F_n = mw_n$ ,

$$T d\theta - \frac{1}{4\pi\epsilon_0} \frac{q_0}{r^2} \left( \frac{q}{2\pi r} r d\theta \right) = (dm) 0,$$

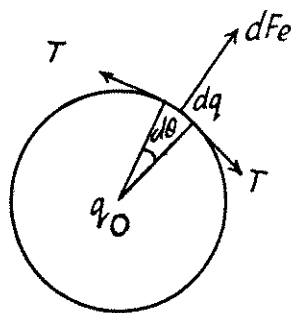
$$\text{or, } T = \frac{q q_0}{8\pi^2 \epsilon_0 r^2}$$

**3.6** Sought field strength

$$\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{q}{|\vec{r} - \vec{r}_0|^2}$$

= 4.5 kV/m on putting the values.

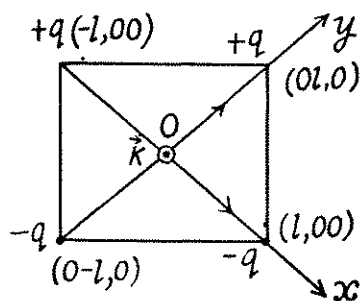
**3.7** Let us fix the coordinate system by taking the point of intersection of the diagonals as the origin and let  $\vec{k}$  be directed normally, emerging from the plane of figure. Hence the sought field strength :





$$\begin{aligned}\vec{E} &= \frac{q}{4\pi\epsilon_0(l^2+x^2)^{3/2}} + \frac{-q}{4\pi\epsilon_0(l^2+x^2)^{3/2}} \frac{l(-\vec{i})+x\vec{k}}{(l^2+x^2)^{3/2}} \\ &+ \frac{-q}{4\pi\epsilon_0(l^2+x^2)^{3/2}} + \frac{q}{4\pi\epsilon_0(l^2+x^2)^{3/2}} \frac{l(-\vec{j})+x\vec{k}}{(l^2+x^2)^{3/2}} \\ &= \frac{q}{4\pi\epsilon_0(l^2+x^2)^{3/2}} [2l\vec{i} - 2l\vec{j}]\end{aligned}$$

Thus  $E = \frac{ql}{\sqrt{2}\pi\epsilon_0(l^2+x^2)^{3/2}}$



3.8 From the symmetry of the problem the sought field.

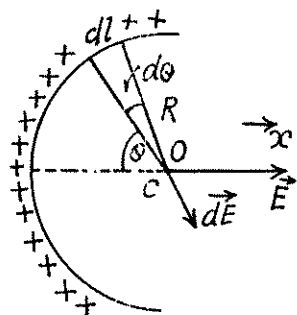
$$E = \int dE_x$$

where the projection of field strength along  $x$ -axis due to an elemental charge is

$$dE_x = \frac{dq \cos \theta}{4\pi\epsilon_0 R^2} = \frac{q R \cos \theta d\theta}{4\pi^2 \epsilon_0 R^3}$$

Hence

$$E = \frac{q}{4\pi^2 \epsilon_0 R^2} \int_{\pi/2}^{\pi/2} \cos \theta d\theta \frac{q}{2\pi^2 \epsilon_0 R^2}$$



3.9 From the symmetry of the condition, it is clear that, the field along the normal will be zero

i.e.

$$E_n = 0 \text{ and } E = E_l$$

Now

$$dE_l = \frac{dq}{4\pi\epsilon_0(R^2+l^2)} \cos \theta$$

But

$$dq = \frac{q}{2\pi R} dx \text{ and } \cos \theta = \frac{l}{(R^2+l^2)^{1/2}}$$

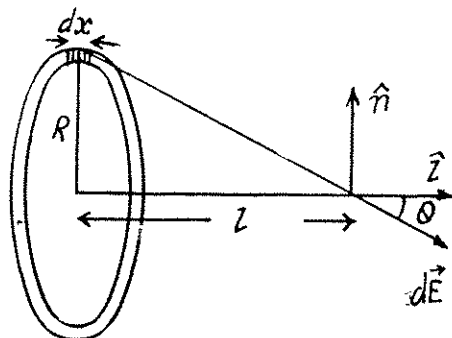
Hence

$$E = \int dE_l = \int_0^{2\pi R} \frac{ql}{2\pi R} \cdot \frac{dx}{4\pi\epsilon_0(R^2+l^2)^{3/2}}$$

$$\text{or } E = \frac{1}{4\pi\epsilon_0} \frac{ql}{(l^2+R^2)^{3/2}}$$

and for  $l \gg R$ , the ring behaves like a point charge, reducing the field to the value,

$$E = \frac{1}{4\pi\epsilon_0} \frac{q}{l^2}$$



For  $E_{\max}$ , we should have  $\frac{dE}{dl} = 0$

$$\text{So, } (l^2 + R^2)^{3/2} - \frac{3}{2} l (l^2 + R^2)^{1/2} 2l = 0 \quad \text{or} \quad l^2 + R^2 - 3l^2 = 0$$

$$\text{Thus } l = \frac{R}{\sqrt{2}} \quad \text{and} \quad E_{\max} = \frac{q}{6\sqrt{3} \pi \epsilon_0 R^2}$$

3.10 The electric potential at a distance  $x$  from the given ring is given by,

$$\varphi(x) = \frac{q}{4\pi\epsilon_0 x} - \frac{q}{4\pi\epsilon_0 (R^2 + x^2)^{1/2}}$$

Hence, the field strength along  $x$ -axis (which is the net field strength in our case),

$$\begin{aligned} E_x &= -\frac{d\varphi}{dx} = \frac{q}{4\pi\epsilon_0 x^2} - \frac{qx}{4\pi\epsilon_0 (R^2 + x^2)^{3/2}} \\ &= \frac{\frac{q}{4\pi\epsilon_0} x^3 \left[ \left(1 + \frac{R^2}{x^2}\right)^{3/2} - 1 \right]}{x^2 (R^2 + x^2)^{3/2}} \\ &= \frac{\frac{q}{4\pi\epsilon_0} x^3 \left[ 1 + \frac{3}{2} \frac{R^2}{x^2} + \frac{3}{8} \frac{R^4}{x^4} + \dots \right]}{x^2 (R^2 + x^2)^{3/2}} \end{aligned}$$

Neglecting the higher power of  $R/x$ , as  $x \gg R$ .

$$E = \frac{3qR^2}{8\pi\epsilon_0 x^4}$$

Note : Instead of  $\varphi(x)$ , we may write  $E(x)$  directly using 3.9

3.11 From the solution of 3.9, the electric field strength due to ring at a point on its axis (say  $x$ -axis) at distance  $x$  from the centre of the ring is given by :

$$E(x) = \frac{qx}{4\pi\epsilon_0 (R^2 + x^2)^{3/2}}$$

And from symmetry  $\vec{E}$  at every point on the axis is directed along the  $x$ -axis (Fig.).

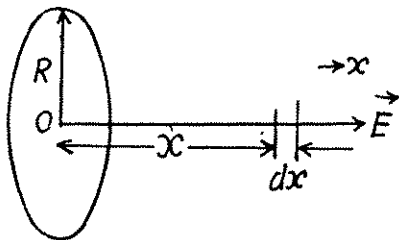
Let us consider an element ( $dx$ ) on thread which carries the charge ( $\lambda dx$ ). The electric force experienced by the element in the field of ring.

$$dF = (\lambda dx) E(x) = \frac{\lambda qx dx}{4\pi\epsilon_0 (R^2 + x^2)^{3/2}}$$

Thus the sought interaction

$$F = \int_0^\infty \frac{\lambda qx dx}{4\pi\epsilon_0 (R^2 + x^2)^{3/2}}$$

On integrating we get,  $F = \frac{\lambda q}{4\pi\epsilon_0 R}$



- 3.12 (a) The given charge distribution is shown in Fig. The symmetry of this distribution implies that vector  $\vec{E}$  at the point  $O$  is directed to the right, and its magnitude is equal to the sum of the projection onto the direction of  $\vec{E}$  of vectors  $d\vec{E}$  from elementary charges  $dq$ . The projection of vector  $d\vec{E}$  onto vector  $\vec{E}$  is

$$dE \cos \varphi = \frac{1}{4 \pi \epsilon_0 R^2} dq \cos \varphi,$$

where  $dq = \lambda R d\varphi = \lambda_0 R \cos \varphi d\varphi$ .

Integrating (1) over  $\varphi$  between 0 and  $2\pi$  we find the magnitude of the vector  $E$ :

$$E = \frac{\lambda_0}{4 \pi \epsilon_0 R} \int_0^{2\pi} \cos^2 \varphi d\varphi = \frac{\lambda_0}{4 \epsilon_0 R}.$$

It should be noted that this integral is evaluated in the most simple way if we take into account that  $\langle \cos^2 \varphi \rangle = 1/2$ . Then

$$\int_0^{2\pi} \cos^2 \varphi d\varphi = \langle \cos^2 \varphi \rangle 2\pi = \pi.$$

- (b) Take an element  $S$  at an azimuthal angle  $\varphi$  from the  $x$ -axis, the element subtending an angle  $d\varphi$  at the centre.

The elementary field at  $P$  due to the element is

$$\frac{\lambda_0 \cos \varphi d\varphi R}{4 \pi \epsilon_0 (x^2 + R^2)} \text{ along } SP \text{ with components}$$

$$\frac{\lambda_0 \cos \varphi d\varphi R}{4 \pi \epsilon_0 (x^2 + R^2)} \times \{ \cos \theta \text{ along } OP, \sin \theta \text{ along } OS \}$$

where

$$\cos \theta = \frac{x}{(x^2 + R^2)^{1/2}}$$

The component along  $OP$  vanishes on integration as  $\int_0^{2\pi} \cos \varphi d\varphi = 0$

The component along  $OS$  can be broken into the parts along  $OX$  and  $OY$  with

$$\frac{\lambda_0 R^2 \cos \varphi d\varphi}{4 \pi \epsilon_0 (x^2 + R^2)^{3/2}} \times \{ \cos \varphi \text{ along } OX, \sin \varphi \text{ along } OY \}$$

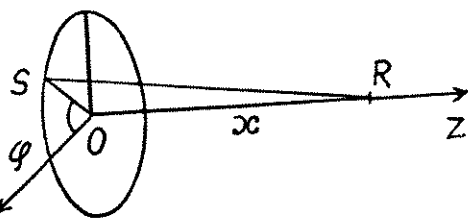
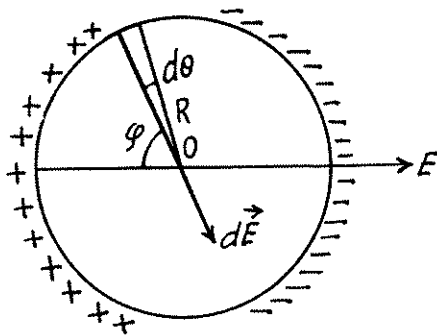
On integration, the part along  $OY$  vanishes.

Finally

$$E = E_x = \frac{\lambda_0 R^2}{4 \epsilon_0 (x^2 + R^2)^{3/2}}$$

For  $x \gg R$

$$E_x = \frac{p}{4 \pi \epsilon_0 x^3} \text{ where } p = \lambda_0 \pi R^2$$



- 3.13 (a) It is clear from symmetry considerations that vector  $\vec{E}$  must be directed as shown in the figure. This shows the way of solving this problem : we must find the component  $dE_r$  of the field created by the element  $dl$  of the rod, having the charge  $dq$  and then integrate the result over all the elements of the rod. In this case

$$dE_r = dE \cos \alpha = \frac{1}{4\pi\epsilon_0} \frac{\lambda dl}{r_0^2} \cos \alpha,$$

where  $\lambda = \frac{q}{2a}$  is the linear charge density. Let us reduce this equation of the form convenient

for integration. Figure shows that  $dl \cos \alpha = r_0 d\alpha$  and  $r_0 = \frac{r}{\cos \alpha}$ ;

Consequently,

$$dE_r = \frac{1}{4\pi\epsilon_0} \frac{\lambda r_0 d\alpha}{r_0^2} = \frac{\lambda}{4\pi\epsilon_0 r} \cos \alpha d\alpha$$

This expression can be easily integrated :

$$E = \frac{\lambda}{4\pi\epsilon_0 r} 2 \int_0^{\alpha_0} \cos \alpha d\alpha = \frac{\lambda}{4\pi\epsilon_0 r} 2 \sin \alpha_0$$

where  $\alpha_0$  is the maximum value of the angle  $\alpha$ ,

$$\sin \alpha_0 = a / \sqrt{a^2 + r^2}$$

$$\text{Thus, } E = \frac{q/2a}{4\pi\epsilon_0 r} 2 \frac{a}{\sqrt{a^2 + r^2}} = \frac{q}{4\pi\epsilon_0 r \sqrt{a^2 + r^2}}$$

Note that in this case also  $E \approx \frac{q}{4\pi\epsilon_0 r^2}$  for  $r \gg a$  as of the field of a point charge.

- (b) Let, us consider the element of length  $dl$  at a distance  $l$  from the centre of the rod, as shown in the figure.

Then field at  $P$ , due to this element.

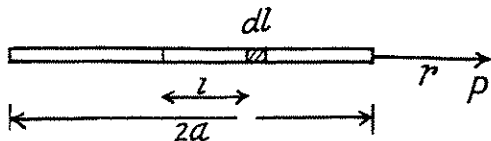
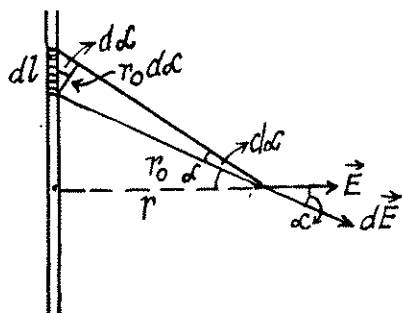
$$dE = \frac{\lambda dl}{4\pi\epsilon_0 (r-l)^2}, \quad \text{if the element lies on the side, shown in the diagram, and } dE = \frac{\lambda dl}{4\pi\epsilon_0 (r+l)^2}, \text{ if it lies on}$$

other side.

$$\text{Hence } E = \int dE = \int_0^a \frac{\lambda dl}{4\pi\epsilon_0 (r-l)^2} + \int_0^a \frac{\lambda dl}{4\pi\epsilon_0 (r+l)^2}$$

On integrating and putting  $\lambda = \frac{q}{2a}$ , we get,  $E = \frac{q}{4\pi\epsilon_0} \frac{1}{(r^2 - a^2)}$

$$\text{For } r \gg a, \quad E \approx \frac{q}{4\pi\epsilon_0 r^2}$$



**3.14** The problem is reduced to finding  $E_x$  and  $E_y$  viz. the projections of  $\vec{E}$  in Fig, where it is assumed that  $\lambda > 0$ .

Let us start with  $E_x$ . The contribution to  $E_x$  from the charge element of the segment  $dx$  is

$$dE_x = \frac{1}{4\pi\epsilon_0} \frac{\lambda dx}{r^2} \sin \alpha \quad (1)$$

Let us reduce this expression to the form convenient for integration. In our case,  $dx = r d\alpha / \cos \alpha$ ,  $r = y / \cos \alpha$ . Then

$$dE_x = \frac{\lambda}{4\pi\epsilon_0 y} \sin \alpha d\alpha.$$

Integrating this expression over  $\alpha$  between

$\theta$  and  $\pi/2$ , we find

$$E_x = \lambda / 4\pi\epsilon_0 y.$$

In order to find the projection  $E_y$  it is sufficient to recall that  $dE_y$  differs from  $dE_x$  in that  $\sin \alpha$  in (1) is simply replaced by  $\cos \alpha$ .

This gives

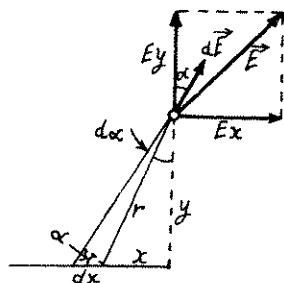
$$dE_y = (\lambda \cos \alpha d\alpha) / 4\pi\epsilon_0 y \text{ and } E_y = \lambda / 4\pi\epsilon_0 y.$$

We have obtained an interesting result :

$E_x = E_y$  independently of  $y$ ,

i.e.  $\vec{E}$  is oriented at the angle of  $45^\circ$  to the rod. The modulus of  $\vec{E}$  is

$$E = \sqrt{E_x^2 + E_y^2} = \lambda\sqrt{2} / 4\pi\epsilon_0 y.$$



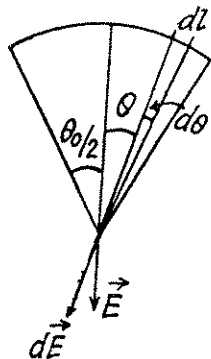
**3.15** (a) Using the solution of 3.14, the net electric field strength at the point  $O$  due to straight parts of the thread equals zero. For the curved part (arc) let us derive a general expression i.e. let us calculate the field strength at the centre of arc of radius  $R$  and linear charge density  $\lambda$  and which subtends angle  $\theta_0$  at the centre.

From the symmetry the sought field strength will be directed along the bisector of the angle  $\theta_0$  and is given by

$$E = \int_{-\theta_0/2}^{+\theta_0/2} \frac{\lambda (R d\theta)}{4\pi\epsilon_0 R^2} \cos \theta = \frac{\lambda}{2\pi\epsilon_0 R} \sin \frac{\theta_0}{2}$$

In our problem  $\theta_0 = \pi/2$ , thus the field strength due to the turned part at the point

$$E_0 = \frac{\sqrt{2} \lambda}{4\pi\epsilon_0 R} \text{ which is also the sought result.}$$



(b) Using the solution of 3.14 (a), net field strength at  $O$  due to straight parts equals

$$\sqrt{2} \left( \frac{\sqrt{2} \lambda}{4\pi\epsilon_0 R} \right) = \frac{\lambda}{2\pi\epsilon_0 R} \text{ and is directed vertically down. Now using the solution of 3.15}$$

(a), field strength due to the given curved part (semi-circle) at the point  $O$  becomes  $\frac{\lambda}{2\pi\epsilon_0 R}$  and is directed vertically upward. Hence the sought net field strength becomes zero.

- 3.16 Given charge distribution on the surface  $\sigma = \vec{a} \cdot \vec{r}$  is shown in the figure. Symmetry of this distribution implies that the sought  $E$  at the centre  $O$  of the sphere is opposite to  $\vec{a}$ .  $dq = \sigma (2\pi r \sin \theta) r d\theta = (\vec{a} \cdot \vec{r}) 2\pi r^2 \sin \theta d\theta = 2\pi a r^3 \sin \theta \cos \theta d\theta$ . Again from symmetry, field strength due to any ring element  $dE$  is also opposite to  $\vec{a}$  i.e.  $dE \uparrow \downarrow \vec{a}$ . Hence

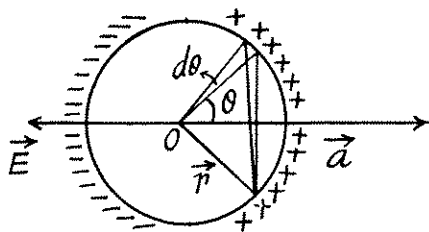
$$d\vec{E} = \frac{dq r \cos \theta}{4\pi\epsilon_0 (r^2 \sin^2 \theta + r^2 \cos^2 \theta)^{3/2}} \frac{-\vec{a}}{a} \quad (\text{Using the result of 3.9})$$

$$= \frac{(2\pi a r^3 \sin \theta \cos \theta d\theta) r \cos \theta}{4\pi\epsilon_0 r^3} \frac{(-\vec{a})}{a}$$

$$= \frac{-\vec{a} r}{2\epsilon_0} \sin \theta \cos^2 \theta d\theta$$

Thus 
$$\vec{E} = \int d\vec{E} = \frac{(-\vec{a}) r}{2\epsilon_0} \int_0^\pi \sin \theta \cos^2 \theta d\theta$$

Integrating, we get 
$$\vec{E} = -\frac{\vec{a} r}{2\epsilon_0} \frac{2}{3} = -\frac{\vec{a} r}{3\epsilon_0}$$



- 3.17 We start from two charged spherical balls each of radius  $R$  with equal and opposite charge densities  $+\rho$  and  $-\rho$ . The centre of the balls are at  $+\frac{\vec{a}}{2}$  and  $-\frac{\vec{a}}{2}$  respectively so the equation of their surfaces are  $\left| \vec{r} - \frac{\vec{a}}{2} \right| = R$  or  $r - \frac{a}{2} \cos \theta = R$  and  $r + \frac{a}{2} \cos \theta = R$ , considering  $a$  to be small. The distance between the two surfaces in the radial direction at angle  $\theta$  is  $|a \cos \theta|$  and does not depend on the azimuthal angle. It is seen from the diagram that the surface of the sphere has in effect a surface density  $\sigma = \sigma_0 \cos \theta$  when

$$\sigma_0 = \rho a.$$

Inside any uniformly charged spherical ball, the field is radial and has the magnitude given by Gauss's theorem

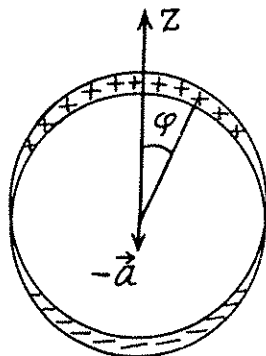
$$4\pi r^2 E = \frac{4\pi}{3} r^3 \rho / \epsilon_0$$

or

$$E = \frac{\rho r}{3\epsilon_0}$$

In vector notation, using the fact the  $V$  must be measured from the centre of the ball, we get, for the present case

$$\vec{E} = \frac{\rho}{3\epsilon_0} \left( \vec{r} - \frac{\vec{a}}{2} \right) - \frac{\rho}{3\epsilon_0} \left( \vec{r} + \frac{\vec{a}}{2} \right)$$



$$= -\rho a \vec{r} / 3\epsilon_0 = \frac{\sigma_0}{3\epsilon_0} \vec{k}$$

When  $\vec{k}$  is the unit vector along the polar axis from which  $\theta$  is measured.

- 3.18** Let us consider an elemental spherical shell of thickness  $dr$ . Thus surface charge density of the shell  $\sigma = \rho dr = (\vec{a} \cdot \vec{r}) dr$ .

Thus using the solution of 3.16, field strength due to this spherical shell

$$d\vec{E} = -\frac{\vec{a} \cdot \vec{r}}{3\epsilon_0} dr$$

Hence the sought field strength

$$\vec{E} = -\frac{\vec{a}}{3\epsilon_0} \int_0^R r dr = -\frac{\vec{a} R^2}{6\epsilon_0}$$

- 3.19** From the solution of 3.14 field strength at a perpendicular distance  $r < R$  from its left end

$$\vec{E}(r) = \frac{\lambda}{4\pi\epsilon_0 r} (-\vec{i}) + \frac{\lambda}{4\pi\epsilon_0 r} (\hat{e}_r)$$

Here  $\hat{e}_r$  is a unit vector along radial direction.

Let us consider an elemental surface,  $dS = dy dz = dz (r d\theta)$  a

figure. Thus

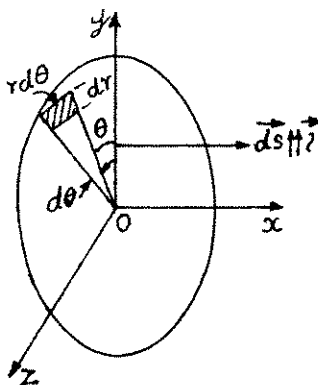
flux of  $\vec{E}(r)$  over the element  $d\vec{S}$  is given by

$$\begin{aligned} d\Phi &= \vec{E} \cdot d\vec{S} = \left[ \frac{\lambda}{4\pi\epsilon_0 r} (-\vec{i}) + \frac{\lambda}{4\pi\epsilon_0 r} (\hat{e}_r) \right] \cdot dr (r d\theta) \vec{i} \\ &= -\frac{\lambda}{4\pi\epsilon_0} dr d\theta \left( \text{as } \vec{e}_r \perp \vec{i} \right) \end{aligned}$$

$$\text{The sought flux, } \Phi = -\frac{\lambda}{4\pi\epsilon_0} \int_0^R dr \int_0^{2\pi} d\theta = -\frac{\lambda R}{2\epsilon_0}$$

If we have taken  $d\vec{S} \uparrow \uparrow (-\vec{i})$ , then  $\Phi$  were  $\frac{\lambda R}{2\epsilon_0}$

$$\text{Hence } |\Phi| = \frac{\lambda R}{2\epsilon_0}$$



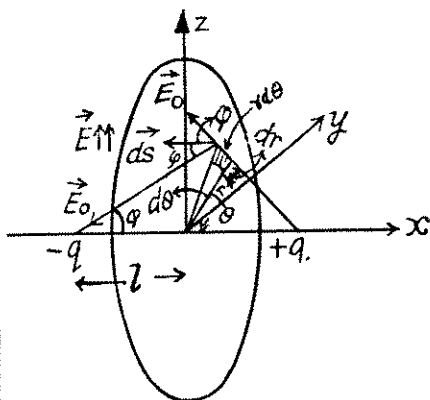
- 3.20** Let us consider an elemental surface area as shown in the figure. Then flux of the vector  $\vec{E}$  through the elemental area,

$$d\Phi = \vec{E} \cdot d\vec{S} = E dS = 2E_0 \cos \varphi dS \text{ (as } \vec{E} \uparrow \uparrow d\vec{S} \text{)}$$

$$= \frac{2q}{4\pi\epsilon_0 (l^2 + r^2)} \frac{l}{(l^2 + r^2)^{1/2}} (r d\theta) dr = \frac{2ql r dr d\theta}{4\pi\epsilon_0 (r^2 + l^2)^{3/2}}$$

where  $E_0 = \frac{q}{4\pi\epsilon_0(l^2 + r^2)}$  is magnitude of field strength due to any point charge at the point of location of considered elemental area.

$$\begin{aligned}\text{Thus } \Phi &= \frac{2ql}{4\pi\epsilon_0} \int_0^R \frac{r dr}{(r^2 + l^2)^{3/2}} \int_0^{2\pi} d\theta \\ &= \frac{2ql \times 2\pi}{4\pi\epsilon_0} \int_0^R \frac{r dr}{(r^2 + l^2)^{3/2}} = \frac{q}{\epsilon_0} \left[ 1 - \frac{l}{\sqrt{l^2 + R^2}} \right]\end{aligned}$$



It can also be solved by considering a ring element or by using solid angle.

- 3.21** Let us consider a ring element of radius  $x$  and thickness  $dx$ , as shown in the figure. Now, flux over the considered element,

$$d\Phi = \vec{E} \cdot d\vec{S} = E_r dS \cos \theta$$

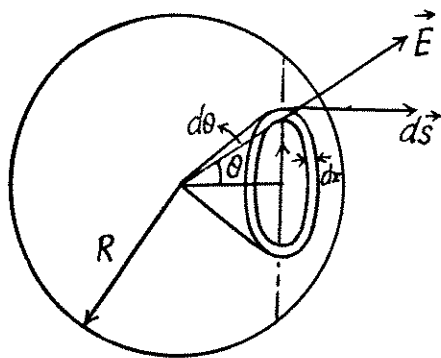
But  $E_r = \frac{\rho r}{3\epsilon_0}$  from Gauss's theorem,

and  $dS = 2\pi x dx$ ,  $\cos \theta = \frac{r_0}{r}$

$$\text{Thus } d\Phi = \frac{\rho r}{3\epsilon_0} 2\pi x dx \frac{r_0}{r} = \frac{\rho r_0}{3\epsilon_0} 2\pi x dx$$

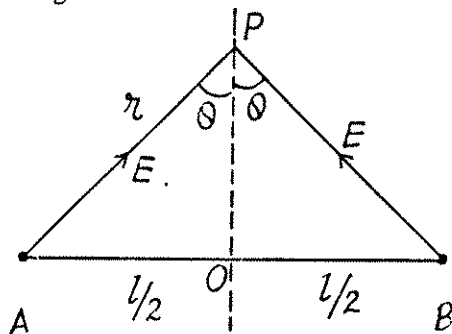
Hence sought flux

$$\begin{aligned}\Phi &= \frac{2\pi\rho r_0}{3\epsilon_0} \int_0^R x dx = \frac{2\pi\rho r_0}{3\epsilon_0} \frac{(R^2 - r_0^2)}{2} = \frac{\pi\rho r_0}{3\epsilon_0} (R^2 - r_0^2)\end{aligned}$$



- 3.22** The field at  $P$  due to the threads at  $A$  and  $B$  are both of magnitude  $\frac{\lambda}{2\pi\epsilon_0(x^2 + l^2/4)^{1/2}}$  and directed along  $AP$  and  $BP$ . The resultant is along  $OP$  with

$$\begin{aligned}E &= \frac{2\lambda \cos \theta}{2\pi\epsilon_0(\pi^2 + \pi^{1/2})^{1/2}} = \frac{\lambda x}{\pi\epsilon_0(x^2 + l^2/4)} \\ &= \frac{\lambda}{\pi\epsilon_0 \left[ x + \frac{l^2}{4x} - 2 \cdot \frac{l}{2\sqrt{x}} \cdot \sqrt{x} + l \right]} \\ &= \frac{\lambda}{\pi\epsilon_0 \left[ \left( \sqrt{x} - \frac{l}{2\sqrt{x}} \right)^2 + l \right]}\end{aligned}$$



This is maximum when  $x = l/2$  and then  $E = E_{\max} = \frac{\lambda}{\pi\epsilon_0 l}$



- 3.23 Take a section of the cylinder perpendicular to its axis through the point where the electric field is to be calculated. (All points on the axis are equivalent.) Consider an element  $S$  with azimuthal angle  $\varphi$ . The length of the element is  $R d\varphi$ ,  $R$  being the radius of cross section of the cylinder. The element itself is a section of an infinite strip. The electric field at  $O$  due to this strip is

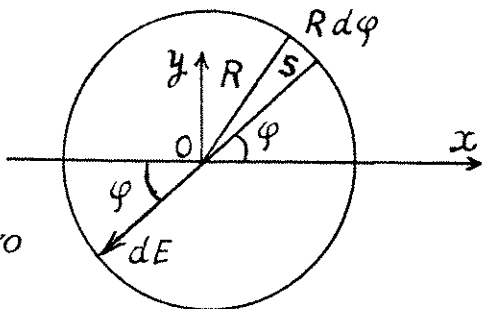
$$\frac{\sigma_0 \cos \varphi (R d\varphi)}{2 \pi \epsilon_0 R} \text{ along } SO$$

This can be resolved into

$$\frac{\sigma_0 \cos \varphi d\varphi}{2 \pi \epsilon_0} \begin{cases} \cos \varphi \text{ along } OX \text{ towards } O \\ \sin \varphi \text{ along } YO \end{cases}$$

On integration the component along  $YO$  vanishes. What remains is

$$\int_0^{2\pi} \frac{\sigma_0 \cos^2 \varphi d\varphi}{2 \pi \epsilon_0} = \frac{\sigma_0}{2 \epsilon_0} \text{ along } XO \text{ i.e. along the direction } \varphi = \pi.$$

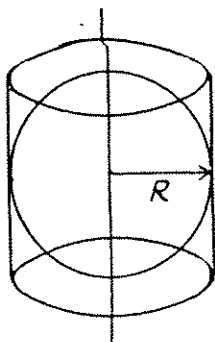


- 3.24 Since the field is axisymmetric (as the field of a uniformly charged filament), we conclude that the flux through the sphere of radius  $R$  is equal to the flux through the lateral surface of a cylinder having the same radius and the height  $2R$ , as arranged in the figure.

$$\text{Now, } \Phi = \oint \vec{E} \cdot d\vec{S} = E_r S$$

$$\text{But } E_r = \frac{a}{R}$$

$$\text{Thus } \Phi = \frac{a}{R} S = \frac{a}{R} 2 \pi R \cdot 2R = 4 \pi a R$$



- 3.25 (a) Let us consider a sphere of radius  $r < R$  then charge, inclosed by the considered sphere,

$$q_{\text{inclosed}} = \int_0^r 4 \pi r^2 dr \rho = \int_0^r 4 \pi r^2 \rho_0 \left(1 - \frac{r}{R}\right) dr \quad (1)$$

Now, applying Gauss' theorem,

$$E_r 4 \pi r^2 = \frac{q_{\text{inclosed}}}{\epsilon_0}, \text{ (where } E_r \text{ is the projection of electric field along the radial line.)}$$

$$= \frac{\rho_0}{\epsilon_0} \int_0^r 4 \pi r^2 \left(1 - \frac{r}{R}\right) dr$$

$$\text{or, } E_r = \frac{\rho_0}{3 \epsilon_0} \left[ r^2 - \frac{3 r^3}{4 R} \right]$$

And for a point, outside the sphere  $r > R$ .

$$q_{\text{inclosed}} = \int_0^R 4\pi r^2 dr \rho_0 \left(1 - \frac{r}{R}\right) \quad (\text{as there is no charge outside the ball})$$

Again from Gauss' theorem,

$$E_r 4\pi r^2 = \int_0^R \frac{4\pi r^2 dr \rho_0 \left(1 - \frac{r}{R}\right)}{\epsilon_0}$$

or, 
$$E_r = \frac{\rho_0}{r^2 \epsilon_0} \left[ \frac{R^3}{3} - \frac{R^4}{4R} \right] = \frac{\rho_0 R^3}{12 r^2 \epsilon_0}$$

(b) As magnitude of electric field decreases with increasing  $r$  for  $r > R$ , field will be maximum for  $r < R$ . Now, for  $E_r$  to be maximum,

$$\frac{d}{dr} \left( r - \frac{3r^2}{4R} \right) = 0 \quad \text{or} \quad 1 - \frac{3r}{2R} = 0 \quad \text{or} \quad r = r_m = \frac{2R}{3}$$

Hence 
$$E_{\text{max}} = \frac{\rho_0 R}{9 \epsilon_0}$$

**3.26** Let the charge carried by the sphere be  $q$ , then using Gauss' theorem for a spherical surface having radius  $r > R$ , we can write.

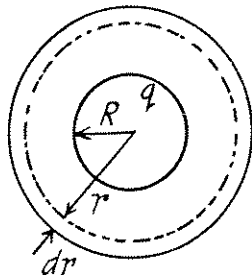
$$E 4\pi r^2 = \frac{q_{\text{inclosed}}}{\epsilon_0} = \frac{q}{\epsilon_0} + \frac{1}{\epsilon_0} \int_R^r \frac{\alpha}{r} 4\pi r^2 dr$$

On integrating we get,

$$E 4\pi r^2 = \frac{(q - 2\pi\alpha R^2)}{\epsilon_0} + \frac{4\pi\alpha r^2}{2\epsilon_0}$$

The intensity  $E$  does not depend on  $r$  when the expression in the parentheses is equal to zero. Hence

$$q = 2\pi\alpha R^2 \quad \text{and} \quad E = \frac{\alpha}{2\epsilon_0}$$



**3.27** Let us consider a spherical layer of radius  $r$  and thickness  $dr$ , having its centre coinciding with the centre of the system. Then using Gauss' theorem for this surface,

$$\begin{aligned} E_r 4\pi r^2 &= \frac{q_{\text{inclosed}}}{\epsilon_0} = \int_0^r \frac{\rho}{\epsilon_0} dV \\ &= \frac{1}{\epsilon_0} \int_0^r \rho_0 e^{-\alpha r^3} 4\pi r^2 dr \end{aligned}$$

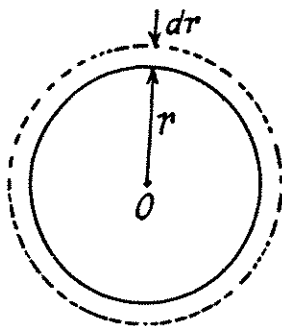
After integration

$$E_r 4 \pi r^2 = \frac{\rho}{3 \epsilon_0} \frac{4 \pi}{\alpha} [1 - e^{-\alpha r^3}]$$

$$\text{or, } E_r = \frac{\rho_0}{3 \epsilon_0 \alpha r^2} [1 - e^{-\alpha r^3}]$$

$$\text{Now when } \alpha r^3 \ll 1, E_r \approx \frac{\rho_0 r}{3 \epsilon_0}$$

$$\text{And when } \alpha r^3 \gg 1, E_r \approx \frac{\rho_0}{3 \epsilon_0 \alpha r^2}$$

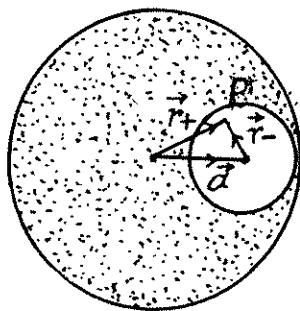


- 3.28** Using Gauss theorem we can easily show that the electric field strength within a uniformly charged sphere is  $\vec{E} = \left( \frac{\rho}{3 \epsilon_0} \right) \vec{r}$

The cavity, in our problem, may be considered as the superposition of two balls, one with the charge density  $\rho$  and the other with  $-\rho$ .

Let  $P$  be a point inside the cavity such that its position vector with respect to the centre of cavity be  $\vec{r}_-$  and with respect to the centre of the ball  $\vec{r}_+$ . Then from the principle of superposition, field inside the cavity, at an arbitrary point  $P$ ,

$$\begin{aligned} \vec{E} &= \vec{E}_+ + \vec{E}_- \\ &= \frac{\rho}{3 \epsilon_0} (\vec{r}_+ - \vec{r}_-) = \frac{\rho}{3 \epsilon_0} \vec{a} \end{aligned}$$



**Note :** Obtained expression for  $\vec{E}$  shows that it is valid regardless of the ratio between the radii of the sphere and the distance between their centres.

- 3.29** Let us consider a cylindrical Gaussian surface of radius  $r$  and height  $h$  inside an infinitely long charged cylinder with charge density  $\rho$ . Now from Gauss theorem :

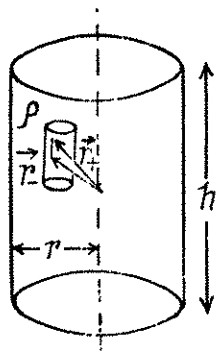
$$E_r 2 \pi r h = \frac{q_{\text{inclosed}}}{\epsilon_0}$$

(where  $E_r$  is the field inside the cylinder at a distance  $r$  from its axis.)

$$\text{or, } E_r 2 \pi r h = \frac{\rho \pi r^2 h}{\epsilon_0} \quad \text{or} \quad E_r = \frac{\rho r}{2 \epsilon_0}$$

Now, using the method of 3.28 field at a point  $P$ , inside the cavity, is

$$\vec{E} = \vec{E}_+ + \vec{E}_- = \frac{\rho}{2 \epsilon_0} (\vec{r}_+ - \vec{r}_-) = \frac{\rho}{2 \epsilon_0} \vec{a}$$



- 3.30 The arrangement of the rings are as shown in the figure. Now, potential at the point 1,  $\varphi_1 =$  potential at 1 due to the ring 1 + potential at 1 due to the ring 2.

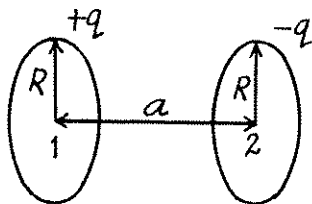
$$= \frac{q}{4\pi\epsilon_0 R} + \frac{-q}{4\pi\epsilon_0 (R^2 + a^2)^{1/2}}$$

Similarly, the potential at point 2,

$$\varphi_2 = \frac{-q}{4\pi\epsilon_0 R} + \frac{q}{4\pi\epsilon_0 (R^2 + a^2)^{1/2}}$$

Hence, the sought potential difference,

$$\begin{aligned}\varphi_1 - \varphi_2 = \Delta\varphi &= 2 \left( \frac{q}{4\pi\epsilon_0 R} + \frac{-q}{4\pi\epsilon_0 (R^2 + a^2)^{1/2}} \right) \\ &= \frac{q}{2\pi\epsilon_0 R} \left( 1 - \frac{1}{\sqrt{1 + (a/R)^2}} \right)\end{aligned}$$



- 3.31 We know from Gauss theorem that the electric field due to an infinitely long straight wire, at a perpendicular distance  $r$  from it equals,  $E_r = \frac{\lambda}{2\pi\epsilon_0 r}$ . So, the work done is

$$\int_1^2 E_r dr = \int_x^{\eta x} \frac{\lambda}{2\pi\epsilon_0 r} dr$$

(where  $x$  is perpendicular distance from the thread by which point 1 is removed from it.)

$$\text{Hence} \quad \Delta\varphi_{12} = \frac{\lambda}{2\pi\epsilon_0} \ln \eta$$

- 3.32 Let us consider a ring element as shown in the figure. Then the charge, carried by the element,  $dq = (2\pi R \sin \theta) R d\theta \sigma$ ,

Hence, the potential due to the considered element at the centre of the hemisphere,

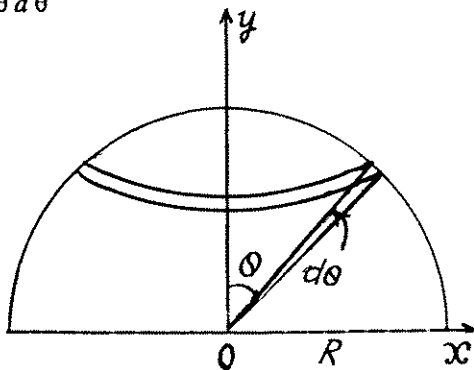
$$d\varphi = \frac{1}{4\pi\epsilon_0} \frac{dq}{R} = \frac{2\pi\sigma R \sin \theta d\theta}{4\pi\epsilon_0} = \frac{\sigma R}{2\epsilon_0} \sin \theta d\theta$$

So potential due to the whole hemisphere

$$\varphi = \frac{R\sigma}{2\epsilon_0} \int_0^{\pi/2} \sin \theta d\theta = \frac{\sigma R}{2\epsilon_0}$$

Now from the symmetry of the problem, net electric field of the hemisphere is directed towards the negative  $y$ -axis. We have

$$dE_y = \frac{1}{4\pi\epsilon_0} \frac{dq \cos \theta}{R^2} = \frac{\sigma}{2\epsilon_0} \sin \theta \cos \theta d\theta$$



$$\text{Thus} \quad E = E_y' = \frac{\sigma}{2\epsilon_0} \int_0^{\pi/2} \sin \theta \cos \theta d\theta = \frac{\sigma}{4\epsilon_0} \int_0^{\pi/2} \sin 2\theta d\theta = \frac{\sigma}{4\epsilon_0}, \text{ along } YO$$

- 3.33 Let us consider an elementary ring of thickness  $dy$  and radius  $y$  as shown in the figure. Then potential at a point  $P$ , at distance  $l$  from the centre of the disc, is

$$d\varphi = \frac{\sigma 2\pi y dy}{4\pi\epsilon_0 (y^2 + l^2)^{1/2}}$$

Hence potential due to the whole disc,

$$\varphi = \int_0^R \frac{\sigma 2\pi y dy}{4\pi\epsilon_0 (y^2 + l^2)^{1/2}} = \frac{\sigma l}{2\epsilon_0} \left( \sqrt{1 + (R/l)^2} - 1 \right)$$

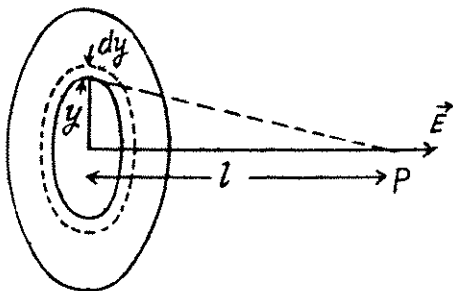
From symmetry

$$E = E_l = -\frac{d\varphi}{dl}$$

$$= -\frac{\sigma}{2\epsilon_0} \left[ \frac{2l}{2\sqrt{R^2 + l^2}} - 1 \right] = \frac{\sigma}{2\epsilon_0} \left[ 1 - \frac{1}{\sqrt{1 + (R/l)^2}} \right]$$

when  $l \rightarrow 0$ ,  $\varphi = \frac{\sigma R}{2\epsilon_0}$ ,  $E = \frac{\sigma}{2\epsilon_0}$  and when  $l \gg R$ ,

$$\varphi \approx \frac{\sigma R^2}{4\epsilon_0 l}, \quad E = \frac{\sigma R^2}{4\epsilon_0 l^2}$$



- 3.34 By definition, the potential in the case of a surface charge distribution is defined by integral

$\varphi = \frac{1}{4\pi\epsilon_0} \int \frac{\sigma dS}{r}$ . In order to simplify integration, we shall choose the area element  $dS$  in the form of a part of the ring of radius  $r$  and width  $dr$  in (Fig.). Then  $dS = 2\theta r dr$ ,  $r = 2R \cos \theta$  and  $dr = -2R \sin \theta d\theta$ . After substituting these expressions into integral

$\varphi = \frac{1}{4\pi\epsilon_0} \int_0^{\pi/2} \frac{\sigma dS}{r}$ , we obtain the expression for  $\varphi$  at the point  $O$ :

$$\varphi = -\frac{\sigma R}{\pi\epsilon_0} \int_{\pi/2}^0 \theta \sin \theta d\theta.$$

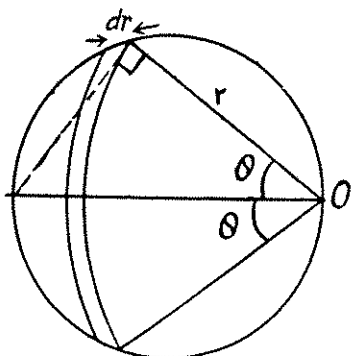
We integrate by parts, denoting  $\theta = u$  and  $\sin \theta d\theta = dv$ :

$$\int \theta \sin \theta d\theta = -\theta \cos \theta$$

$$+ \int \cos \theta d\theta = -\theta \cos \theta + \sin \theta$$

which gives -1 after substituting the limits of integration. As a result, we obtain

$$\varphi = \sigma R / \pi \epsilon_0.$$



3.35 In accordance with the problem  $\varphi = \vec{a} \cdot \vec{r}$

Thus from the equation :  $\vec{E} = -\vec{\nabla} \varphi$

$$\vec{E} = - \left[ \frac{\partial}{\partial x} (a_x x) \vec{i} + \frac{\partial}{\partial y} (a_y y) \vec{j} + \frac{\partial}{\partial z} (a_z z) \vec{k} \right] = - [a_x \vec{i} + a_y \vec{j} + a_z \vec{k}] = -\vec{a}$$

3.36 (a) Given,  $\varphi = a(x^2 - y^2)$

So, 
$$\vec{E} = -\vec{\nabla} \varphi = -2a(x\vec{i} - y\vec{j})$$

The sought shape of field lines is as shown in the figure (a) of answersheet assuming  $a > 0$ :

(b) Since  $\varphi = axy$

So, 
$$\vec{E} = -\vec{\nabla} \varphi = -ay\vec{i} - ax\vec{j}$$

Plot as shown in the figure (b) of answersheet.

3.37 Given,  $\varphi = a(x^2 + y^2) + bz^2$

So, 
$$\vec{E} = -\vec{\nabla} \varphi = -[2ax\vec{i} + 2ay\vec{j} + 2bz\vec{k}]$$

Hence 
$$|\vec{E}| = 2\sqrt{a^2(x^2 + y^2) + b^2z^2}$$

Shape of the equipotential surface :

Put 
$$\vec{\rho} = x\vec{i} + y\vec{j} \text{ or } \rho^2 = x^2 + y^2$$

Then the equipotential surface has the equation

$$a\rho^2 + bz^2 = \text{constant} = \varphi$$

If  $a > 0$ ,  $b > 0$  then  $\varphi > 0$  and the equation of the equipotential surface is

$$\frac{\rho^2}{\varphi/a} + \frac{z^2}{\varphi/b} = 1$$

which is an ellipse in  $\rho, z$  coordinates. In three dimensions the surface is an ellipsoid of revolution with semi-axis  $\sqrt{\varphi/a}$ ,  $\sqrt{\varphi/a}$ ,  $\sqrt{\varphi/b}$ .

If  $a > 0$ ,  $b < 0$  then  $\varphi$  can be  $\geq 0$ . If  $\varphi > 0$  then the equation is

$$\frac{\rho^2}{\varphi/a} - \frac{z^2}{\varphi/|b|} = 1$$

This is a single cavity hyperboloid of revolution about  $z$  axis. If  $\varphi = 0$  then

$$a\rho^2 - |b|z^2 = 0$$

or

$$z = \pm \sqrt{\frac{a}{|b|}} \rho$$

is the equation of a right circular cone.

If  $\varphi < 0$  then the equation can be written as

$$|b|z^2 - a\rho^2 = |\varphi|$$

or

$$\frac{z^2}{|\varphi|/|b|} - \frac{\rho^2}{|\varphi|/a} = 1$$

This is a two cavity hyperboloid of revolution about  $z$ -axis.

**3.38** From Gauss' theorem intensity at a point, inside the sphere at a distance  $r$  from the centre is given by,  $E_r = \frac{\rho r}{3 \epsilon_0}$  and outside it, is given by  $E_r = \frac{1}{4 \pi \epsilon_0} \frac{q}{r^2}$ .

(a) Potential at the centre of the sphere,

$$\varphi_0 = \int_0^\infty \vec{E} \cdot d\vec{r} = \int_0^R \frac{\rho r}{3 \epsilon_0} dr + \int_R^\infty \frac{q}{4 \pi \epsilon_0 r^2} dr = \frac{\rho}{3 \epsilon_0} \frac{R^2}{2} + \frac{q}{4 \pi \epsilon_0 R}$$

as 
$$= \frac{q}{8 \pi \epsilon_0 R} + \frac{q}{4 \pi \epsilon_0 R} = \frac{3q}{8 \pi \epsilon_0 R} \quad \left( \text{as } \rho = \frac{3q}{4 \pi R^3} \right)$$

(b) Now, potential at any point, inside the sphere, at a distance  $r$  from its centre.

$$\varphi(r) = \int_r^R \frac{\rho}{3 \epsilon_0} r dr + \int_r^\infty \frac{q}{4 \pi \epsilon_0 r^2} dr$$

On integration : 
$$\varphi(r) = \frac{3q}{8 \pi \epsilon_0 R} \left[ 1 - \frac{r^2}{R^2} \right] = \varphi_0 \left[ 1 - \frac{r^2}{R^2} \right]$$

**3.39** Let two charges  $+q$  and  $-q$  be separated by a distance  $l$ . Then electric potential at a point at distance  $r \gg l$  from this dipole,

$$\varphi(r) = \frac{+q}{4 \pi \epsilon_0 r_+} + \frac{-q}{4 \pi \epsilon_0 r_-} = \frac{q}{4 \pi \epsilon_0} \left( \frac{r_- - r_+}{r_+ r_-} \right) \quad (1)$$

But

$$r_- - r_+ = l \cos \theta \quad \text{and} \quad r_+ r_- = r^2$$

From Eqs. (1) and (2),

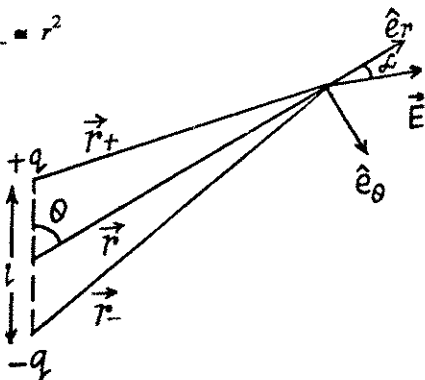
$$\varphi(r) = \frac{q l \cos \theta}{4 \pi \epsilon_0 r^2} = \frac{p \cos \theta}{4 \pi \epsilon_0 r^2} \quad \varphi = \frac{\vec{p} \cdot \vec{r}}{4 \pi \epsilon_0 r^3}$$

where  $p$  is magnitude of electric moment vector.

Now, 
$$E_r = -\frac{\partial \varphi}{\partial r} = \frac{2p \cos \theta}{4 \pi \epsilon_0 r^3}$$

and 
$$E_\theta = -\frac{\partial \varphi}{r \partial \theta} = \frac{p \sin \theta}{4 \pi \epsilon_0 r^3}$$

So 
$$E = \sqrt{E_r^2 + E_\theta^2} = \frac{p}{4 \pi \epsilon_0 r^3} \sqrt{4 \cos^2 \theta + \sin^2 \theta}$$



**3.40** From the results, obtained in the previous problem,

$$E_r = \frac{2p \cos \theta}{4 \pi \epsilon_0 r^3} \quad \text{and} \quad E_\theta = \frac{p \sin \theta}{4 \pi \epsilon_0 r^3}$$

From the given figure, it is clear that,

$$E_z = E_r \cos \theta - E_\theta \sin \theta = \frac{p}{4 \pi \epsilon_0 r^3} (3 \cos^2 \theta - 1)$$

and 
$$E_{\perp} = E_r \sin \theta + E_0 \cos \theta = \frac{3 p \sin \theta \cos \theta}{4 \pi \epsilon_0 r^3}$$

When  $\vec{E} \perp \vec{r}$ ,  $|\vec{E}| = E_{\perp}$  and  $E_z = 0$

So  $3 \cos^2 \theta = 1$  and  $\cos \theta = \frac{1}{\sqrt{3}}$

Thus  $\vec{E} \perp \vec{r}$  at the points located on the lateral surface of the cone, having its axis, coinciding with the direction of  $z$ -axis and semi vertex angle  $\theta = \cos^{-1} 1/\sqrt{3}$ .

- 3.41 Let us assume that the dipole is at the centre of the one equipotential surface which is spherical (Fig.). On an equipotential surface the net electric field strength along the tangent of it becomes zero. Thus

$$-E_0 \sin \theta + E_r = 0 \quad \text{or} \quad -E_0 \sin \theta + \frac{p \sin \theta}{4 \pi \epsilon_0 r^3} = 0$$

Hence 
$$r = \left( \frac{p}{4 \pi \epsilon_0 E_0} \right)^{1/3}$$

Alternate : Potential at the point, near the dipole is given by,

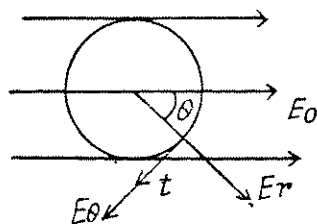
$$\varphi = \frac{\vec{p} \cdot \vec{r}}{4 \pi \epsilon_0 r^3} - \vec{E}_0 \cdot \vec{r} + \text{constant},$$

$$= \left( \frac{p}{4 \pi \epsilon_0 r^3} - E_0 \right) \cos \theta + \text{Const}$$

For  $\varphi$  to be constant,

$$\frac{p}{4 \pi \epsilon_0 r^3} - E_0 = 0 \quad \text{or} \quad \frac{p}{4 \pi \epsilon_0 r^3} = E_0$$

Thus 
$$r = \left( \frac{p}{4 \pi \epsilon_0 E_0} \right)^{1/3}$$



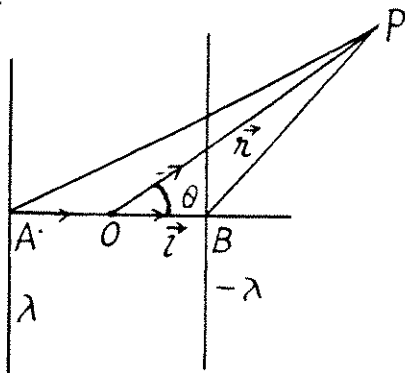
- 3.42 Let  $P$  be a point, at distance  $r \gg l$  and at an angle to  $\theta$  the vector  $\vec{l}$  (Fig.).

$$\text{Thus } \vec{E} \text{ at } P = \frac{\lambda}{2 \pi \epsilon_0} \frac{\vec{r} + \frac{\vec{l}}{2}}{\left| \vec{r} + \frac{\vec{l}}{2} \right|^2} - \frac{\lambda}{2 \pi \epsilon_0} \frac{\vec{r} - \frac{\vec{l}}{2}}{\left| \vec{r} - \frac{\vec{l}}{2} \right|^2}$$

$$= \frac{\lambda}{2 \pi \epsilon_0} \left[ \frac{\vec{r} + \vec{l}/2}{r^2 + \frac{l^2}{4} + r l \cos \theta} - \frac{\vec{r} - \vec{l}/2}{r^2 + \frac{l^2}{4} - r l \cos \theta} \right]$$

$$= \frac{\lambda}{2 \pi \epsilon_0} \left( \frac{\vec{l}}{r^2} - \frac{2 l \vec{r}}{r^3} \cos \theta \right)$$

Hence  $E = |\vec{E}| = \frac{\lambda l}{2 \pi \epsilon_0 r^2}$ ,  $r \gg l$





Also,

$$\varphi = \frac{\lambda}{2\pi\epsilon_0} \ln |\vec{r} + \vec{l}/2| - \frac{\lambda}{2\pi\epsilon_0} \ln |\vec{r} - \vec{l}/2|$$

$$= \frac{\lambda}{4\pi\epsilon_0} \ln \frac{r^2 + rl \cos \theta + l^2/4}{r^2 - rl \cos \theta + l^2/4} = \frac{\lambda l \cos \theta}{2\pi\epsilon_0 r}, \quad r \gg l$$

- 3.43 The potential can be calculated by superposition. Choose the plane of the upper ring as  $x = l/2$  and that of the lower ring as  $x = -l/2$ .

Then

$$\varphi = \frac{q}{4\pi\epsilon_0 [R^2 + (x - l/2)^2]^{1/2}} - \frac{q}{4\pi\epsilon_0 [R^2 + (x + l/2)^2]^{1/2}}$$

$$= \frac{q}{4\pi\epsilon_0 [R^2 + x^2 - lx]^{1/2}} - \frac{q}{4\pi\epsilon_0 [R^2 + x^2 + lx]^{1/2}}$$

$$= \frac{q}{4\pi\epsilon_0 (R^2 + x^2)^{1/2}} \left( 1 + \frac{lx}{2(R^2 + x^2)} \right) - \frac{q}{4\pi\epsilon_0 (R^2 + x^2)^{1/2}} \left( 1 - \frac{lx}{2(R^2 + x^2)} \right)$$

$$= \frac{qlx}{4\pi\epsilon_0 (R^2 + x^2)^{3/2}}$$

For  $|x| \gg R$ ,  $\varphi = \frac{ql}{4\pi x^2}$

The electric field is  $E = -\frac{\partial \varphi}{\partial x}$

$$= -\frac{ql}{4\pi\epsilon_0 (R^2 + x^2)^{3/2}} + \frac{3}{2} \frac{ql}{(R^2 + x^2)^{5/2}} \times 2x = \frac{ql(2x^2 - R^2)}{4\pi\epsilon_0 (R^2 + x^2)^{5/2}}$$

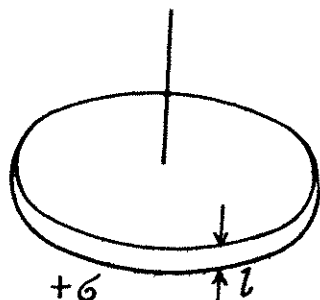
For  $|x| \gg R$ ,  $E = \frac{ql}{2\pi\epsilon_0 x^3}$ . The plot is as given in the book.

- 3.44 The field of a pair of oppositely charged sheets with holes can by superposition be reduced to that of a pair of uniform opposite charged sheets and discs with opposite charges. Now the charged sheets do not contribute any field outside them. Thus using the result of the previous problem

$$\varphi = \int_0^R \frac{(-\sigma) l 2\pi r dr x}{4\pi\epsilon_0 (r^2 + x^2)^{3/2}}$$

$$= -\frac{\sigma xl}{4\epsilon_0} \int_0^{R^2+x^2} \frac{dy}{y^{3/2}} = -\frac{\sigma xl}{2\epsilon_0 \sqrt{R^2+x^2}}$$

$$E_x = -\frac{\partial \varphi}{\partial x} = -\frac{\sigma l}{2\epsilon_0} \left[ \frac{1}{\sqrt{R^2+x^2}} - \frac{x^2}{(R^2+x^2)^{3/2}} \right] = -\frac{\sigma l R^2}{2\epsilon_0 (R^2+x^2)^{3/2}}$$



The plot is as shown in the answersheet.

3.45 For  $x > 0$  we can use the result as given above and write

$$\varphi = \pm \frac{\sigma l}{2 \epsilon_0} \left( 1 - \frac{|x|}{(R^2 + x^2)^{1/2}} \right)$$

for the solution that vanishes at  $\alpha$ . There is a discontinuity in potential for  $|x| = 0$ . The solution for negative  $x$  is obtained by  $\sigma \rightarrow -\sigma$ . Thus

$$\varphi = -\frac{\sigma l x}{2 \epsilon_0 (R + x^2)^{1/2}} + \text{constant}$$

Hence ignoring the jump

$$E = -\frac{\partial \varphi}{\partial x} = \frac{\sigma l R^2}{2 \epsilon_0 (R^2 + x^2)^{3/2}}$$

for large  $|x|$   $\varphi = \pm \frac{p}{4 \pi \epsilon_0 x^2}$  and  $E = \frac{p}{2 \pi \epsilon_0 |x|^3}$  (where  $p = \pi R^2 \sigma l$ )

3.46 Here  $E_r = \frac{\lambda}{2 \pi \epsilon_0 r}$ ,  $E_\theta = E_\varphi = 0$  and  $\vec{F} = p \frac{\partial \vec{E}}{\partial l}$

(a)  $\vec{p}$  along the thread.

$\vec{E}$  does not change as the point of observation is moved along the thread.

$$\vec{F} = 0$$

(b)  $\vec{p}$  along  $\vec{r}$ ,

$$\vec{F} = F_r \vec{e}_r = \frac{\lambda p}{2 \pi \epsilon_0 r^2} \vec{e}_r = -\frac{\lambda \vec{p}}{2 \pi \epsilon_0 r^2} \left( \text{On using } \frac{\partial}{\partial r} \vec{e}_r = 0 \right)$$

(c)  $\vec{p}$  along  $\vec{e}_\theta$

$$\begin{aligned} \vec{F} &= p \frac{\partial}{\partial \theta} \frac{\lambda}{2 \pi \epsilon_0 r} \vec{e}_r \\ &= \frac{p \lambda}{2 \pi \epsilon_0 r^2} \frac{\partial \vec{e}_r}{\partial \theta} = \frac{p \lambda}{2 \pi \epsilon_0 r^2} \vec{e}_\theta = \frac{\vec{p} \lambda}{2 \pi \epsilon_0 r^2} \end{aligned}$$

3.47 Force on a dipole of moment  $p$  is given by,

$$F = \left| \varphi \frac{\partial \vec{E}}{\partial l} \right|$$

In our problem, field, due to a dipole at a distance  $l$ , where a dipole is placed,

$$|\vec{E}| = \frac{p}{2 \pi \epsilon_0 l^3}$$

Hence, the force of interaction,

$$F = \frac{3 p^2}{2 \pi \epsilon_0 l^4} = 2.1 \times 10^{-16} \text{ N}$$

3.48  $-d\varphi = \vec{E} \cdot d\vec{r} = a(y dx + x dy) = a d(xy)$

On integrating,  $\varphi = -a xy + C$

3.49  $-d\varphi = \vec{E} \cdot d\vec{r} = [2axy \vec{i} + 2(x^2 - y^2) \vec{j}] \cdot [dx \vec{i} + dy \vec{j}]$

or,  $d\varphi = 2axy dx + a(x^2 - y^2) dy = ad(x^2 y) - ay^2 dy$

On integrating, we get,

$$\varphi = ay \left( \frac{y^2}{3} - x^2 \right) + C$$

3.50 Given, again

$$\begin{aligned} -d\varphi &= \vec{E} \cdot d\vec{r} = (ay\vec{i} + (ax + bz)\vec{j} + by\vec{k}) \cdot (dx\vec{i} + dy\vec{j} + dz\vec{k}) \\ &= a(y dx + ax dy) + b(z dy + y dz) = ad(xy) + bd(yz) \end{aligned}$$

On integrating,

$$\varphi = -(axy + byz) + C$$

3.51 Field intensity along x-axis.

$$E_x = -\frac{\partial \varphi}{\partial x} = 3ax^2 \quad (1)$$

Then using Gauss's theorem in differential form

$$\frac{\partial E_x}{\partial x} = \frac{\rho(x)}{\epsilon_0} \quad \text{so, } \rho(x) = 6a\epsilon_0 x.$$

3.52 In the space between the plates we have the Poisson equation

$$\frac{\partial^2 \varphi}{\partial x^2} = -\frac{\rho_0}{\epsilon_0}$$

or,

$$\varphi = -\frac{\rho_0}{2\epsilon_0} x^2 + Ax + B$$

where  $\rho_0$  is the constant space charge density between the plates.

We can choose

$$\varphi(0) = 0 \quad \text{so } B = 0$$

Then

$$\varphi(d) = \Delta \varphi = Ad - \frac{\rho_0 d^2}{2\epsilon_0} \quad \text{or, } A = \frac{\Delta \varphi}{d} + \frac{\rho_0 d}{2\epsilon_0}$$

Now

$$E = -\frac{\partial \varphi}{\partial x} = \frac{\rho_0}{\epsilon_0} x - A = 0 \quad \text{for } x = 0$$

if

$$A = \frac{\Delta \varphi}{d} + \frac{\rho_0 d}{2\epsilon_0} = 0$$

then

$$\rho_0 = -\frac{2\epsilon_0 \Delta \varphi}{d^2}$$

Also

$$E(d) = \frac{\rho_0 d}{\epsilon_0}.$$

3.53 Field intensity is along radial line and is

$$E_r = -\frac{\partial \varphi}{\partial r} = -2ar \quad (1)$$

From the Gauss' theorem,

$$4\pi r^2 E_r = \int \frac{dq}{\epsilon_0}$$

where  $dq$  is the charge contained between the sphere of radii  $r$  and  $r + dr$ .

$$\text{Hence} \quad 4\pi r^2 E_r = 4\pi r^2 \times (-2ar) = \frac{4\pi}{\epsilon_0} \int_0^r r'^2 \rho(r') dr' \quad (2)$$

Differentiating (2)  $\rho = -6\epsilon_0 a$

### 3.2 CONDUCTORS AND DIELECTRICS IN AN ELECTRIC FIELD

- 3.54 When the ball is charged, for the equilibrium of ball, electric force on it must counter balance the excess spring force, exerted, on the ball due to the extension in the spring.

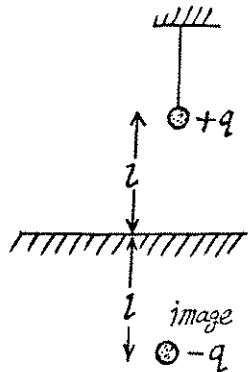
Thus  $F_d = F_{spr}$

or,  $\frac{q^2}{4\pi\epsilon_0(2l)^2} = \kappa x$ , (The force on the charge

$q$  might be considered as arising from attraction by the electrical image)

or,  $q = 4l\sqrt{\pi\epsilon_0\kappa x}$ ,

sought charge on the sphere.

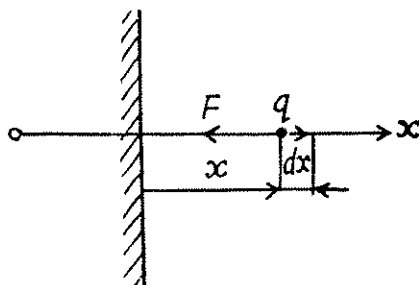


- 3.55 By definition, the work of this force done upon an elementary displacement  $dx$  (Fig.) is given by

$$dA = F_x dx = -\frac{q^2}{4\pi\epsilon_0(2x)^2} dx,$$

where the expression for the force is obtained with the help of the image method. Integrating this equation over  $x$  between  $l$  and  $\infty$ , we find

$$A = -\frac{q^2}{16\pi\epsilon_0} \int_l^\infty \frac{dx}{x^2} = -\frac{q^2}{16\pi\epsilon_0 l}.$$



- 3.56 (a) Using the concept of electrical image, it is clear that the magnitude of the force acting on each charge,

$$|\vec{F}| = \sqrt{2} \frac{q^2}{4\pi\epsilon_0 l^2} - \frac{q^2}{4\pi\epsilon_0 (\sqrt{2}l)^2}$$

$$= \frac{q^2}{8\pi\epsilon_0 l^2} (2\sqrt{2} - 1)$$

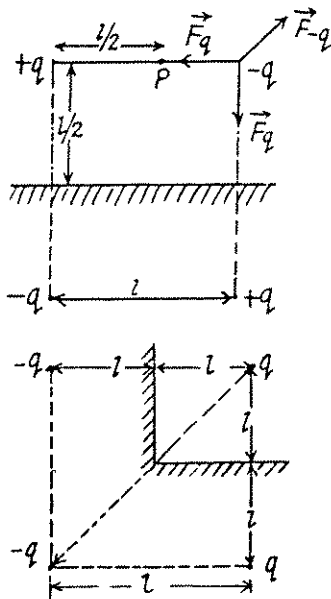
- (b) Also, from the figure, magnitude of electrical field strength at  $P$

$$E = 2 \left( 1 - \frac{1}{5\sqrt{5}} \right) \frac{q}{\pi\epsilon_0 l^2}$$

- 3.57 Using the concept of electrical image, it is easily seen that the force on the charge  $q$  is,

$$F = \frac{\sqrt{2} q^2}{4\pi\epsilon_0 (2l)^2} + \frac{(-q)^2}{4\pi\epsilon_0 (2\sqrt{2}l)^2}$$

$$= \frac{(2\sqrt{2} - 1) q^2}{32\pi\epsilon_0 l^2} \quad (\text{It is attractive})$$



- 3.58 Using the concept of electrical image, force on the dipole  $\vec{p}$ ,

$\vec{F} = p \frac{\partial \vec{E}}{\partial l}$ , where  $\vec{E}$  is field at the location of  $\vec{p}$  due to  $(-\vec{p})$

or,  $|\vec{F}| = \left| \frac{\partial \vec{E}}{\partial l} \right| p = \frac{3p^2}{32\pi\epsilon_0 l^4}$

as,  $|\vec{E}| = \frac{p}{4\pi\epsilon_0 (2l)^3}$



- 3.59 To find the surface charge density, we must know the electric field at the point  $P$  (Fig.) which is at a distance  $r$  from the point  $O$ .

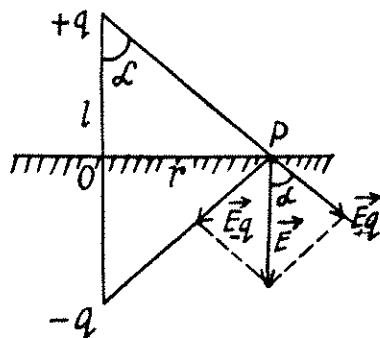
Using the image mirror method, the field at  $P$ ,

$$E = 2E \cos \alpha = 2 \frac{q}{4\pi\epsilon_0 x^2} \frac{l}{x} = \frac{ql}{2\pi\epsilon_0 (l^2 + r^2)^{3/2}}$$

Now from Gauss' theorem the surface charge density on conductor is connected with the electric field near its surface (in vacuum) through the relation  $\sigma = \epsilon_0 E_n$ , where  $E_n$  is the projection of  $\vec{E}$  onto the outward normal  $\vec{n}$  (with respect to the conductor).

As our field strength  $\vec{E} \uparrow \downarrow \vec{n}$ , so

$$\sigma = -\epsilon_0 E = -\frac{ql}{2\pi (l^2 + r^2)^{3/2}}$$



- 3.60 (a) The force  $F_1$  on unit length of the thread is given by

$$F_1 = \lambda E_1$$

where  $E_1$  is the field at the thread due to image charge :

$$E_1 = \frac{-\lambda}{2\pi\epsilon_0 (2l)}$$

Thus  $F_1 = \frac{-\lambda^2}{4\pi\epsilon_0 l}$

minus sign means that the force is one of attraction.

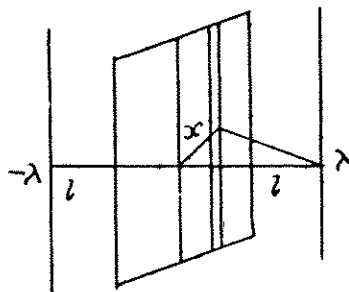
(b) There is an image thread with charge density  $-\lambda$  behind the conducting plane. We calculate the electric field on the conductor. It is

$$E(x) = E_n(x) = \frac{\lambda l}{\pi\epsilon_0 (x^2 + l^2)}$$

on considering the thread and its image.

Thus

$$\sigma(x) = \epsilon_0 E_n = \frac{\lambda l}{\pi (x^2 + l^2)}$$



3.61 (a) At  $O$ ,

$$E_n(O) = 2 \int_l^{\infty} \frac{\lambda dx}{4 \pi \epsilon_0 x^2} = \frac{\lambda}{2 \pi \epsilon_0 l}$$

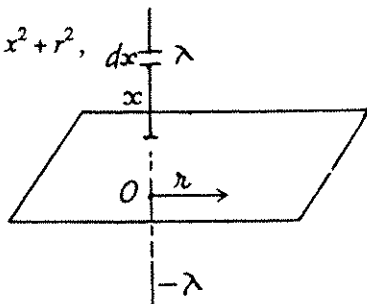
So  $\sigma(O) = \epsilon_0 E_n = \frac{\lambda}{2 \pi l}$

$$(b) E_n(r) = 2 \int_l^{\infty} \frac{\lambda dx}{4 \pi \epsilon_0 (x^2 + r^2)} \frac{x}{(x^2 + r^2)^{1/2}} = \frac{\lambda}{2 \pi \epsilon_0} \int_l^{\infty} \frac{x dx}{(x^2 + r^2)^{3/2}}$$

$$= \frac{\lambda}{4 \pi \epsilon_0} \int_{l^2 + r^2}^{\infty} \frac{dy}{y^{3/2}}, \text{ on putting } y = x^2 + r^2, \quad \begin{array}{c} dx \\ \hline x \\ \hline \lambda \\ \hline \end{array}$$

$$= \frac{\lambda}{2 \pi \epsilon_0 \sqrt{l^2 + r^2}}$$

Hence  $\sigma(r) = \epsilon_0 E_n = \frac{\lambda}{2 \pi \sqrt{l^2 + r^2}}$



3.62 It can be easily seen that in accordance with the image method, a charge  $-q$  must be located on a similar ring but on the other side of the conducting plane. (Fig.) at the same perpendicular distance. From the solution of 3.9 net electric field at  $O$ ,

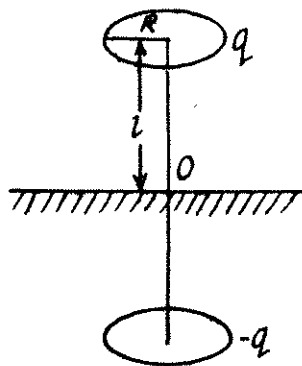
$$\vec{E} = 2 \frac{ql}{4 \pi \epsilon_0 (R^2 + l^2)^{3/2}} (-\vec{n}) \text{ where } \vec{n} \text{ is}$$

outward normal with respect to the conducting plane.

Now  $E_n = \frac{\sigma}{\epsilon_0}$

Hence  $\sigma = \frac{-ql}{2 \pi (R^2 + l^2)^{3/2}}$

where minus sign indicates that the induced charge is opposite in sign to that of charge  $q > 0$ .

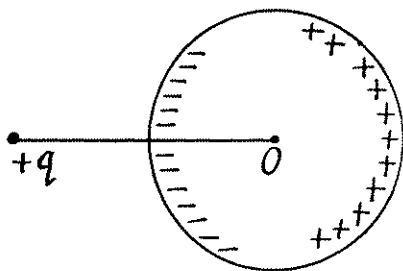


3.63 Potential  $\varphi$  is the same for all the points of the sphere. Thus we calculate its value at the centre  $O$  of the sphere. Thus we can calculate its value at the centre  $O$  of the sphere, because only for this point, it can be calculated in the most simple way.

$$\varphi = \frac{1}{4 \pi \epsilon_0} \frac{q}{l} + \varphi' \quad (1)$$

where the first term is the potential of the charge  $q$ , while the second is the potential due to the charges induced on the surface of the sphere. But since all induced charges are at the same distance equal to the radius of the circle from the point  $C$  and the total induced charge is equal to zero,  $\varphi' = 0$ , as well. Thus equation (1) is reduced to the form,

$$\varphi = \frac{1}{4\pi\epsilon_0} \frac{q}{l}$$

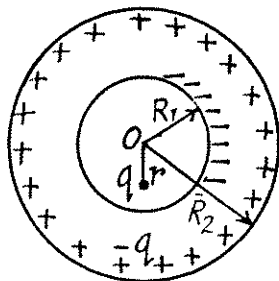


- 3.64** As the sphere has conducting layers, charge  $-q$  is induced on the inner surface of the sphere  $q$  and consequently charge  $+q$  is induced on the outer layer as the sphere as a whole is uncharged.

Hence, the potential at  $O$  is given by,

$$\varphi_0 = \frac{q}{4\pi\epsilon_0 r} + \frac{(-q)}{4\pi\epsilon_0 R_1} + \frac{q}{4\pi\epsilon_0 R_2}$$

It should be noticed that the potential can be found in such a simple way only at  $O$ , since all the induced charges are at the same distance from this point, and their distribution, (which is unknown to us), does not play any role.



- 3.65** Potential at the inside sphere,

$$\varphi_a = \frac{q_1}{4\pi\epsilon_0 a} + \frac{q_2}{4\pi\epsilon_0 b}$$

Obviously  $\varphi_a = 0$  for  $q_2 = -\frac{b}{a} q_1$  (1)

When  $r \geq b$ ,

$$\varphi_r = \frac{q_1}{4\pi\epsilon_0 r} + \frac{q_2}{4\pi\epsilon_0 r} = \frac{q_1}{4\pi\epsilon_0} \left(1 - \frac{b}{a}\right) / r, \text{ using Eq. (1).}$$

And when  $r \leq b$

$$\varphi_r = \frac{q_1}{4\pi\epsilon_0 r} + \frac{q_2}{4\pi\epsilon_0 b} = \frac{q_1}{4\pi\epsilon_0} \left(\frac{1}{r} - \frac{1}{a}\right)$$

- 3.66** (a) As the metallic plates 1 and 4 are isolated and connected by means of a conductor,  $\varphi_1 = \varphi_4$ . Plates 2 and 3 have the same amount of positive and negative charges and due to induction, plates 1 and 4 are respectively negatively and positively charged and in addition to it all the four plates are located a small but at equal distance  $d$  relative to each

other, the magnitude of electric field strength between 1 - 2 and 3 - 4 are both equal in magnitude and direction (say  $\vec{E}$ ). Let  $\vec{E}'$  be the field strength between the plates 2 and 3, which is directed from 2 to 3. Hence  $\vec{E}' \uparrow \downarrow \vec{E}$  (Fig.).

According to the problem

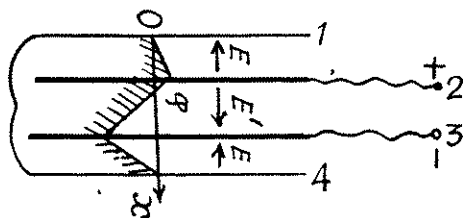
$$E' d = \Delta\varphi = \varphi_2 - \varphi_3 \quad (1)$$

In addition to

$$\varphi_1 - \varphi_4 = 0 = (\varphi_1 - \varphi_2) + (\varphi_2 - \varphi_3) + (\varphi_3 - \varphi_4)$$

$$\text{or, } 0 = -Ed + \Delta\varphi - Ed$$

$$\text{or, } \Delta\varphi = 2Ed \text{ or } E = \frac{\Delta\varphi}{2d}$$



$$\text{Hence } E = \frac{E'}{2} = \frac{\Delta\varphi}{2d} \quad (2)$$

(b) Since  $E \propto \sigma$ , we can state that according to equation (2) for part (a) the charge on the plate 2 is divided into two parts; such that  $1/3$  rd of it lies on the upper side and  $2/3$  rd on its lower face.

Thus charge density of upper face of plate 2 or of plate 1 or plate 4 and lower face of 3  $\sigma = \epsilon_0 E = \frac{\epsilon_0 \Delta\varphi}{2d}$  and charge density of lower face of 2 or upper face of 3

$$\sigma' = \epsilon_0 E' = \epsilon_0 \frac{\Delta\varphi}{d}$$

Hence the net charge density of plate 2 or 3 becomes  $\sigma + \sigma' = \frac{3 \epsilon_0 \Delta\varphi}{2d}$ , which is obvious from the argument.

**3.67** The problem of point charge between two conducting planes is more easily tackled (if we want only the total charge induced on the planes) if we replace the point charge by a uniformly charged plane sheet.

Let  $\sigma$  be the charge density on this sheet and  $E_1, E_2$  outward electric field on the two sides of this sheet.

$$\text{Then } E_1 + E_2 = \frac{\sigma}{\epsilon_0}$$

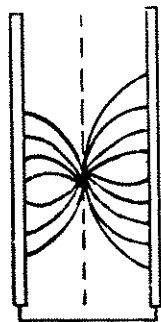
The conducting planes will be assumed to be grounded. Then  $E_1 x = E_2 (l - x)$ .

$$\text{Hence } E_1 = \frac{\sigma}{l \epsilon_0} (l - x), E_2 = \frac{\sigma}{l \epsilon_0} x$$

This means that the induced charge density on the plane conductors are

$$\sigma_1 = -\frac{\sigma}{l} (l - x), \sigma_2 = -\frac{\sigma}{l} x$$

$$\text{Hence } q_1 = -\frac{q}{l} (l - x), q_2 = -\frac{q}{l} x$$





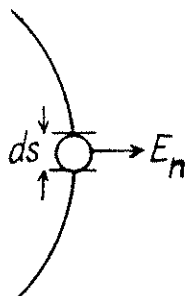
3.68 Near the conductor  $E = E_n = \frac{\sigma}{\epsilon_0}$

This field can be written as the sum of two parts  $E_1$  and  $E_2$ .  $E_1$  is the electric field due to an infinitesimal area  $dS$ .

Very near it  $E_1 = \pm \frac{\sigma}{2\epsilon_0}$

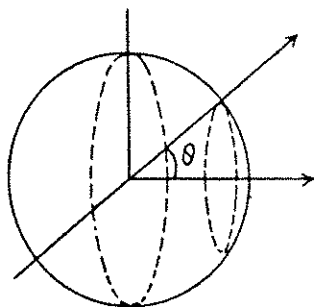
The remaining part contributes  $E_2 = \frac{\sigma}{2\epsilon_0}$  on both sides. In calculating the force on the element  $dS$  we drop  $E_1$  (because it is a self-force.) Thus

$$\frac{dF}{dS} = \sigma \cdot \frac{\sigma}{2\epsilon_0} = \frac{\sigma^2}{2\epsilon_0}$$



3.69 The total force on the hemisphere is

$$\begin{aligned} F &= \int_0^{\pi/2} \frac{\sigma^2}{2\epsilon_0} \cdot \cos \theta \cdot 2\pi R \sin \theta R d\theta \\ &= \frac{2\pi R^2 \sigma^2}{2\epsilon_0} \int_0^{\pi/2} \cos \theta \sin \theta d\theta \\ &= \frac{2\pi R^2}{2\epsilon_0} \times \frac{1}{2} \times \left( \frac{q}{4\pi R^2} \right)^2 = \frac{q^2}{32\pi\epsilon_0 R} \end{aligned}$$



3.70 We know that the force acting on the area element  $dS$  of a conductor is,

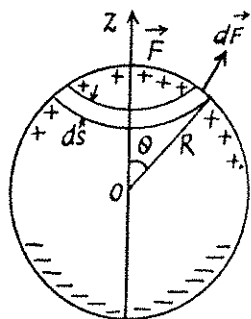
$$d\vec{F} = \frac{1}{2} \sigma \vec{E} dS \quad (1)$$

It follows from symmetry considerations that the resultant force  $F$  is directed along the  $z$ -axis, and hence it can be represented as the sum (integral) of the projection of elementary forces (1) onto the  $z$ -axis :

$$dF_z = dF \cos \theta \quad (2)$$

For simplicity let us consider an element area  $dS = 2\pi R \sin \theta R d\theta$  (Fig.). Now considering that  $E = \sigma/\epsilon_0$ , Equation (2) takes the form

$$\begin{aligned} dF_z &= \frac{\pi \sigma^2 R^2}{\epsilon_0} \sin \theta \cos \theta d\theta \\ &= - \left( \frac{\pi \sigma^2 R^2}{\epsilon_0} \right) \cos^3 \theta d \cos \theta \end{aligned}$$



Integrating this expression over the half sphere (i.e. with respect to  $\cos \theta$  between 1 and 0),

we obtain 
$$F = F_z = \frac{\pi \sigma_0^2 R^2}{4 \epsilon_0}$$

**3.71** The total polarization is  $P = (\epsilon - 1) \epsilon_0 E$ . This must equal  $\frac{n_0 P}{N}$  where  $n_0$  is the concentration of water molecules. Thus

$$N = \frac{n_0 P}{(\epsilon - 1) \epsilon_0 E} = 2.93 \times 10^3 \text{ on putting the values}$$

**3.72** From the general formula

$$\vec{E} = \frac{1}{4 \pi \epsilon_0} \frac{3 \vec{p} \cdot \vec{r} \vec{r} - \vec{p} r^2}{r^5}$$

$$\vec{E} = \frac{1}{4 \pi \epsilon_0} \frac{2 \vec{p}}{l^3}, \text{ where } r = l \text{ and } \vec{r} \uparrow \vec{p}$$

This will cause the induction of a dipole moment.

$$\vec{p}_{ind} = \beta \frac{1}{4 \pi \epsilon_0} \frac{2 \vec{p}}{l^3} \times \epsilon_0$$

Thus the force,

$$\vec{F} = \frac{\beta}{4 \pi} \frac{2 p}{l^3} \frac{\partial}{\partial l} \frac{1}{4 \pi \epsilon_0} \frac{2 p}{l^3} = \frac{3 \beta p^2}{4 \pi^2 \epsilon_0 l^7}$$

**3.73** The electric field  $E$  at distance  $x$  from the centre of the ring is,

$$E(x) = \frac{qx}{4 \pi \epsilon_0 (R^2 + x^2)^{3/2}}$$

The induced dipole moment is  $p = \beta \epsilon_0 E = \frac{q \beta x}{4 \pi (R^2 + x^2)^{3/2}}$

The force on this molecule is

$$F = p \frac{\partial}{\partial x} E = \frac{q \beta x}{4 \pi (R^2 + x^2)^{3/2}} \frac{q}{4 \pi \epsilon_0} \frac{\partial}{\partial x} \frac{x}{(R^2 + x^2)^{3/2}} = \frac{q^2 \beta}{16 \pi^2 \epsilon_0} \frac{x (R^2 - 2x^2)}{(R^2 + x^2)^4}$$

This vanishes for  $x = \frac{\pm R}{\sqrt{2}}$  (apart from  $x = 0, x = \infty$ )

It is maximum when

$$\frac{\partial}{\partial x} \frac{x (R^2 - 2x^2)}{(R^2 + x^2)^4} = 0$$

or,  $(R^2 - 2x^2)(R^2 + x^2) - 4x^2(R^2 + x^2) - 8x^2(R^2 - 2x^2) = 0$

or,  $R^4 - 13x^2 R^2 + 10x^4 = 0$  or,  $x^2 = \frac{R^2}{20} (13 \pm \sqrt{129})$

or,  $x = \frac{R}{\sqrt{20}} \sqrt{13 \pm \sqrt{129}}$  (on either side), Plot of  $F_x(x)$  is as shown in the answersheet.

## 3.74 Inside the ball

$$\vec{D}(\vec{r}) = \frac{q}{4\pi r^3} \vec{r} = \epsilon \epsilon_0 \vec{E}.$$

Also  $\epsilon_0 \vec{E} + \vec{P} = \vec{D}$  or  $\vec{P} = \frac{\epsilon - 1}{\epsilon} \vec{D} = \frac{\epsilon - 1}{\epsilon} \frac{q}{4\pi r^3} \vec{r}$

Also,  $q' = -\oint \vec{P} \cdot d\vec{S} = -\frac{\epsilon - 1}{\epsilon} \frac{q}{4\pi} \int d\Omega = -\frac{\epsilon - 1}{\epsilon} q$

3.75  $D_{diel} = \epsilon \epsilon_0 E_{diel} = D_{conductor} = \sigma$  or,  $E_{diel} = \frac{\sigma}{\epsilon \epsilon_0}$

$$P_n = (\epsilon - 1) \epsilon_0 E_{diel} = \frac{\epsilon - 1}{\epsilon} \sigma$$

$$\sigma' = -P_n = -\frac{\epsilon - 1}{\epsilon} \sigma$$

This is the surface density of bound charges.

3.76 From the solution of the previous problem  $q'_{in}$  = charge on the interior surface of the conductor

$$= -(\epsilon - 1)/\epsilon \int \sigma dS = -\frac{\epsilon - 1}{\epsilon} q$$

Since the dielectric as a whole is neutral there must be a total charge equal to

$$q'_{outer} = +\frac{\epsilon - 1}{\epsilon} q \text{ on the outer surface of the dielectric.}$$

3.77 (a) Positive extraneous charge is distributed uniformly over the internal surface layer. Let  $\sigma_0$  be the surface density of the charge.

Clearly,  $E = 0$ , for  $r < a$

For  $a < r$

$$\epsilon_0 E \times 4\pi r^2 = 4\pi a^2 \sigma_0 \text{ by Gauss theorem.}$$

or,  $E = \frac{\sigma_0}{\epsilon_0 \epsilon} \left(\frac{a}{r}\right)^2, a < r < b$

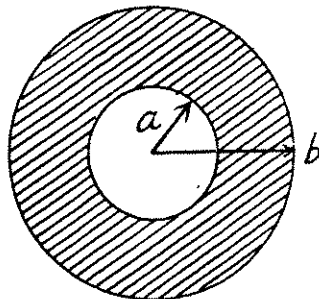
For  $r > b$ , similarly

$$E = \frac{\sigma_0}{\epsilon_0} \left(\frac{a}{r}\right)^2, r > b$$

Now,  $E = -\frac{\partial \varphi}{\partial r}.$

So by integration from infinity where  $\varphi(\infty) = 0$ ,

$$\varphi = \frac{\sigma_0 a^2}{\epsilon_0 r} \quad r > b$$



$$a < r < b \quad \varphi = \frac{\sigma_0 a^2}{\epsilon \epsilon r} + B, \quad B \text{ is a constant}$$

$$\text{or by continuity, } \varphi = \frac{\sigma_0 a^2}{\epsilon_0 \epsilon} \left( \frac{1}{r} - \frac{1}{b} \right) + \frac{\sigma_0 a^2}{\epsilon_0 b}, \quad a < r < b$$

$$\text{For } r < a, \quad \varphi = A = \text{Constant}$$

$$\text{By continuity, } \varphi = \frac{\sigma_0 a^2}{\epsilon_0 \epsilon} \left( \frac{1}{a} - \frac{1}{b} \right) + \frac{\sigma_0 a^2}{\epsilon_0 b}$$

(b) Positive extraneous charge is distributed uniformly over the internal volume of the dielectric

Let  $\rho_0$  = Volume density of the charge in the dielectric, for  $a < r < b$ .

$$E = 0, \quad r < a$$

$$\epsilon_0 \epsilon 4 \pi r^2 E = \frac{4 \pi}{3} (r^3 - a^3) \rho_0, \quad (a < r < b)$$

$$\text{or,} \quad E = \frac{\rho_0}{3 \epsilon_0 \epsilon} \left( r - \frac{a^3}{r^2} \right)$$

$$E = \frac{4 \pi}{3} (b^3 - a^3) \rho_0 / \epsilon_0 4 \pi r^2, \quad r > b$$

$$\text{or,} \quad E = \frac{(b^3 - a^3) \rho_0}{3 \epsilon_0 r^2} \quad \text{for } r > b$$

By integration,

$$\varphi = \frac{(b^3 - a^3) \rho_0}{3 \epsilon_0 r} \quad \text{for } r > b$$

$$\text{or,} \quad \varphi = B - \frac{\rho_0}{3 \epsilon_0 \epsilon} \left( \frac{r^2}{2} + \frac{a^3}{r} \right), \quad a < r < b$$

By continuity

$$\frac{b^3 - a^3}{3 \epsilon_0 b} \rho_0 = B - \frac{\rho_0}{3 \epsilon_0 \epsilon} \left( \frac{b^2}{2} + \frac{a^3}{b} \right)$$

$$\text{or,} \quad B = \frac{\rho_0}{3 \epsilon_0 \epsilon} \left\{ \frac{\epsilon (b^3 - a^3)}{b} + \left( \frac{b^2}{2} + \frac{a^3}{b} \right) \right\}$$

$$\text{Finally} \quad \varphi = B - \frac{\rho_0}{3 \epsilon_0 \epsilon} \left( \frac{a^2}{2} + a^2 \right) = B - \frac{\rho_0 a^2}{2 \epsilon_0 \epsilon}, \quad r < a$$

On the basis of obtained expressions  $E(r)$  and  $(\varphi)(r)$  can be plotted as shown in the answer-sheet.

3.78 Let the field in the dielectric be  $\vec{E}$  making an angle  $\alpha$  with  $\vec{n}$ . Then we have the boundary conditions,

$$E_0 \cos \alpha_0 = \epsilon E \cos \alpha \text{ and } E_0 \sin \alpha_0 = E \sin \alpha$$

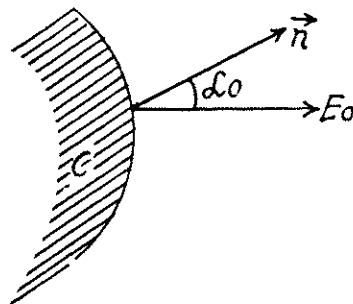
$$\text{So } E = E_0 \sqrt{\sin^2 \alpha_0 + \frac{1}{\epsilon^2} \cos^2 \alpha_0} \text{ and } \tan \alpha = \epsilon \tan \alpha_0$$

In the dielectric the normal component of the induction vector is

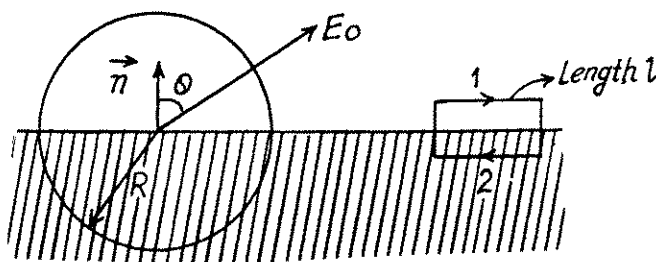
$$D_n = \epsilon_0 \epsilon E_n = \epsilon_0 \epsilon E \cos \alpha = \epsilon_0 E_0 \cos \alpha_0$$

$$\sigma' = P_n = D_n - \epsilon_0 E_n = \left(1 - \frac{1}{\epsilon}\right) \epsilon_0 E_0 \cos \alpha_0$$

$$\text{or, } \sigma' = \frac{\epsilon - 1}{\epsilon} \epsilon_0 E_0 \cos \alpha_0$$



3.79 From the previous problem,  $\sigma' = \epsilon_0 \frac{\epsilon - 1}{\epsilon} E_0 \cos \theta$



$$(a) \text{ Then } \oint \vec{E} \cdot d\vec{S} = \frac{1}{\epsilon_0} Q = \pi R^2 E_0 \cos \theta \frac{\epsilon - 1}{\epsilon}$$

$$(b) \oint \vec{D} \cdot d\vec{l} = (D_{1t} - D_{2t}) l = (\epsilon_0 E_0 \sin \theta - \epsilon \epsilon_0 E_0 \sin \theta) = -(\epsilon - 1) \epsilon_0 E_0 l \sin \theta$$

3.80 (a)  $\text{div} \vec{D} = \frac{\partial D_x}{\partial x} = \rho$  and  $D = \rho l$

$$E_x = \frac{\rho l}{\epsilon \epsilon_0}, l < d \text{ and } E_x = \frac{\rho d}{\epsilon_0} \text{ constant for } l > d$$

$$\varphi(x) = -\frac{\rho l^2}{2\epsilon \epsilon_0}, l < d \text{ and } \varphi(x) = A - \frac{\rho l d}{\epsilon_0}, l > d \text{ then } \varphi(x) = \frac{\rho d}{\epsilon_0} \left(d - \frac{d}{2\epsilon} - l\right),$$

by continuity.

On the basis of obtained expressions  $E_x(x)$  and  $\varphi(x)$  can be plotted as shown in the figure of answersheet.

$$(b) \rho' = -\operatorname{div} \vec{P} = -\operatorname{div} (\epsilon - 1) \epsilon_0 \vec{E} = -\rho \frac{(\epsilon - 1)}{\epsilon}$$

$$\begin{aligned} \sigma' &= P_{1n} - P_{2n}, \text{ where } n \text{ is the normal from 1 to 2.} \\ &= P_{1n}, \quad (\vec{P}_2 = 0 \text{ as 2 is vacuum.}) \end{aligned}$$

$$= (\rho d - \rho d/\epsilon) = \rho d \frac{\epsilon - 1}{\epsilon}$$

$$3.81 \quad \operatorname{div} \vec{D} = \frac{1}{r^2} \frac{\partial}{\partial r} r^2 D_r = \rho$$

$$r^2 D_r = \rho \frac{r^3}{3} + A \quad D_r = \frac{1}{3} \rho r + \frac{A}{r^2}, \quad r < R$$

$$A = 0 \text{ as } D_r \neq \infty \text{ at } r = 0, \text{ Thus, } E_r = \frac{\rho r}{3 \epsilon \epsilon_0}$$

$$\text{For } r > R, \quad D_r = \frac{B}{r^2}$$

$$\text{By continuity of } D_r \text{ at } r = R; \quad B = \frac{\rho R^3}{3}$$

$$\text{so, } E_r = \frac{\rho R^3}{3 \epsilon_0 r^2}, \quad r > R$$

$$\varphi = \frac{\rho R^3}{3 \epsilon_0 r}, \quad r > R \text{ and } \varphi = -\frac{\rho r^2}{6 \epsilon \epsilon_0} + C, \quad r < R$$

$$C = +\frac{\rho R^2}{3 \epsilon_0} + \frac{\rho R^2}{6 \epsilon \epsilon_0}, \text{ by continuity of } \varphi.$$

See answer sheet for graphs of  $E(r)$  and  $\varphi(r)$

$$(b) \rho' = \operatorname{div} \vec{P} = -\frac{1}{r^2} \frac{\partial}{\partial r} \left\{ \frac{r^3}{3} \rho \left( 1 - \frac{1}{\epsilon} \right) \right\} = -\frac{\rho (\epsilon - 1)}{\epsilon}$$

$$\sigma' = P_{1r} - P_{2r} = P_{1r} = \frac{1}{3} \rho R \left( 1 - \frac{1}{\epsilon} \right)$$

3.82 Because there is a discontinuity in polarization at the boundary of the dielectric disc, a bound surface charge appears, which is the source of the electric field inside and outside the disc.

We have for the electric field at the origin.

$$\vec{E} = -\int \frac{\sigma' dS}{4 \pi \epsilon_0 r^3} \vec{r},$$

where  $\vec{r}$  = radius vector to the origin from the element  $dS$ .

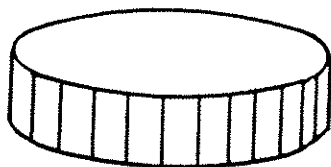
$\sigma' = P_n = P \cos \theta$  on the curved surface

( $P_n = 0$  on the flat surface.)

Here  $\theta$  = angle between  $\vec{r}$  and  $\vec{P}$

By symmetry,  $\vec{E}$  will be parallel to  $\vec{P}$ . Thus

$$E = - \int_0^{2\pi} \frac{P \cos \theta R d\theta \cdot \cos \theta}{4\pi \epsilon_0 R^2} \cdot d$$



where,  $r = R$  if  $d \ll R$ .

So,  $E = -\frac{Pd}{4\epsilon_0 R}$  and  $\vec{E} = -\frac{\vec{P}d}{4\epsilon_0 R}$

3.83. Since there are no free extraneous charges anywhere

$$\text{div } \vec{D} = \frac{\partial D_x}{\partial x} = 0 \text{ or, } D_x = \text{Constant}$$

But

$$D_x = 0 \text{ at } \infty, \text{ so, } D_x = 0, \text{ every where.}$$

Thus,

$$\vec{E} = -\frac{\vec{P}_0}{\epsilon_0} \left(1 - \frac{x^2}{d^2}\right) \text{ or, } E_x = -\frac{P_0}{\epsilon_0} \left(1 - \frac{x^2}{d^2}\right)$$

So,

$$\varphi = \frac{P_0 x}{\epsilon_0} - \frac{P_0 x^3}{3\epsilon_0 d^2} + \text{constant}$$

Hence,

$$\varphi(+d) - \varphi(-d) = \frac{2P_0 d}{\epsilon_0} - \frac{2P_0 d^3}{3d^2 \epsilon_0} = \frac{4P_0 d}{3\epsilon_0}$$

3.84 (a) We have  $D_1 = D_2$ , or,  $\epsilon E_2 = E_1$

Also,

$$E_1 \frac{d}{2} + E_2 \frac{d}{2} = E_0 d \text{ or, } E_1 + E_2 = 2E_0$$

Hence,

$$E_2 = \frac{2E_0}{\epsilon + 1} \text{ and } E_1 = \frac{2\epsilon E_0}{\epsilon + 1} \text{ and } D_1 = D_2 = \frac{2\epsilon \epsilon_0 E_0}{\epsilon + 1}$$

(b)  $D_1 = D_2$ , or,  $\epsilon E_2 = E_1 = \frac{\sigma}{\epsilon_0} = E_0$

Thus,

$$E_1 = E_0, E_2 = \frac{E_0}{\epsilon} \text{ and } D_1 = D_2 = \epsilon_0 E_0$$

3.85 (a) Constant voltage across the plates;

$$E_1 = E_2 = E_0, D_1 = \epsilon_0 E_0, D_2 = \epsilon_0 \epsilon E_0$$

(b) Constant charge across the plates;

$$E_1 = E_2, D_1 = \epsilon_0 E_1, D_2 = \epsilon \epsilon_0 E_2 = \epsilon D_1$$

$$E_1 (1 + \epsilon) = 2 E_0 \quad \text{or} \quad E_1 = E_2 = \frac{2 E_0}{\epsilon + 1}$$

3.86 At the interface of the dielectric and vacuum,

$$E_{1r} = E_{2r}$$

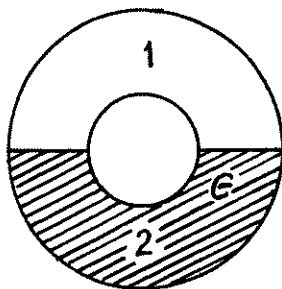
The electric field must be radial and

$$E_1 = E_2 = \frac{A}{\epsilon_0 \epsilon r^2}, \quad a < r < b$$

$$\text{Now, } q = \frac{A}{R^2} (2 \pi R^2) + \frac{A}{\epsilon R^2} (2 \pi R^2)$$

$$= A \left( 1 + \frac{1}{\epsilon} \right) 2 \pi$$

$$\text{or, } E_1 = E_2 = \frac{q}{2 \pi \epsilon_0 r^2 (1 + \epsilon)}$$



3.87 In air the forces are as shown. In K-oil,

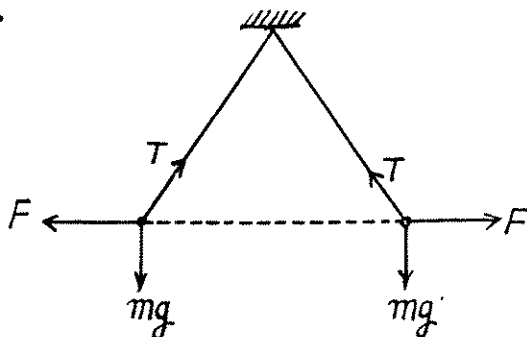
$$F \rightarrow F' = F/\epsilon \quad \text{and} \quad mg \rightarrow mg \left( 1 - \frac{\rho_0}{\rho} \right)$$

Since the inclinations do not change

$$\frac{1}{\epsilon} = 1 - \frac{\rho_0}{\rho}$$

$$\text{or, } \frac{\rho_0}{\rho} = 1 - \frac{1}{\epsilon} = \frac{\epsilon - 1}{\epsilon}$$

$$\text{or, } \rho = \rho_0 \frac{\epsilon}{\epsilon - 1}$$



where  $\rho_0$  is the density of K-oil and  $\rho$  that of the material of which the balls are made.

3.88 Within the ball the electric field can be resolved into normal and tangential components.

$$E_n = E \cos \theta, E_t = E \sin \theta$$

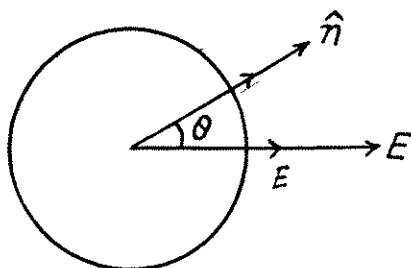
$$\text{Then, } D_n = \epsilon \epsilon_0 E \cos \theta$$

$$\text{and } P_n = (\epsilon - 1) \epsilon_0 E \cos \theta$$

$$\text{or, } \sigma' = (\epsilon - 1) \epsilon_0 E \cos \theta$$

$$\text{so, } \sigma_{\max} = (\epsilon - 1) \epsilon_0 E,$$

and total charge of one sign,





$$q' = \int_0^1 (\epsilon - 1) \epsilon_0 E \cos \theta \, 2\pi R^2 d(\cos \theta) = \pi R^2 \epsilon_0 (\epsilon - 1) E$$

(Since we are interested in the total charge of one sign we must integrate  $\cos \theta$  from 0 to 1 only).

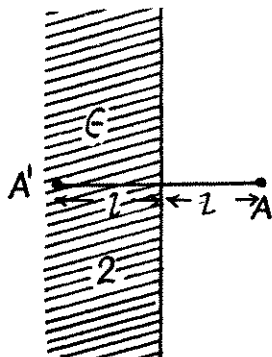
**3.89** The charge is at  $A$  in the medium 1 and has an image point at  $A'$  in the medium 2. The electric field in the medium 1 is due to the actual charge  $q$  at  $A$  and the image charge  $q'$  at  $A'$ . The electric field in 2 is due to a corrected charge  $q''$  at  $A$ . Thus on the boundary between 1 and 2,

$$E_{1n} = \frac{q'}{4\pi\epsilon_0 r^2} \cos \theta - \frac{q}{4\pi\epsilon_0 r^2} \cos \theta$$

$$E_{2n} = \frac{-q''}{4\pi\epsilon_0 r^2} \cos \theta$$

$$E_{1t} = \frac{q'}{4\pi\epsilon_0 r^2} \sin \theta + \frac{q}{4\pi\epsilon_0 r^2} \sin \theta$$

$$E_{2t} = \frac{q''}{4\pi\epsilon_0 r^2} \sin \theta$$



The boundary conditions are

$$D_{1n} = D_{2n} \text{ and } E_{1t} = E_{2t}$$

$$\epsilon q'' = q - q'$$

$$q'' = q + q'$$

So, 
$$q'' = \frac{2q}{\epsilon + 1}, \quad q' = -\frac{\epsilon - 1}{\epsilon + 1} q$$

(a) The surface density of the bound charge on the surface of the dielectric

$$\begin{aligned} \sigma' &= P_{2n} = D_{2n} - \epsilon_0 E_{2n} = (\epsilon - 1) \epsilon_0 E_{2n} \\ &= -\frac{\epsilon - 1}{\epsilon + 1} \frac{q}{2\pi r^2} \cos \theta = -\frac{\epsilon - 1}{\epsilon + 1} \frac{ql}{2\pi r^3} \end{aligned}$$

(b) Total bound charge is, 
$$-\frac{\epsilon - 1}{\epsilon + 1} q \int_0^\infty \frac{l}{2\pi(l^2 + x^2)^{3/2}} 2\pi x dx = -\frac{\epsilon - 1}{\epsilon + 1} q$$

**3.90** The force on the point charge  $q$  is due to the bound charges. This can be calculated from the field at this charge after extracting out the self field. This image field is

$$E_{\text{image}} = \frac{\epsilon - 1}{\epsilon + 1} \frac{q}{4\pi\epsilon_0 (2l)^2}$$

Thus, 
$$F = \frac{\epsilon - 1}{\epsilon + 1} \frac{q^2}{16\pi\epsilon_0 l^2}$$

$$3.91 \quad E_P = \frac{q \vec{r}_1}{4 \pi \epsilon_0 r_1^3} + \frac{q' \vec{r}_2}{4 \pi r_2^3 \epsilon_0}; P \text{ in } 1$$

$$E_P = \frac{q'' \vec{r}_1}{4 \pi \epsilon_0 r_1^3}, P \text{ in } 2$$

$$\text{where } q'' = \frac{2q}{\epsilon + 1}, q' = q'' - q$$

In the limit  $\vec{l} \rightarrow 0$

$$\vec{E}_P = \frac{(q + q') \vec{r}}{4 \pi \epsilon_0 r^3} = \frac{q \vec{r}}{2 \pi \epsilon_0 (1 + \epsilon) r^3}, \text{ in either part.}$$

Thus,

$$E_P = \frac{q}{2 \pi \epsilon_0 (1 + \epsilon) r^2}$$

$$\varphi = \frac{q}{2 \pi \epsilon_0 (1 + \epsilon) r}$$

$$D = \frac{q}{2 \pi \epsilon_0 (1 + \epsilon) r^2} \times \begin{cases} 1 & \text{in vacuum} \\ \epsilon & \text{in dielectric} \end{cases}$$

$$3.92 \quad \vec{E}_P = \frac{q \vec{r}_2}{4 \pi \epsilon_0 \epsilon r_2^3} + \frac{q' \vec{r}_1}{4 \pi \epsilon_0 r_1^3}; P \text{ in } 2$$

$$\vec{E}_P = \frac{q'' \vec{r}_2}{4 \pi \epsilon_0 r_2^3}; P \text{ in } 1$$

Using the boundary conditions,

$$E_{1n} = \epsilon E_{2n}, E_{1t} = E_{2t}$$

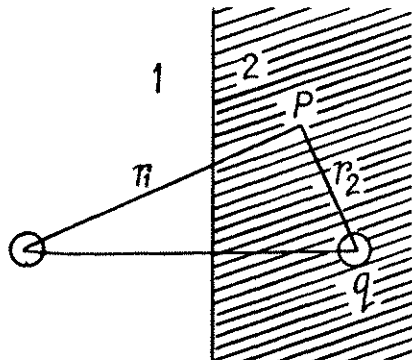
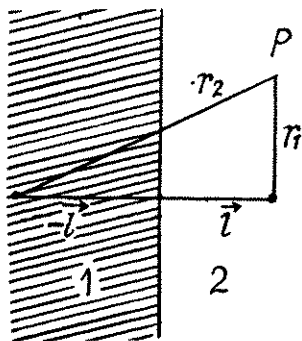
This implies

$$q - \epsilon q' = q'' \text{ and } q + \epsilon q' = \epsilon q''$$

$$\text{So, } q'' = \frac{2q}{\epsilon + 1}, q' = \frac{\epsilon - 1}{\epsilon + 1} q$$

Then, as earlier,

$$\sigma' = \frac{ql}{2 \pi r^3} \cdot \left( \frac{\epsilon - 1}{\epsilon + 1} \right) \cdot \frac{1}{\epsilon}$$



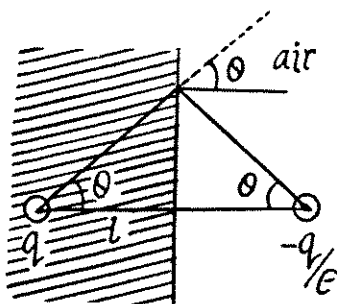
**3.93** To calculate the electric field, first we note that an image charge will be needed to ensure that the electric field on the metal boundary is normal to the surface.

The image charge must have magnitude  $-\frac{q}{\epsilon}$  so that the tangential component of the electric field may vanish. Now,

$$E_n = \frac{1}{4\pi\epsilon_0} \left( \frac{q}{\epsilon r^2} \right) 2 \cos \theta = \frac{ql}{2\pi\epsilon_0 \epsilon r^3}$$

$$\text{Then } P_n = D_n - \epsilon_0 E_n = \frac{(\epsilon - 1) ql}{2\pi\epsilon r^3} = \sigma'$$

This is the density of bound charge on the surface.



3.94 Since the condenser plates are connected,

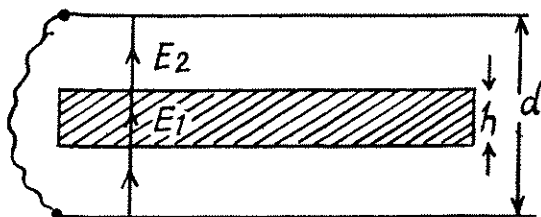
$$E_1 h + E_2 (d - h) = 0$$

and  $P + \epsilon_0 E_1 = \epsilon_0 E_2$

or,  $E_1 + \frac{P}{\epsilon_0} = E_2$

Thus,  $E_2 d - \frac{Ph}{\epsilon_0} = 0$ , or,  $E_2 = \frac{Ph}{\epsilon_0 d}$

$$E_1 = -\frac{P}{\epsilon_0} \left( 1 - \frac{h}{d} \right)$$



3.95 Given  $\vec{P} = \alpha \vec{r}$ , where  $\vec{r}$  = distance from the axis. The space density of charges is given by,  $\rho' = -\text{div } \vec{P} = -2\alpha$

On using,  $\text{div } \vec{r} = \frac{1}{r} \frac{\partial}{\partial r} (r \cdot \vec{r}) = 2$

3.96 In a uniformly charged sphere,

$$E_r = \frac{\rho_0 r}{3\epsilon_0} \text{ or, } \vec{E} = \frac{\rho_0}{3\epsilon_0} \vec{r}$$

The total electric field is

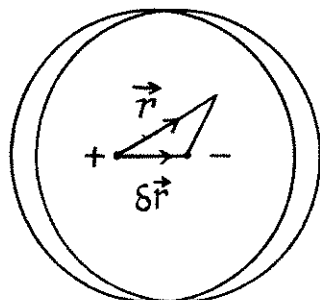
$$\begin{aligned} \vec{E} &= \frac{1}{3\epsilon_0} \rho_0 \vec{r} - \frac{1}{3\epsilon_0} (\vec{r} - \delta \vec{r}) \rho_0 \\ &= \frac{1}{3\epsilon_0} \rho_0 \delta \vec{r} = -\frac{\vec{P}}{3\epsilon_0} \end{aligned}$$

where  $\rho \delta \vec{r} = -\vec{P}$  (dipole moment is defined with its direction being from the -ve charge to +ve charge.)

The potential outside is

$$\varphi = \frac{1}{4\pi\epsilon_0} \left( \frac{Q}{r} - \frac{Q}{|\vec{r} - \delta \vec{r}|} \right), = \frac{\vec{P}_0 \cdot \vec{r}}{4\pi\epsilon_0 r^3}, \quad r > R$$

where  $\vec{P}_0 = -\frac{4\pi}{3} R^3 \rho_0 \delta \vec{r}$  is the total dipole moment.



- 3.97 The electric field  $\vec{E}_0$  in a spherical cavity in a uniform dielectric of permittivity  $\epsilon$  is related to the far away field  $\vec{E}$ , in the following manner. Imagine the cavity to be filled up with the dielectric. Then there will be a uniform field  $\vec{E}$  everywhere and a polarization  $\vec{P}$ , given by,

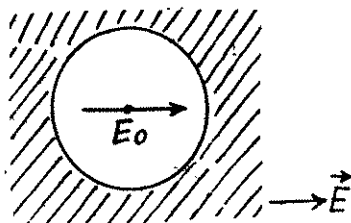
$$\vec{P} = (\epsilon - 1) \epsilon_0 \vec{E}$$

Now take out the sphere making the cavity, the electric field inside the sphere will be

$$-\frac{\vec{P}}{3\epsilon_0}$$

By superposition,  $\vec{E}_0 - \frac{\vec{P}}{3\epsilon_0} = \vec{E}$

$$\text{or, } \vec{E}_0 = \vec{E} + \frac{1}{3}(\epsilon - 1)\vec{E} = \frac{1}{3}(\epsilon + 2)\vec{E}$$



- 3.98 By superposition the field  $\vec{E}$  inside the ball is given by

$$\vec{E} = \vec{E}_0 - \frac{\vec{P}}{3\epsilon_0}$$

On the other hand, if the sphere is not too small, the macroscopic equation  $\vec{P} = (\epsilon - 1) \epsilon_0 \vec{E}$  must hold. Thus,

$$\vec{E} \left( 1 + \frac{1}{3}(\epsilon - 1) \right) = \vec{E}_0 \quad \text{or,} \quad \vec{E} = \frac{3\vec{E}_0}{\epsilon + 2}$$

Also

$$\vec{P} = 3\epsilon_0 \frac{\epsilon - 1}{\epsilon + 2} \vec{E}_0$$

- 3.99 This is to be handled by the same trick as in 3.96. We have effectively a two dimensional situation. For a uniform cylinder full of charge with charge density  $\rho_0$  (charge per unit volume), the electric field  $E$  at an inside point is along the (cylindrical) radius vector  $\vec{r}$  and equal to,

$$\vec{E} = \frac{1}{2\epsilon_0} \rho \vec{r}$$

$$\left( \text{div } \vec{E} = \frac{1}{r} \frac{\partial}{\partial r} (rE_r) = \frac{\rho}{\epsilon_0}, \quad \text{hence, } E_r = \frac{\rho}{2\epsilon_0} r \right)$$

Therefore the polarized cylinder can be thought of as two equal and opposite charge distributions displaced with respect to each other

$$\vec{E} = \frac{1}{2\epsilon_0} \rho \vec{r} - \frac{1}{2\epsilon_0} \rho (\vec{r} - \delta \vec{r}) = \frac{1}{2\epsilon_0} \rho \delta \vec{r} = -\frac{\vec{P}}{2\epsilon_0}$$

Since  $\vec{P} = -\rho \delta \vec{r}$  (direction of electric dipole moment vector being from the negative charge to positive charge.)

- 3.100 As in 3.98, we write  $\vec{E} = \vec{E}_0 - \frac{\vec{P}}{2\epsilon_0}$

using here the result of the foregoing problem.

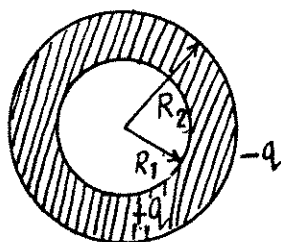
Also  $\vec{P} = (\epsilon - 1) \epsilon_0 \vec{E}$

$$\text{So, } \vec{E} \left( \frac{\epsilon + 1}{2} \right) = \vec{E}_0, \quad \text{or, } \vec{E} = \frac{2\vec{E}_0}{\epsilon + 1} \quad \text{and} \quad \vec{P} = 2\epsilon_0 \frac{\epsilon - 1}{\epsilon + 1} \vec{E}_0$$

### 3.3 ELECTRIC CAPACITANCE ENERGY OF AN ELECTRIC FIELD

3.101 Let us mentally impart a charge  $q$  on the conductor, then

$$\begin{aligned}\varphi_+ - \varphi_- &= \int_{R_1}^{R_2} \frac{q}{4\pi\epsilon_0\epsilon r^2} dr + \int_{R_2}^{\infty} \frac{q}{4\pi\epsilon_0 r^2} dr \\ &= \frac{q}{4\pi\epsilon_0\epsilon} \left[ \frac{1}{R_1} - \frac{1}{R_2} \right] + \frac{q}{4\pi\epsilon_0 R_2} \\ &= \frac{q}{4\pi\epsilon_0\epsilon} \left[ \frac{(\epsilon-1)}{R_2} + \frac{1}{R_1} \right]\end{aligned}$$



Hence the sought capacitance,

$$C = \frac{q}{\varphi_+ - \varphi_-} = \frac{q 4\pi\epsilon_0\epsilon}{q \left[ \frac{(\epsilon-1)}{R_2} + \frac{1}{R_1} \right]} = \frac{4\pi\epsilon_0\epsilon R_1}{(\epsilon-1) \frac{R_1}{R_2} + 1}$$

3.102 From the symmetry of the problem, the voltage across each capacitor,  $\Delta\varphi = \xi/2$  and charge on each capacitor  $q = C \xi/2$  in the absence of dielectric.

Now when the dielectric is filled up in one of the capacitors, the equivalent capacitance of the system,

$$C'_0 = \frac{C\epsilon}{1+\epsilon}$$

and the potential difference across the capacitor, which is filled with dielectric,

$$\Delta\varphi' = \frac{q'}{\epsilon C} = \frac{C\epsilon}{(1+\epsilon)} \frac{\xi}{C\epsilon} = \frac{\xi}{(1+\epsilon)}$$

But

$$\varphi \propto E$$

So, as  $\varphi$  decreases  $\frac{1}{2}(1+\epsilon)$  times, the field strength also decreases by the same factor and flow of charge,  $\Delta q = q' - q$

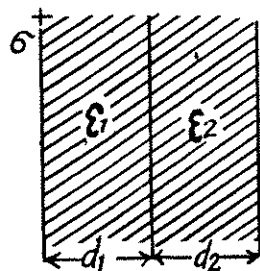
$$= \frac{C\epsilon}{(1+\epsilon)} \xi - \frac{C}{2} \xi = \frac{1}{2} C \xi \frac{(\epsilon-1)}{(\epsilon+1)}$$

3.103 (a) As it is series combination of two capacitors,

$$\frac{1}{C} = \frac{d_1}{\epsilon_0\epsilon_1 S} + \frac{d_2}{\epsilon_0\epsilon_2 S} \quad \text{or,} \quad C = \frac{\epsilon_0 S}{(d_1/\epsilon_1) + (d_2/\epsilon_2)}$$

(b) Let,  $\sigma$  be the initial surface charge density, then density of bound charge on the boundary plane.

$$\sigma' = \sigma \left( 1 - \frac{1}{\epsilon_1} \right) - \sigma \left( 1 - \frac{1}{\epsilon_2} \right) = \sigma \left( \frac{1}{\epsilon_2} - \frac{1}{\epsilon_1} \right)$$



But, 
$$\sigma = \frac{q}{S} = \frac{CV}{S} = \frac{\epsilon_0 S \epsilon_1 \epsilon_2}{\epsilon_2 d_1 + \epsilon_1 d_2} \frac{V}{S}$$

So, 
$$\sigma' = \frac{\epsilon_0 V (\epsilon_1 - \epsilon_2)}{\epsilon_2 d_1 + \epsilon_1 d_2}$$

**3.104** (a) We point the  $x$ -axis lowards right and place the origin on the left hand side plate. The left plate is assumed to be positively charged.

Since  $\epsilon$  varies linearly, we can write,

$$\epsilon(x) = a + bx$$

where  $a$  and  $b$  can be determined from the boundary condition. We have

$$\epsilon = \epsilon_1 \text{ at } x = 0 \text{ and } \epsilon = \epsilon_2 \text{ at } x = d,$$

Thus, 
$$\epsilon(x) = \epsilon_1 + \left( \frac{\epsilon_2 - \epsilon_1}{d} \right) x$$

Now potential difference between the plates

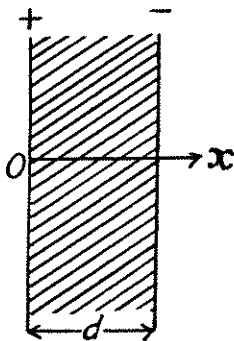
$$\begin{aligned} \varphi_+ - \varphi_- &= \int_0^d \vec{E} \cdot d\vec{r} = \int_0^d \frac{\sigma}{\epsilon_0 \epsilon(x)} dx \\ &= \int_0^d \frac{\sigma}{\epsilon_0 \left( \epsilon_1 + \frac{\epsilon_2 - \epsilon_1}{d} x \right)} dx = \frac{\sigma d}{(\epsilon_2 - \epsilon_1) \epsilon_0} \ln \frac{\epsilon_2}{\epsilon_1} \end{aligned}$$

Hence, the sought capacitance, 
$$C = \frac{\sigma S}{\varphi_+ - \varphi_-} = \frac{(\epsilon_2 - \epsilon_1) \epsilon_0 S}{(\ln \epsilon_2 / \epsilon_1) d}$$

(b)  $D = \frac{q}{S}$  and  $P = \frac{q}{S} - \frac{q}{S \epsilon(x)}$

and the space density of bound charges is

$$\rho' = -\operatorname{div} P = -\frac{q(\epsilon_2 - \epsilon_1)}{S d \epsilon^2(x)}$$



**3.105** Let, us mentally impart a charge  $q$  to the conductor. Now potential difference between the plates,

$$\begin{aligned} \varphi_+ - \varphi_- &= \int_{R_1}^{R_2} \vec{E} \cdot d\vec{r} \\ &= \int_{R_1}^{R_2} \frac{q}{4\pi\epsilon_0 a/r} \frac{1}{r^2} dr = \frac{q}{4\pi\epsilon_0 a} \ln R_2/R_1 \end{aligned}$$

Hence, the sought capacitance,

$$C = \frac{q}{\varphi_+ - \varphi_-} = \frac{q 4\pi\epsilon_0 a}{q \ln R_2/R_1} = \frac{4\pi\epsilon_0 a}{\ln R_2/R_1}$$

3.106 Let  $\lambda$  be the linear charge density then,

$$E_{1m} = \frac{\lambda}{2\pi\epsilon_0 R_1 \epsilon_1} \quad (1)$$

and,

$$E_{2m} = \frac{\lambda}{2\pi\epsilon_0 R_2 \epsilon_2} \quad (2)$$

The breakdown in either case will occur at the smaller value of  $r$  for a simultaneous breakdown of both dielectrics.

From (1) and (2)

$E_{1m} R_1 \epsilon_1 = E_{2m} R_2 \epsilon_2$ , which is the sought relationship.

3.107 Let,  $\lambda$  be the linear charge density then, the sought potential difference,

$$\begin{aligned} \varphi_+ - \varphi_- &= \int_{R_1}^{R_2} \frac{\lambda}{2\pi\epsilon_0 \epsilon_1 r} dr + \int_{R_2}^{R_3} \frac{\lambda}{2\pi\epsilon_0 \epsilon_2 r} dr \\ &= \frac{\lambda}{2\pi\epsilon_0} \left[ \frac{1}{\epsilon_1} \ln R_2/R_1 + \frac{1}{\epsilon_2} \ln R_3/R_2 \right] \end{aligned}$$

Now, as,  $E_1 R_1 \epsilon_1 < E_2 R_2 \epsilon_2$ , so

$$\frac{\lambda}{2\pi\epsilon_0} = E_1 R_1 \epsilon_1$$

is the maximum acceptable value, and for values greater than  $E_1 R_1 \epsilon_1$ , dielectric breakdown will take place,

Hence, the maximum potential difference between the plates,

$$\varphi_+ - \varphi_- = E_1 R_1 \epsilon_1 \left[ \frac{1}{\epsilon_1} \ln R_2/R_1 + \frac{1}{\epsilon_2} \ln R_3/R_2 \right] = E_1 R_1 \left[ \ln R_2/R_1 + \frac{\epsilon_1}{\epsilon_2} \ln R_3/R_2 \right]$$

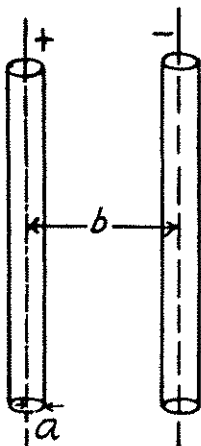
3.108 Let us suppose that linear charge density of the wires be  $\lambda$  then, the potential difference,  $\varphi_+ - \varphi_- = \varphi - (-\varphi) = 2\varphi$ . The intensity of the electric field created by one of the wires at a distance  $x$  from its axis can be easily found with the help of the Gauss's theorem,

$$E = \frac{\lambda}{2\pi\epsilon_0 x} \quad b-a$$

$$\text{Then, } \varphi = \int_a^b E dx = \frac{\lambda}{2\pi\epsilon_0} \ln \frac{b-a}{a}$$

Hence, capacitance, per unit length,

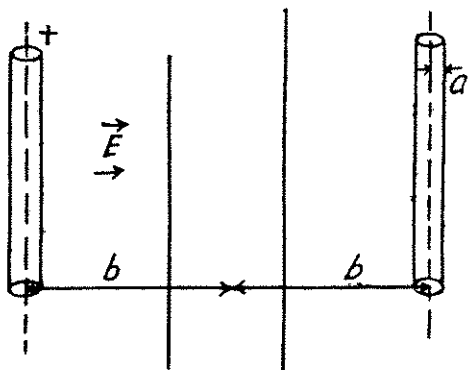
$$\frac{\lambda}{\varphi_+ - \varphi_-} = \frac{2\pi\epsilon_0}{\ln b/a}$$



- 3.109** The field in the region between the conducting plane and the wire can be obtained by using an oppositely charged wire as an image on the other side.

Then the potential difference between the wire and the plane,

$$\begin{aligned}\Delta\varphi &= \int_b \vec{E} \cdot d\vec{r} \\ &= \int_a \left[ \frac{\lambda}{2\pi\epsilon_0 r} + \frac{\lambda}{2\pi\epsilon_0 (2b-r)} \right] dr \\ &= \frac{\lambda}{2\pi\epsilon_0} \ln \frac{b}{a} - \frac{\lambda}{2\pi\epsilon_0} \ln \frac{b}{2b-a} \\ &= \frac{\lambda}{2\pi\epsilon_0} \ln \frac{2b-a}{a} \\ &= \frac{\lambda}{2\pi\epsilon_0} \ln \frac{2b}{a}, \text{ as } b \gg a\end{aligned}$$



Hence, the sought mutual capacitance of the system per unit length of the wire

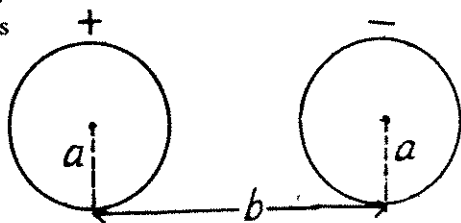
$$= \frac{\lambda}{\Delta\varphi} = \frac{2\pi\epsilon_0}{\ln 2b/a}$$

- 3.110** When  $b \gg a$ , the charge distribution on each spherical conductor is practically unaffected by the presence of the other conductor. Then, the potential  $\varphi_+$  ( $\varphi_-$ ) on the positive (respectively negative) charged conductor is

$$+ \frac{q}{4\pi\epsilon_0\epsilon a} \left( - \frac{q}{4\pi\epsilon_0\epsilon a} \right)$$

$$\text{Thus } \varphi_+ - \varphi_- = \frac{q}{2\pi\epsilon_0 a}$$

$$\text{and } C = \frac{q}{\varphi_+ - \varphi_-} = 2\pi\epsilon_0\epsilon a.$$



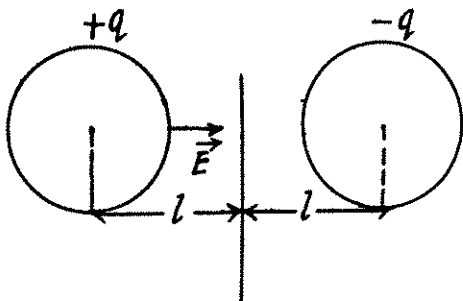
**Note :** if we require terms which depend on  $\frac{a}{b}$ , we have to take account of distribution of charge on the conductors.

- 3.111** As in 3.109 we apply the method of image. Then the potential difference between the +vely charged sphere and the conducting plane is one half the nominal potential difference between the sphere and its image and is

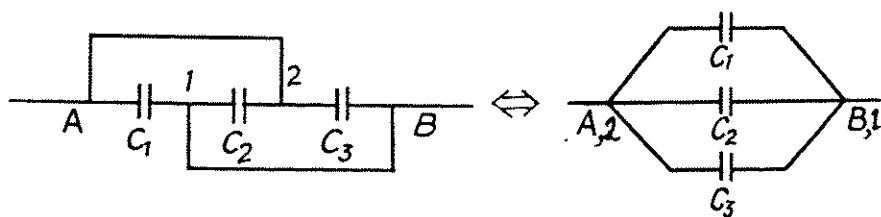
$$\Delta\varphi = \frac{1}{2}(\varphi_+ - \varphi_-) = \frac{q}{4\pi\epsilon_0 a}$$

Thus

$$C = \frac{q}{\Delta\varphi} = 4\pi\epsilon_0 a. \text{ for } l \gg a.$$

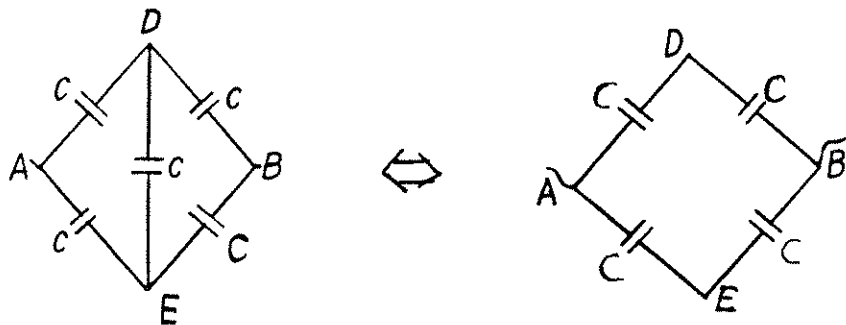






(a) Since  $\varphi_1 = \varphi_B$  and  $\varphi_2 = \varphi_A$

The arrangement of capacitors shown in the problem is equivalent to the arrangement shown in the Fig.



and hence the capacitance between  $A$  and  $B$  is,

$$C = C_1 + C_2 + C_3$$

(B) From the symmetry of the problem, there is no P.d. between  $D$  and  $E$ . So, the combination reduces to a simple arrangement shown in the Fig and hence the net capacitance,

$$C_0 = \frac{C}{2} + \frac{C}{2} = C$$

3.113 (a) In the given arrangement, we have three

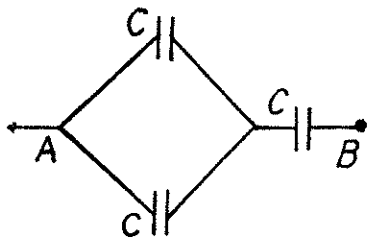
capacitors of equal capacitance  $C = \frac{\epsilon_0 S}{d}$  and

the first and third plates are at the same potential.

Hence, we can resolve the network into a simple form using series and parallel grouping of capacitors, as shown in the figure.

Thus the equivalent capacitance

$$C_0 = \frac{(C + C)C}{(C + C) + C} = \frac{2}{3}C$$



(b) Let us mentally impart the charges  $+q$  and  $-q$  to the plates 1 and 2 and then distribute them to other plates using charge conservation and electric induction. (Fig.).

As the potential difference between the plates 1 and 2 is zero,

$$-\frac{q_1}{C} + \frac{q_2}{C} - \frac{q_1}{C} = 0, \quad \left( \text{where } C = \frac{\epsilon_0 S}{d} \right)$$

or,  $q_2 = 2q_1$ ,

The potential difference between A and B,

$$\varphi = \varphi_A - \varphi_B = q_2/C$$

Hence the sought capacitance,

$$C_0 = \frac{q}{\varphi} = \frac{q_1 + q_2}{q_2/C} = \frac{3q_1}{2q_1/C} = \frac{3}{2}C = \frac{3\epsilon_0 S}{2d}$$

**3.114** Amount of charge, that the capacitor of capacitance  $C_1$  can withstand,  $q_1 = C_1 V_1$  and similarly the charge, that the capacitor of capacitance  $C_2$  can withstand,  $q_2 = C_2 V_2$ . But in series combination, charge on both the capacitors will be same, so,  $q_{\max}$ , that the combination can withstand  $= C_1 V_1$ ,

as  $C_1 V_1 < C_2 V_2$ , from the numerical data, given.

Now, net capacitance of the system,

$$C_0 = \frac{C_1 C_2}{C_1 + C_2}$$

and hence,  $V_{\max} = \frac{q_{\max}}{C_0} = \frac{C_1 V_1}{C_1 C_2 / C_1 + C_2} = V_1 \left( 1 + \frac{C_1}{C_2} \right) = 9 \text{ kV}$

**3.115** Let us distribute the charges, as shown in the figure.

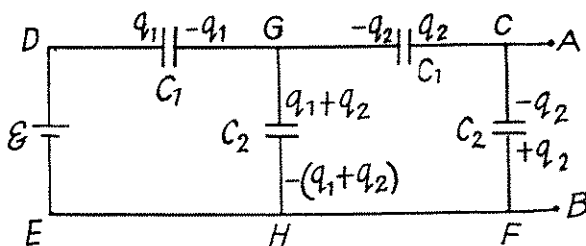
Now, we know that in a closed circuit,  $-\Delta\varphi = 0$

So, in the loop, DCFED,

$$\frac{q_1}{C_1} - \frac{q_2}{C_1} - \frac{q_2}{C_2} = \xi \quad \text{or, } q_1 = C_1 \left[ \xi + q_2 \left( \frac{1}{C_1} + \frac{1}{C_2} \right) \right] \quad (1)$$

Again in the loop DGHED,

$$\frac{q_1}{C_1} + \frac{q_1 + q_2}{C_2} = \xi \quad (2)$$



Using Eqs. (1) and (2), we get

$$q_2 \left[ \frac{1}{C_1} + \frac{3}{C_2} + \frac{C_1}{C_2} \right] = -\frac{\xi C_1}{C_2}$$

$$\text{Now, } \varphi_A - \varphi_B = \frac{-q_2}{C_2} = \frac{\xi}{C_2^2/C_1} \left[ \frac{1}{C_1} + \frac{3}{C_2} + \frac{C_1}{C_2^2} \right]$$

$$\text{or, } \varphi_A - \varphi_B = \frac{\xi}{\left[ \frac{C_2^2}{C_1^2} + \frac{3C_2}{C_1} + 1 \right]} = \frac{\xi}{\eta^2 + 3\eta + 1} = 10 \text{ V}$$

**3.116** The infinite circuit, may be reduced to the circuit, shown in the Fig. where,  $C_0$  is the net capacitance of the combination.

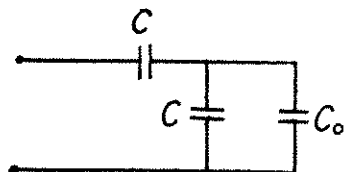
$$\text{So, } \frac{1}{C+C_0} + \frac{1}{C} = \frac{1}{C_0}$$

Solving the quadratic,

$$C C_0 + C_0^2 - C^2 = 0,$$

we get,

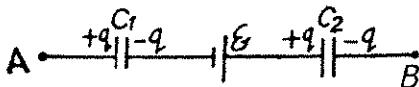
$$C_0 = \frac{(\sqrt{5} - 1)}{2} C, \text{ taking only +ve value as } C_0 \text{ can not be negative.}$$



**3.117** Let, us make the charge distribution, as shown in the figure.

$$\text{Now, } \varphi_A - \varphi_B = \frac{q}{C_1} - \xi + \frac{q}{C_2}$$

$$\text{or, } q = \frac{(\varphi_A - \varphi_B) + \xi}{C_1 + C_2} C_1 C_2$$



Hence, voltage across the capacitor  $C_1$

$$= \frac{q}{C_1} = \frac{(\varphi_A - \varphi_B) + \xi}{C_1 + C_2} C_2 = 10 \text{ V}$$

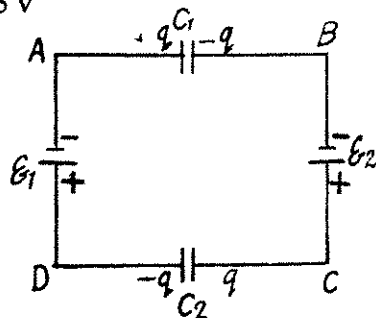
and voltage across the capacitor,  $C_2$

$$= \frac{q}{C_2} = \frac{(\varphi_A - \varphi_B) + \xi}{C_1 + C_2} C_1 = 5 \text{ V}$$

**3.118** Let  $\xi_2 > \xi_1$ , then using  $-\Delta\varphi = 0$  in the closed circuit, (Fig.)

$$\frac{-q}{C_1} + \xi_2 - \frac{q}{C_2} - \xi_1 = 0$$

$$\text{or, } q = \frac{(\xi_2 - \xi_1) C_1 C_2}{(C_1 + C_2)}$$



Hence the P.D. across the left and right plates of capacitors,

$$\varphi_1 = \frac{q}{C_1} = \frac{(\xi_2 - \xi_1) C_2}{C_1 + C_2}$$

and similarly

$$\varphi_2 = \frac{-q}{C_2} = \frac{(\xi_1 - \xi_2) C_1}{C_1 + C_2}$$

3.119 Taking benefit of the foregoing problem, the amount of charge on each capacitor

$$|q| = \frac{|\xi_2 - \xi_1| C_1 C_2}{C_1 + C_2}$$

3.120 Make the charge distribution, as shown in the figure. In the circuit, 12561.

$-\Delta\varphi = 0$  yields

$$\frac{q_1}{C_4} + \frac{q_1}{C_3} - \xi = 0 \quad \text{or,} \quad q_1 = \frac{\xi C_3 C_4}{C_3 + C_4}$$

and in the circuit 13461,

$$\frac{q_2}{C_2} + \frac{q_2}{C_1} - \xi = 0 \quad \text{or,} \quad q_2 = \frac{\xi C_1 C_2}{C_1 + C_2}$$

$$\text{Now} \quad \varphi_A - \varphi_B = \frac{q_2}{C_1} - \frac{q_1}{C_3}$$

$$= \xi \left[ \frac{C_2}{C_1 + C_2} - \frac{C_4}{C_3 + C_4} \right] = \xi \left[ \frac{C_2 C_3 - C_1 C_4}{(C_1 + C_2)(C_3 + C_4)} \right]$$

It becomes zero, when

$$(C_2 C_3 - C_1 C_4) = 0. \quad \text{or} \quad \frac{C_1}{C_2} = \frac{C_3}{C_4}$$

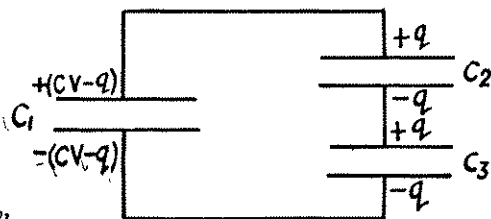
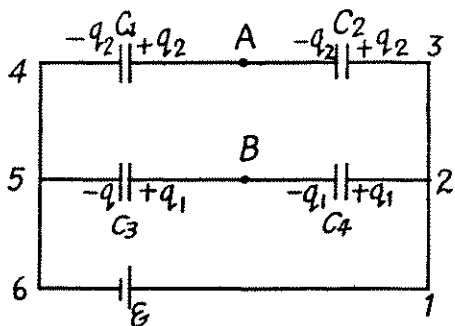
3.121 Let, the charge  $q$  flows through the connecting wires, then at the state of equilibrium, charge distribution will be as shown in the Fig. In the closed circuit 12341, using  $-\Delta\varphi = 0$

$$-\frac{(C_1 V - q)}{C_1} + \frac{q}{C_2} + \frac{q}{C_3} = 0$$

$$\text{or, } q = \frac{V}{(1/C_1 + 1/C_2 + 1/C_3)} = 0.06 \text{ mC}$$

3.122 Initially, charge on the capacitor  $C_1$  or  $C_2$ ,

$$q = \frac{\xi C_1 C_2}{C_1 + C_2}, \text{ as they are in series combination (Fig.-a)}$$

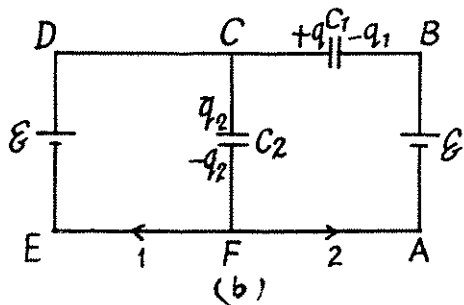
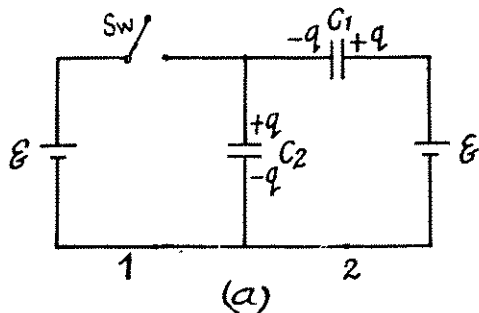


when the switch is closed, in the circuit CDEFC' from  $-\Delta\varphi = 0$ , (Fig. b)

$$\xi - \frac{q_2}{C_2} = 0 \quad \text{or} \quad q_2 = C_2 \xi \quad (1)$$

And in the closed loop BCFAB from  $-\Delta\varphi = 0$

$$\frac{-q_1}{C_1} + \frac{q_2}{C_2} - \xi = 0 \quad (2)$$



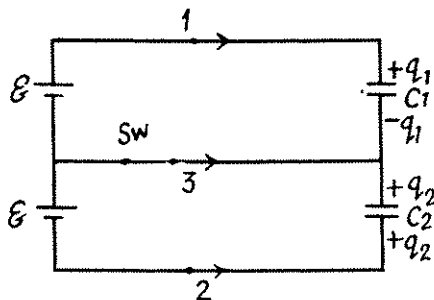
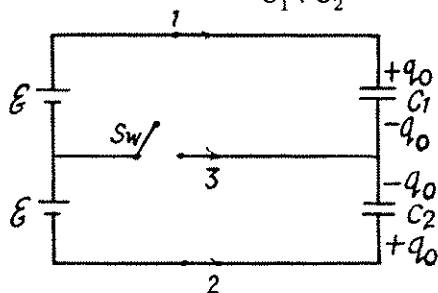
From (1) and (2)  $q_1 = 0$

Now, charge flown through section 1 =  $(q_1 + q_2) - 0 = C_2 \xi$

and charge flown through section 2 =  $-q_1 - q = -\frac{\xi C_1 C_2}{C_1 + C_2}$

**3.123** When the switch is open, (Fig-a)

$$q_0 = \frac{2 \xi C_1 C_2}{C_1 + C_2}$$



and when the switch is closed,

$$q_1 = \xi C_1 \quad \text{and} \quad q_2 = \xi C_2$$

Hence, the flow of charge, due to the shortening of switch,

$$\text{through section 1} = q_1 - q_0 = \xi C_1 \left[ \frac{C_1 - C_2}{C_1 + C_2} \right] = -24 \mu\text{C}$$

$$\text{through the section 2} = -q_2 - (q_0) = \xi C_2 \left[ \frac{C_1 - C_2}{C_1 + C_2} \right] = -36 \mu\text{C}$$

$$\text{and through the section 3} = q_2 - (q_2 - q_1) - 0 = \xi (C_2 - C_1) = -60 \mu\text{C}$$

**3.124** First of all, make the charge distribution, as shown in the figure.

In the loop 12341, using  $-\Delta\varphi = 0$

$$\frac{q_1}{C_1} - \xi_1 + \frac{q_1 - q_2}{C_3} = 0 \quad (1)$$

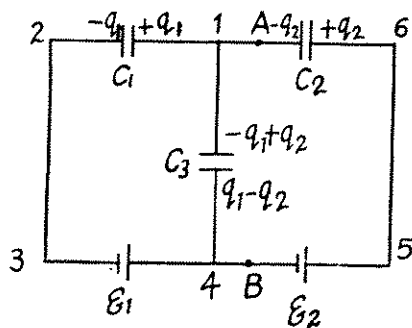
Similarly, in the loop 61456, using  $-\Delta\varphi = 0$

$$\frac{q_2}{C_2} + \frac{q_2 - q_1}{C_3} - \xi_2 = 0 \quad (2)$$

From Eqs. (1) and (2) we have

$$q_2 - q_1 = \frac{\xi_2 C_2 - \xi_1 C_1}{\frac{C_2}{C_3} + \frac{C_1}{C_3} + 1}$$

Hence, 
$$\varphi_A - \varphi_B = \frac{q_2 - q_1}{C_3} = \frac{\xi_2 C_2 - \xi_1 C_1}{C_1 + C_2 + C_3}$$



**3.125** In the loop ABDEA, using  $-\Delta\varphi = 0$

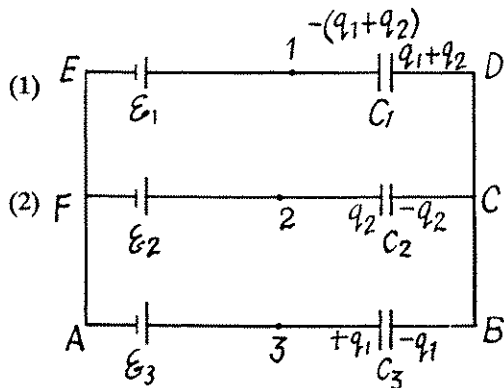
$$-\xi_3 + \frac{q_1}{C_3} + \frac{q_1 + q_2}{C_1} + \xi_1 = 0$$

Similarly in the loop ODEF, O

$$\frac{q_1 + q_2}{C_1} + \xi_1 - \xi_2 + \frac{q_2}{C_2} = 0$$

Solving Eqs. (1) and (2), we get,

$$q_1 + q_2 = \frac{\xi_2 C_2 - \xi_1 C_2 - \xi_1 C_3 + \xi_3 C_3}{\frac{C_3}{C_1} + \frac{C_2}{C_1} + 1}$$



Now,  $\varphi_1 - \varphi_0 = \varphi_1 = -\frac{(q_1 + q_2)}{C_1}$ , as  $(\varphi_0 = 0)$

$$= \frac{\xi_1 (C_2 + C_3) - \xi_2 C_2 - \xi_3 C_3}{C_1 + C_2 + C_3}$$

And using the symmetry,  $\varphi_2 = \frac{\xi_2 (C_1 + C_3) - \xi_1 C_1 - \xi_3 C_3}{C_1 + C_2 + C_3}$

and 
$$\varphi_3 = \frac{\xi_3 (C_1 + C_2) - \xi_1 C_1 - \xi_2 C_2}{C_1 + C_2 + C_3}$$

The answers have wrong sign in the book.

**3.126** Taking the advantage of symmetry of the problem charge distribution may be made, as shown in the figure.

In the loop, 12561,  $-\Delta\varphi = 0$

$$\text{or } \frac{q_2}{C_2} + \frac{q_2 - q_1}{C_3} - \frac{q_1}{C_1} = 0$$

$$\text{or } \frac{q_1}{q_2} = \frac{C_1(C_3 + C_2)}{C_2(C_1 + C_3)} \quad (1)$$

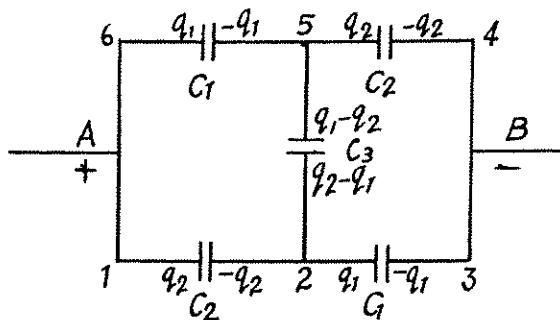
Now, capacitance of the network,

$$C_0 = \frac{q_1 + q_2}{\Phi_A - \Phi_B} = \frac{q_1 + q_2}{q_2/C_2 + q_1/C_1}$$

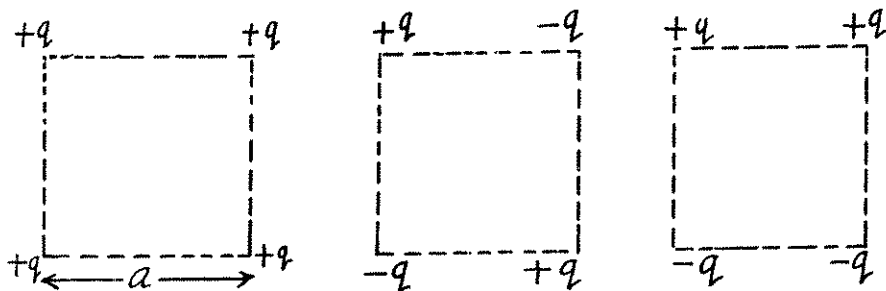
$$= \frac{(1 + q_1/q_2)}{\left(\frac{1}{C_2} + \frac{q_1}{q_2 C_1}\right)} \quad (2)$$

From Eqs. (1) and (2)

$$C_0 = \frac{2 C_1 C_2 + C_3 (C_1 + C_2)}{C_1 + C_2 + 2 C_3}$$



- 3.127 (a) Interaction energy of any two point charges  $q_1$  and  $q_2$  is given by  $\frac{q_1 q_2}{4 \pi \epsilon_0 r}$  where  $r$  is the separation between the charges.



Hence, interaction energy of the system,

$$U_a = 4 \frac{q^2}{4 \pi \epsilon_0 a} + 2 \frac{q^2}{4 \pi \epsilon_0 (\sqrt{2} a)}$$

$$U_b = 4 \frac{-q^2}{4 \pi \epsilon_0 a} + 2 \frac{q^2}{4 \pi \epsilon_0 (\sqrt{2} a)}$$

$$\text{and } U_c = 2 \frac{q^2}{4 \pi \epsilon_0 a} - \frac{2 q^2}{4 \pi \epsilon_0 a} - \frac{2 q^2}{4 \pi \epsilon_0 (\sqrt{2} a)} = - \frac{\sqrt{2} q^2}{4 \pi \epsilon_0 a}$$

- 3.128** As the chain is of infinite length any two charge of same sign will occur symmetrically to any other charge of opposite sign.

So, interaction energy of each charge with all the others,

$$U = -2 \frac{q^2}{4\pi\epsilon_0 a} \left[ 1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \dots \text{up to } \infty \right] \quad (1)$$

But  $\ln(1+x) = x - \frac{1}{2}x^2 + \frac{1}{3}x^3 - \dots \text{up to } \infty$

and putting  $x = 1$  we get  $\ln 2 = 1 - \frac{1}{2} + \frac{1}{3} - \dots \text{up to } \infty$  (2)

From Eqs. (1) and (2),

$$U = \frac{-2q^2 \ln 2}{4\pi\epsilon_0 a}$$

- 3.129** Using electrical image method, interaction energy of the charge  $q$  with those induced on the plane.

$$U = \frac{-q^2}{4\pi\epsilon_0 (2l)} = -\frac{q^2}{8\pi\epsilon_0 l}$$

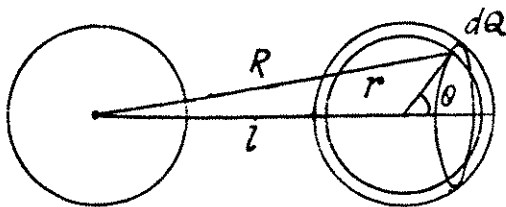
- 3.130** Consider the interaction energy of one of the balls (say 1) and thin spherical shell of the other. This interaction energy can be written as  $\int d\varphi q$

$$= \int \frac{q_1}{4\pi\epsilon_0 R} \rho_2(r) 2\pi r^2 \sin\theta d\theta dr = \int_0^\pi \frac{\rho_2(r) q_1 r^2 \sin\theta d\theta dr}{2\epsilon_0 (l^2 + r^2 + 2lr \cos\theta)^{1/2}}$$

$$= \frac{q_1 r}{2\epsilon_0 l} dr \int_{l-r}^{l+r} dx \rho_2(r)$$

$$= \frac{q_1 r}{2\epsilon_0 l} dr \cdot 2r \rho_2(r) \cdot 2$$

$$= \frac{q_1}{4\pi\epsilon_0 l} 4\pi r^2 dr \rho_2(r)$$



Hence finally integrating

$$U_{\text{int}} = \frac{q_1 q_2}{4\pi\epsilon_0 l} \quad \text{where, } q_2 = \int_0^\infty 4\pi r^2 \rho_2(r) dr$$

- 3.131** Charge contained in the capacitor of capacitance  $C_1$  is  $q = C_1 \varphi$  and the energy, stored in it :

$$U_i = \frac{q^2}{2C_1} = \frac{1}{2} C_1 \varphi^2$$

Now, when the capacitors are connected in parallel, equivalent capacitance of the system,  $C = C_1 + C_2$  and hence, energy stored in the system :



$$U_f = \frac{C_1^2 \varphi^2}{2(C_1 + C_2)}, \text{ as charge remains conserved during the process.}$$

So, increment in the energy,

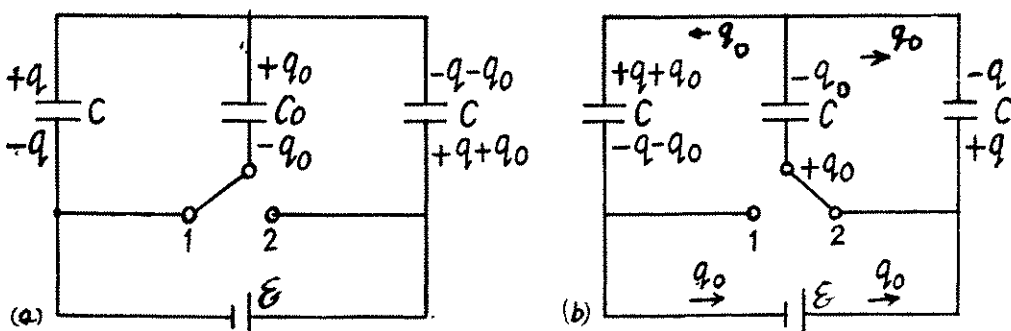
$$\Delta U = \frac{C_1^2 \varphi^2}{2} \left( \frac{1}{C_1 + C_2} - \frac{1}{C_1} \right) = \frac{-C_2 C_1 \varphi^2}{2(C_1 + C_2)} = -0.03 \text{ mJ}$$

**3.132** The charge on the condensers in position 1 are as shown. Here

$$\frac{q}{C} = \frac{q_0}{C_0} = \frac{q + q_0}{C + C_0}$$

$$\text{and } (q + q_0) \left( \frac{1}{C + C_0} + \frac{1}{C} \right) = \xi \text{ or, } q + q_0 = \frac{C(C + C_0)\xi}{C_0 + 2C}$$

$$\text{Hence, } q = \frac{C^2 \xi}{C_0 + 2C} \text{ and } q_0 = \frac{C C_0 \xi}{C_0 + 2C}$$



After the switch is thrown to position 2, the charges change as shown in (Fig-b).

A charge  $q_0$  has flown in the right loop through the two condensers and a charge  $q_0$  through the cell. Because of the symmetry of the problem there is no change in the energy stored in the condensers. Thus

$H$  (Heat produced) = Energy delivered by the cell

$$= \Delta q \xi = q_0 \xi = \frac{C C_0 \xi^2}{C_0 + 2C}$$

**3.133** Initially, the charge on the right plate of the capacitor,  $q = C(\xi_1 - \xi_2)$  and finally, when switched to the position, 2, charge on the same plate of capacitor ;

$$q' = C \xi_1$$

So,

$$\Delta q = q' = C \xi_2$$

Now, from energy conservation,

$\Delta U + \text{Heat liberated} = A_{\text{cell}}$ , where  $\Delta U$  is the electrical energy.

$$\frac{1}{2} C \xi_1^2 - \frac{1}{2} C (\xi_1 - \xi_2)^2 + \text{Heat liberated} = \Delta q \xi_1$$

as only the cell with e.m.f.  $\xi_1$  is responsible for redistribution of the charge. So,

$$C \xi_1 \xi_2 - \frac{1}{2} C \xi_2^2 + \text{Heat liberated} = C \xi_2 \xi_1.$$

$$\text{Hence heat liberated} = \frac{1}{2} C \xi_2^2$$

**3.134** Self energy of each shell is given by  $\frac{q\varphi}{2}$ , where  $\varphi$  is the potential of the shell, created only by the charge  $q$ , on it.

Hence, self energy of the shells 1 and 2 are :

$$W_1 = \frac{q_1^2}{8\pi\epsilon_0 R_1} \text{ and } W_2 = \frac{q_2^2}{8\pi\epsilon_0 R_2}$$

The interaction energy between the charged shells equals charge  $q$  of one shell, multiplied by the potential  $\varphi$ , created by other shell, at the point of location of charge  $q$ .

$$\text{So, } W_{12} = q_1 \frac{q_2}{4\pi\epsilon_0 R_2} = \frac{q_1 q_2}{4\pi\epsilon_0 R_2}$$

Hence, total energy of the system,

$$U = W_1 + W_2 + W_{12}$$

$$= \frac{1}{4\pi\epsilon_0} \left[ \frac{q_1^2}{2R_1} + \frac{q_2^2}{2R_2} + \frac{q_1 q_2}{R_2} \right]$$

**3.135** Electric fields inside and outside the sphere with the help of Gauss theorem :

$$E_1 = \frac{qr}{4\pi\epsilon_0 R^2} (r \leq R), E_2 = \frac{q}{4\pi\epsilon_0 r^2} (r > R)$$

Sought self energy of the ball

$$U = W_1 + W_2$$

$$= \int_0^R \frac{\epsilon_0 E_1^2}{2} 4\pi r^2 dr + \int_R^\infty \frac{\epsilon_0 E_2^2}{2} 4\pi r^2 dr = \frac{q^2}{8\pi\epsilon_0 R} \left( \frac{1}{5} + 1 \right)$$

$$\text{Hence, } U = \frac{3q^2}{4\pi\epsilon_0 5R} \text{ and } \frac{W_1}{W_2} = \frac{1}{5}$$

**3.136** (a) By the expression  $\int \frac{1}{2} \epsilon_0 \epsilon E^2 dV = \int \frac{1}{2} \epsilon \epsilon_0 E^2 4\pi r^2 dr$ , for a spherical layer.

To find the electrostatic energy inside the dielectric layer, we have to integrate the upper expression in the limit  $[a, b]$

$$U = \frac{1}{2} \epsilon_0 \epsilon \int_a^b \left( \frac{q}{4\pi\epsilon_0 \epsilon r^2} \right)^2 4\pi r^2 dr = \frac{q^2}{8\pi\epsilon_0 \epsilon} \left[ \frac{1}{a} - \frac{1}{b} \right] = 27 \text{ mJ}$$

3.137 As the field is conservative total work done by the field force,

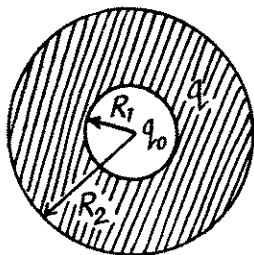
$$\begin{aligned} A_{fd} &= U_i - U_f = \frac{1}{2} q (\varphi_1 - \varphi_2) \\ &= \frac{1}{2} \frac{q^2}{4 \pi \epsilon_0} \left[ \frac{1}{R_1} - \frac{1}{R_2} \right] = \frac{q^2}{8 \pi \epsilon_0} \left[ \frac{1}{R_1} - \frac{1}{R_2} \right] \end{aligned}$$

3.138 Initially, energy of the system,  $U_i = W_1 + W_{12}$  where,  $W_1$  is the self energy and  $W_{12}$  is the mutual energy.

So, 
$$U_i = \frac{1}{2} \frac{q^2}{4 \pi \epsilon_0 R_1} + \frac{qq_0}{4 \pi \epsilon_0 R_1}$$

and on expansion, energy of the system,

$$\begin{aligned} U_f &= W'_1 + W'_{12} \\ &= \frac{1}{2} \frac{q^2}{4 \pi \epsilon_0 R_2} + \frac{qq_0}{4 \pi \epsilon_0 R_2} \end{aligned}$$



Now, work done by the field force,  $A$  equals the decrement in the electrical energy,

i.e. 
$$A = (U_i - U_f) = \frac{q(q_0 + q/2)}{4 \pi \epsilon_0} \left( \frac{1}{R_1} - \frac{1}{R_2} \right)$$

**Alternate :** The work of electric forces is equal to the decrease in electric energy of the system,

$$A = U_i - U_f$$

In order to find the difference  $U_i - U_f$  we note that upon expansion of the shell, the electric field and hence the energy localized in it, changed only in the hatched spherical layer consequently (Fig.).

$$U_i - U_f = \int_{R_1}^{R_2} \frac{\epsilon_0}{2} (E_1^2 - E_2^2) \cdot 4 \pi r^2 dr$$

where  $E_1$  and  $E_2$  are the field intensities (in the hatched region at a distance  $r$  from the centre of the system) before and after the expansion of the shell. By using Gauss' theorem, we find

$$E_1 = \frac{1}{4 \pi \epsilon_0} \frac{q + q_0}{r^2} \text{ and } E_2 = \frac{1}{4 \pi \epsilon_0} \frac{q_0}{r^2}$$

As a result of integration, we obtain

$$A = \frac{q(q_0 + q/2)}{4 \pi \epsilon_0} \left( \frac{1}{R_1} - \frac{1}{R_2} \right)$$

**3.139** Energy of the charged sphere of radius  $r$ , from the equation

$$U = \frac{1}{2} q \varphi = \frac{1}{2} q \frac{q}{4 \pi \epsilon_0 r} = \frac{q^2}{8 \pi \epsilon_0 r}$$

If the radius of the shell changes by  $dr$  then work done is

$$4 \pi r^2 F_u dr = -dU = q^2 / 8 \pi \epsilon_0 r^2$$

Thus sought force per unit area,

$$F_u = \frac{q^2}{4 \pi r^2 (8 \pi \epsilon_0 r^2)} = \frac{(4 \pi r^2 \sigma)^2}{4 \pi r^2 \times 8 \pi \epsilon_0 r^2} = \frac{\sigma^2}{2 \epsilon_0}$$

**3.140** Initially, there will be induced charges of magnitude  $-q$  and  $+q$  on the inner and outer surface of the spherical layer respectively. Hence, the total electrical energy of the system is the sum of self energies of spherical shells, having radii  $a$  and  $b$ , and their mutual energies including the point charge  $q$ .

$$U_i = \frac{1}{2} \frac{q^2}{4 \pi \epsilon_0 b} + \frac{1}{2} \frac{(-q)^2}{4 \pi \epsilon_0 a} + \frac{-q q}{4 \pi \epsilon_0 a} + \frac{q q}{4 \pi \epsilon_0 b} + \frac{-q q}{4 \pi \epsilon_0 b}$$

or 
$$U_i = \frac{q^2}{8 \pi \epsilon_0} \left[ \frac{1}{b} - \frac{1}{a} \right]$$

Finally, charge  $q$  is at infinity hence,  $U_f = 0$

Now, work done by the agent = increment in the energy

$$= U_f - U_i = \frac{q^2}{8 \pi \epsilon_0} \left[ \frac{1}{a} - \frac{1}{b} \right]$$

**3.141** (a) Sought work is equivalent to the work performed against the electric field created by one plate, holding at rest and to bring the other plate away. Therefore the required work,

$$A_{\text{agent}} = q E (x_2 - x_1),$$

where  $E = \frac{\sigma}{2 \epsilon_0}$  is the intensity of the field created by one plate at the location of other.

So, 
$$A_{\text{agent}} = q \frac{\sigma}{2 \epsilon_0} (x_2 - x_1) = \frac{q^2}{2 \epsilon_0 S} (x_2 - x_1)$$

**Alternate :**  $A_{\text{ext}} = \Delta U$  (as field is potential)

$$= \frac{q^2}{2 \epsilon_0 S} x_2 - \frac{q^2}{2 \epsilon_0 S} x_1 = \frac{q^2}{2 \epsilon_0 S} (x_2 - x_1)$$

(b) When voltage is kept const., the force acting on each plate of capacitor will depend on the distance between the plates.

So, elementary work done by agent, in its displacement over a distance  $dx$ , relative to the other,

$$dA = -F_x dx$$

But, 
$$F_x = - \left( \frac{\sigma(x)}{2 \epsilon_0} \right) S \sigma(x) \quad \text{and} \quad \sigma(x) = \frac{\epsilon_0 V}{x}$$

Hence, 
$$A = \int dA = \int_{x_1}^{x_2} \frac{1}{2} \epsilon_0 \frac{S V^2}{x^2} dx = \frac{\epsilon_0 S V^2}{2} \left[ \frac{1}{x_1} - \frac{1}{x_2} \right]$$

**Alternate :** From energy Conservation,

$$U_f - U_i = A_{\text{cell}} + A_{\text{agent}}$$

$$\text{or} \quad \frac{1}{2} \frac{\epsilon_0 S}{x_2} V^2 - \frac{1}{2} \frac{\epsilon_0 S}{x_1} V^2 = \left[ \frac{\epsilon_0 S}{x_2} - \frac{\epsilon_0 S}{x_1} \right] V^2 + A_{\text{agent}}$$

$$(\text{as } A_{\text{cell}} = (q_f - q_i) V = (C_f - C_i) V^2)$$

$$\text{So} \quad A_{\text{agent}} = \frac{\epsilon_0 S V^2}{2} \left[ \frac{1}{x_1} - \frac{1}{x_2} \right]$$

**3.142** (a) When metal plate of thickness  $\eta d$  is inserted inside the capacitor, capacitance of the system becomes  $C_0 = \frac{\epsilon_0 S}{d(1-\eta)}$

$$\text{Now, initially, charge on the capacitor, } q_0 = C_0 V = \frac{\epsilon_0 S V}{d(1-\eta)}$$

$$\text{Finally, capacitance of the capacitor, } C = \frac{\epsilon_0 S}{d}$$

As the source is disconnected, charge on the plates will remain same during the process. Now, from energy conservation,

$$U_f - U_i = A_{\text{agent}} \quad (\text{as cell does no work})$$

$$\text{or,} \quad \frac{1}{2} \frac{q_0^2}{C} - \frac{1}{2} \frac{q_0^2}{C_0} = A_{\text{agent}}$$

$$\text{Hence } A_{\text{agent}} = \frac{1}{2} \left[ \frac{\epsilon_0 S V}{d(1-\eta)} \right]^2 \left[ \frac{1}{C} - \frac{(1-\eta)}{C} \right] = \frac{1}{2} \frac{C V^2 \eta}{(1-\eta)^2} = 1.5 \text{ mJ}$$

(b) Initially, capacitance of the system is given by,

$$C_0 = \frac{C \epsilon}{\eta(1-\epsilon) + \epsilon} \quad (\text{this is the capacitance of two capacitors in series})$$

$$\text{So, charge on the plate, } q_0 = C_0 V$$

Capacitance of the capacitor, after the glass plate has been removed equals  $C$

From energy conservation,

$$\begin{aligned} A_{\text{agent}} &= U_f - U_i \\ &= \frac{1}{2} q_0^2 \left[ \frac{1}{C} - \frac{1}{C_0} \right] = \frac{1}{2} \frac{C V^2 \epsilon \eta (\epsilon - 1)}{[\epsilon - \eta(\epsilon - 1)]^2} = 0.8 \text{ mJ} \end{aligned}$$

**3.143** When the capacitor which is immersed in water is connected to a constant voltage source, it gets charged. Suppose  $\sigma_0$  is the free charge density on the condenser plates. Because water is a dielectric, bound charges also appear in it. Let  $\sigma'$  be the surface density of bound charges. (Because of homogeneity of the medium and uniformity of the field when we ignore edge effects no volume density of bound charges exists.) The electric field due to free charges only  $\frac{\sigma_0}{\epsilon_0}$ ; that due to bound charges is  $\frac{\sigma'}{\epsilon_0}$  and the total electric field is

$\frac{\sigma_0}{\epsilon \epsilon_0}$ . Recalling that the sign of bound charges is opposite of the free charges, we have

$$\frac{\sigma_0}{\epsilon\epsilon_0} = \frac{\sigma_0}{\epsilon_0} - \frac{\sigma'}{\epsilon_0} \quad \text{or,} \quad \sigma' = \left( \frac{\epsilon - 1}{\epsilon} \right) \sigma_0$$

Because of the field that exists due to the free charges (not the total field; the field due to the bound charges must be excluded for this purpose as they only give rise to self energy effects), there is a force attracting the bound charges to the near by plates. This force is

$$\frac{1}{2} \sigma' \frac{\sigma_0}{\epsilon_0} = \frac{(\epsilon - 1) \sigma_0^2}{2\epsilon\epsilon_0} \text{ per unit area.}$$

The factor  $\frac{1}{2}$  needs an explanation. Normally the force on a test charge is  $qE$  in an electric field  $E$ . But if the charge itself is produced by the electric field then the force must be constructed bit by bit and is

$$F = \int_0^E q(E') dE'$$

if

$q(E') \propto E'$  then we get

$$F = \frac{1}{2} q(E) E$$

This factor of  $\frac{1}{2}$  is well known. For example the energy of a dipole of moment  $\vec{p}$  in an electric field  $\vec{E}_0$  is  $-\vec{p} \cdot \vec{E}_0$  while the energy per unit volume of a linear dielectric in an electric field is  $-\frac{1}{2} \vec{P} \cdot \vec{E}_0$  where  $\vec{P}$  is the polarization vector (i.e. dipole moment per unit volume). Now the force per unit area manifests itself as excess pressure of the liquid.

Noting that

$$\frac{V}{d} = \frac{\sigma_0}{\epsilon\epsilon_0}$$

We get

$$\Delta p = \frac{\epsilon_0 \epsilon (\epsilon - 1) V^2}{2d^2}$$

Substitution, using  $\epsilon = 81$  for water, gives  $\Delta p = 7.17 \text{ kPa} = 0.07 \text{ atm}$ .

**3.144** One way of doing this problem will be exactly as in the previous case so let us try an alternative method based on energy. Suppose the liquid rises by a distance  $h$ . Then let us calculate the extra energy of the liquid as a sum of polarization energy and the ordinary gravitational energy. The latter is

$$\frac{1}{2} h \cdot \rho g \cdot Sh = \frac{1}{2} \rho g S h^2$$

If  $\sigma$  is the free charge surface density on the plate, the bound charge density is, from the previous problem,

$$\sigma' = \frac{\epsilon - 1}{\epsilon} \sigma$$

This is also the volume density of induced dipole moment i.e. Polarization. Then the energy is, as before

$$-\frac{1}{2} \cdot \sigma' E_0 = -\frac{1}{2} \cdot \sigma' \frac{\sigma}{\epsilon_0} = -\frac{(\epsilon - 1) \sigma^2}{2\epsilon_0 \epsilon}$$

and the total polarization energy is

$$-S(a+h) \frac{(\epsilon-1)\sigma^2}{2\epsilon_0\epsilon}$$

Then, total energy is

$$U(h) = -S(a+h) \frac{(\epsilon-1)\sigma^2}{2\epsilon_0\epsilon} + \frac{1}{2}\rho g S h^2$$

The actual height to which the liquid rises is determined from the formula

$$\frac{dU}{dh} = U'(h) = 0$$

This gives

$$h = \frac{(\epsilon-1)\sigma^2}{2\epsilon_0\epsilon\rho g}$$

**3.145** We know that energy of a capacitor,  $U = \frac{q^2}{2C}$ .

Hence, from  $F_x = \left. \frac{\partial U}{\partial x} \right|_{q=\text{Const.}}$  we have,  $F_x = \frac{q^2}{2} \frac{\partial C}{\partial x} / C^2$  (1)

Now, since  $d \ll R$ , the capacitance of the given capacitor can be calculated by the formula of a parallel plate capacitor. Therefore, if the dielectric is introduced upto a depth  $x$  and the length of the capacitor is  $l$ , we have,

$$C = \frac{2\pi\epsilon_0\epsilon R x}{d} + \frac{2\pi R\epsilon_0(l-x)}{d} \quad (2)$$

From (1) and (2), we get,

$$F_x = \epsilon_0(\epsilon-1) \frac{\pi R V^2}{d}$$

**3.146** When the capacitor is kept at a constant potential difference  $V$ , the work performed by the moment of electrostatic forces between the plates when the inner moveable plate is rotated by an angle  $d\varphi$  equals the increase in the potential energy of the system. This comes about because when charges are made, charges flow from the battery to keep the potential constant and the amount of the work done by these charges is twice in magnitude and opposite in sign to the change in the energy of the capacitor. Thus

$$N_z = \frac{\partial U}{\partial \varphi} = \frac{1}{2} V^2 \frac{\partial C}{\partial \varphi}$$

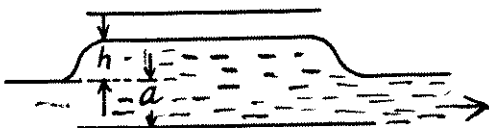
Now the capacitor can be thought of as made up two parts (with and without the dielectric) in parallel.

Thus  $C = \frac{\epsilon_0 R^2 \varphi}{2d} + \frac{\epsilon_0 \epsilon (\pi - \varphi) R^2}{2d}$

as the area of a sector of angle  $\varphi$  is  $\frac{1}{2} R^2 \varphi$ . Differentiation then gives

$$N_z = - \frac{(\epsilon-1)\epsilon_0 R^2 V^2}{4d}$$

The negative sign of  $N_z$  indicates that the moment of the force is acting clockwise (i.e. trying to suck in the dielectric).



### 3.4 ELECTRIC CURRENT

3.147 The convection current is

$$I = \frac{dq}{dt} \quad (1)$$

here,  $dq = \lambda dx$ , where  $\lambda$  is the linear charge density.

But, from the Gauss' theorem, electric field at the surface of the cylinder,

$$E = \frac{\lambda}{2\pi\epsilon_0 a}$$

Hence, substituting the value of  $\lambda$  and subsequently of  $dq$  in Eqs. (1), we get

$$\begin{aligned} I &= \frac{2E\pi\epsilon_0 a dx}{dt} \\ &= 2\pi\epsilon_0 E a v, \text{ as } \frac{dx}{dt} = v \end{aligned}$$

3.148 Since  $d \ll r$ , the capacitance of the given capacitor can be calculated using the formula for a parallel plate capacitor. Therefore if the water (permittivity  $\epsilon$ ) is introduced up to a height  $x$  and the capacitor is of length  $l$ , we have,

$$C = \frac{\epsilon\epsilon_0 \cdot 2\pi r x}{d} + \frac{\epsilon_0 (l-x) 2\pi r}{d} = \frac{\epsilon_0 2\pi r}{d} (\epsilon x + l - x)$$

Hence charge on the plate at that instant,  $q = CV$

Again we know that the electric current intensity,

$$\begin{aligned} I &= \frac{dq}{dt} = \frac{d(CV)}{dt} \\ &= \frac{V\epsilon_0 2\pi r}{d} \frac{d(\epsilon x + l - x)}{dt} = \frac{V 2\pi r \epsilon_0}{d} (\epsilon - 1) \frac{dx}{dt} \end{aligned}$$

But, 
$$\frac{dx}{dt} = v,$$

So, 
$$I = \frac{2\pi r \epsilon_0 (\epsilon - 1) V}{d} v = 0.11 \mu A$$

3.149 We have,  $R_t = R_0 (1 + \alpha t)$ , (1)

where  $R_t$  and  $R_0$  are resistances at  $t^\circ C$  and  $0^\circ C$  respectively and  $\alpha$  is the mean temperature coefficient of resistance.

So,  $R_1 = R_0 (1 + \alpha_1 t)$  and  $R_2 = \eta R_0 (1 + \alpha_2 t)$

(a) In case of series combination,  $R = \Sigma R_i$

so 
$$R = R_1 + R_2 = R_0 [(1 + \eta) + (\alpha_1 + \eta \alpha_2) t] \quad (1)$$

$$= R_0 (1 + \eta) \left[ 1 + 2 \frac{\alpha_1 + \eta \alpha_2}{1 + \eta} t \right] \quad (2)$$



Comparing Eqs. (1) and (2), we conclude that temperature co-efficient of resistance of the circuit,

$$\alpha = \frac{\alpha_1 + \eta \alpha_2}{1 + \eta}$$

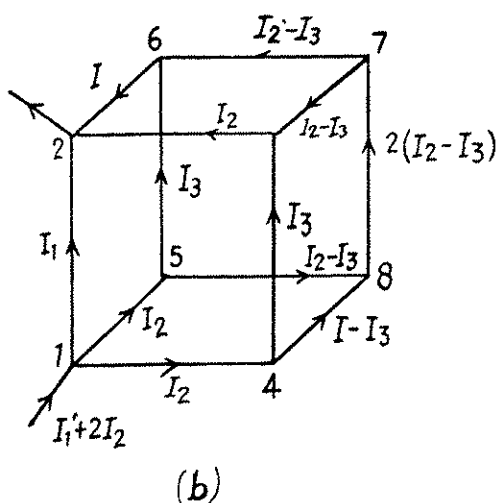
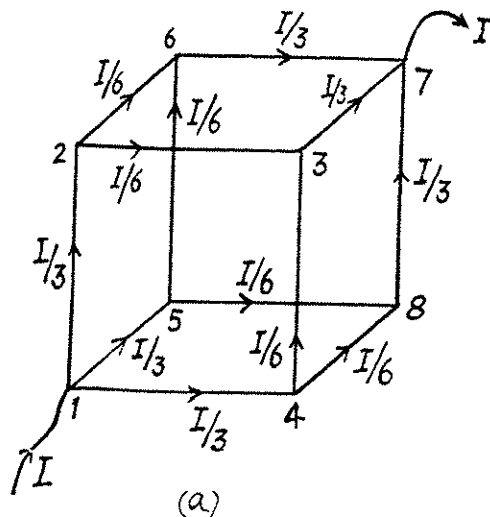
(b) In parallel combination

$$R = \frac{R_0 (1 + \alpha_1 t) R_0 \eta (1 + \alpha_2 t)}{R_0 (1 + \alpha_1 t) + \eta R_0 (1 + \alpha_2 t)} = R' (1 + \alpha' t), \text{ where } R' = \frac{\eta R_0}{1 + \eta}$$

Now, neglecting the terms, proportional to the product of temperature coefficients, as being very small, we get,

$$\alpha' \approx \frac{\eta \alpha_1 + \alpha_2}{1 + \eta}$$

3.150 (a) The currents are as shown. From Ohm's law applied between 1 and 7 via 1487 (say)



$$IR_{eq} = \frac{I}{3}R + \frac{I}{6}R + \frac{I}{3}R = \frac{5}{6}RI$$

Thus,

$$R_{eq} = \frac{5R}{6}$$

(b) Between 1 and 2 from the loop 14321,

$$I_1 R = 2I_2 R + I_3 R \text{ or } I_1 = I_3 + 2I_2$$

From the loop 48734,

$$(I_2 - I_3) R + 2(I_2 - I_3) R + (I_2 - I_3) R = I_3 R.$$

or,

$$4(I_2 - I_3) = I_3 \text{ or } I_3 = \frac{4}{5}I_2$$

so

$$I_1 = \frac{14}{5}I_2$$

$$\text{Then, } (I_1 + 2I_2) R_{eq} = \frac{24}{5}I_2 R_{eq} = I_1 R = \frac{14}{5}I_2 R$$

or  $R_{eq} = \frac{7}{12} R$

(c) Between 1 and 3

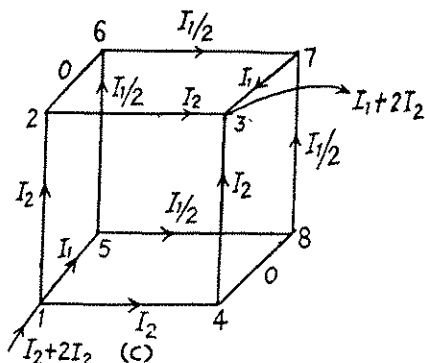
From the loop 15621

$$I_2 R = I_1 R + \frac{I_1}{2} R \quad \text{or,} \quad I_2 = 3 \frac{I_1}{2}$$

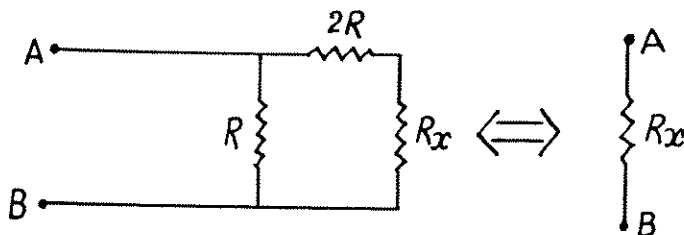
Then,  $(I_1 + 2I_2) R_{eq} = 4 I_1 R_{eq}$

$$= I_2 R + I_2 R = 3 I_1 R$$

Hence,  $R_{eq} = \frac{3}{4} R$



3.151 Total resistance of the circuit will be independent of the number of cells,



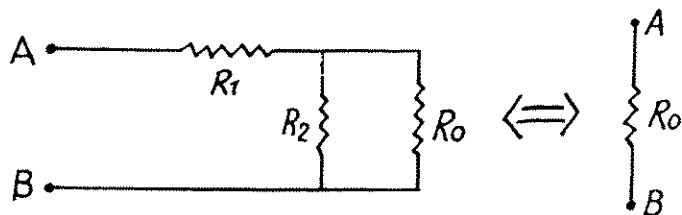
if  $R_x = \frac{(R_x + 2R) R}{R_x + 2R + R}$

or,  $R_x^2 + 2R R_x - 2R^2 = 0$

On solving and rejecting the negative root of the quadratic equation, we have,

$$R_x = R(\sqrt{3} - 1)$$

3.152 Let  $R_0$  be the resistance of the network,



then,  $R_0 = \frac{R_0 R_2}{R_0 + R_2}$  or  $R_0^2 - R_0 R_1 - R_1 R_2 = 0$

On solving we get,

$$R_0 = \frac{R_1}{2} \left( 1 + \sqrt{1 + 4 \frac{R_2}{R_1}} \right) = 6 \Omega$$

3.153 Suppose that the voltage  $V$  is applied between the points  $A$  and  $B$  then

$$V = IR = I_0 R_0$$

where  $R$  is resistance of whole the grid,  $I$ , the current through the grid and  $I_0$ , the current through the segment  $AB$ . Now from symmetry,  $I/4$  is the part of the current, flowing through all the four wire segments, meeting at the point  $A$  and similarly the amount of current flowing through the wires, meeting at  $B$  is also  $I/4$ . Thus a current  $I/2$  flows through the conductor  $AB$ , i.e.

$$I_0 = \frac{I}{2}$$

Hence,

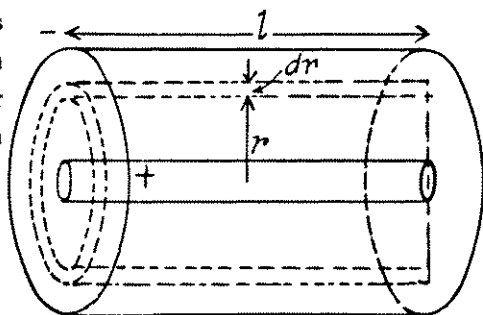
$$R = \frac{R_0}{2}$$

3.154 Let us mentally isolate a thin cylindrical layer of inner and outer radii  $r$  and  $r + dr$  respectively. As lines of current at all the points of this layer are perpendicular to it, such a layer can be treated as a cylindrical conductor of thickness  $dr$  and cross-sectional area  $2\pi rl$ . So, we have,

$$dR = \rho \frac{dr}{S(r)} = \rho \frac{dr}{2\pi rl}$$

and integrating between the limits, we get,

$$R = \frac{\rho}{2\pi l} \ln \frac{b}{a}$$



3.155 Let us mentally isolate a thin spherical layer of inner and outer radii  $r$  and  $r + dr$ . Lines of current at all the points of the this layer are perpendicular to it and therefore such a layer can be treated as a spherical conductor of thickness  $dr$  and cross sectional area  $4\pi r^2$ . So

$$dR = \rho \frac{dr}{4\pi r^2} \quad (1)$$

And integrating (1) between the limits  $[a, b]$ , we get,

$$R = \frac{\rho}{4\pi} \left[ \frac{1}{a} - \frac{1}{b} \right]$$

Now, for  $b \rightarrow \infty$ , we have

$$R = \frac{\rho}{4\pi a}$$

3.156 In our system, resistance of the medium  $R = \frac{\rho}{4\pi} \left[ \frac{1}{a} - \frac{1}{b} \right]$ ,

where  $\rho$  is the resistivity of the medium

The current

$$i = \frac{\Phi}{R} = \frac{\Phi}{\frac{\rho}{4\pi} \left[ \frac{1}{a} - \frac{1}{b} \right]}$$

Also,  $i = \frac{-dq}{dt} = -\frac{d(C\varphi)}{dt} = -C \frac{d\varphi}{dt}$ , as capacitance is constant. (2)

So, equating (1) and (2) we get,

$$\frac{\varphi}{\frac{\rho}{4\pi} \left[ \frac{1}{a} - \frac{1}{b} \right]} = -C \frac{d\varphi}{dt}$$

or, 
$$-\int \frac{d\varphi}{\varphi} = \frac{\Delta t}{\frac{C\rho}{4\pi} \left[ \frac{1}{a} - \frac{1}{b} \right]}$$

or, 
$$\ln \eta = \frac{\Delta t \cdot 4\pi ab}{C\rho(b-a)}$$

Hence, resistivity of the medium,

$$\rho = \frac{4\pi \Delta t ab}{C(b-a) \ln \eta}$$

**3.157** Let us mentally impart the charge  $+q$  and  $-q$  to the balls respectively. The electric field strength at the surface of a ball will be determined only by its own charge and the charge can be considered to be uniformly distributed over the surface, because the other ball is at infinite distance. Magnitude of the field strength is given by,

$$E = \frac{q}{4\pi\epsilon_0 a^2}$$

So, current density  $j = \frac{1}{\rho} \frac{q}{4\pi\epsilon_0 a^2}$  and electric current

$$I = \int \vec{j} \cdot d\vec{S} = jS = \frac{q}{\rho 4\pi\epsilon_0 a^2} \cdot 4\pi a^2 = \frac{q}{\rho\epsilon_0}$$

But, potential difference between the balls,

$$\varphi_+ - \varphi_- = 2 \frac{q}{4\pi\epsilon_0 a}$$

Hence, the sought resistance,

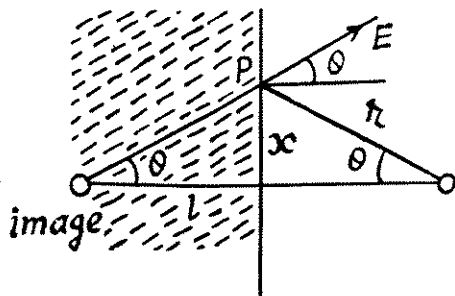
$$R = \frac{\varphi_+ - \varphi_-}{I} = \frac{2q/4\pi\epsilon_0 a}{q/\rho\epsilon_0} = \frac{\rho}{2\pi a}$$

**3.158** (a) The potential in the unshaded region beyond the conductor as the potential of the given charge and its image and has the form

$$\varphi = A \left( \frac{1}{r_1} - \frac{1}{r_2} \right)$$

where  $r_1, r_2$  are the distances of the point from the charge and its image. The potential has been taken to be zero on the conducting plane and on the ball

$$\varphi = A \left( \frac{1}{a} - \frac{1}{2l} \right) = V$$



So  $A \approx Va$ . In this calculation the conditions  $a \ll l$  is used to ignore the variation of  $\varphi$  over the ball.

The electric field at  $P$  can be calculated similarly. The charge on the ball is

$$Q = 4\pi\epsilon_0 Va$$

and 
$$E_P = \frac{Va}{r^2} 2 \cos\theta = \frac{2aV}{r^3}$$

Then  $j = \frac{1}{\rho} E = \frac{2aV}{\rho r^3}$  normal to the plane.

(b) The total current flowing into the conducting plane is

$$I = \int_0^\infty 2\pi x dx j = \int_0^\infty 2\pi x dx \frac{2aV}{\rho (\pi^2 + l^2)^{3/2}}$$

(On putting  $y = x^2 + l^2$ )

$$I = \frac{2\pi aV}{\rho} \int_l^\infty \frac{dy}{y^{3/2}} = \frac{4\pi aV}{\rho}$$

Hence 
$$R = \frac{V}{I} = \frac{\rho}{2\pi a}$$

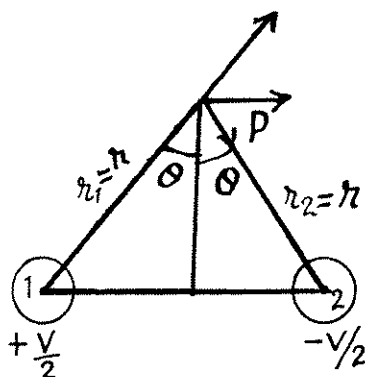
- 3.159** (a) The wires themselves will be assumed to be perfect conductors so the resistance is entirely due to the medium. If the wire is of length  $L$ , the resistance  $R$  of the medium is  $\propto \frac{1}{L}$  because different sections of the wire are connected in parallel (by the medium) rather than in series. Thus if  $R_1$  is the resistance per unit length of the wire then  $R = R_1/L$ . Unit of  $R_1$  is ohm-meter.

The potential at a point  $P$  is by symmetry and superposition

(for  $l \gg a$ )

$$\begin{aligned} \varphi &= \frac{A}{2} \ln \frac{r_1}{a} - \frac{A}{2} \ln \frac{r_2}{a} \\ &= \frac{A}{2} \ln \frac{r_1}{r_2} \end{aligned}$$

Then  $\varphi_1 = \frac{V}{2} = \frac{A}{2} \ln \frac{a}{l}$  (for the potential of 1)



or,

$$A = -V/\ln \frac{l}{a}$$

and

$$\varphi = -\frac{V}{2 \ln l/a} \ln r_1/r_2$$

We then calculate the field at a point  $P$  which is equidistant from 1 & 2 and at a distance  $r$  from both :

$$\begin{aligned} \text{Then } E &= \frac{V}{2 \ln l/a} \left( \frac{1}{r} \right) \times 2 \sin \theta \\ &= \frac{Vl}{2 \ln l/a} \frac{1}{r^2} \end{aligned}$$

and

$$J = \sigma E = \frac{1}{\rho} \frac{V}{2 \ln l/a} \frac{1}{r^2}$$

(b) Near either wire

$$E = \frac{V}{2 \ln l/a} \frac{1}{a}$$

and

$$J = \sigma E = \frac{1}{\rho} \frac{V}{2 \ln l/a}$$

Then

$$I = \frac{V}{R} = L \frac{V}{R_1} = J 2\pi a L$$

Which gives

$$R_1 = \frac{\rho}{\pi} \ln l/a$$

**3.160** Let us mentally impart the charges  $+q$  and  $-q$  to the plates of the capacitor.

Then capacitance of the network,

$$C = \frac{q}{\varphi} = \frac{\epsilon \epsilon_0 \int E_n dS}{\varphi} \quad (1)$$

Now, electric current,

$$i = \int \vec{j} \cdot d\vec{S} = \int \sigma E_n dS \text{ as } \vec{j} \uparrow \uparrow \vec{E}. \quad (2)$$

Hence, using (1) in (2), we get,

$$i = \frac{C \varphi}{\epsilon \epsilon_0} \sigma = \frac{C \varphi}{\rho \epsilon \epsilon_0} = 1.5 \mu \text{ A}$$

**3.161** Let us mentally impart charges  $+q$  and  $-q$  to the conductors. As the medium is poorly conducting, the surfaces of the conductors are equipotential and the field configuration is same as in the absence of the medium.

Let us surround, for example, the positively charged conductor, by a closed surface  $S$ , just containing the conductor,

$$\text{then, } R = \frac{\varphi}{i} = \frac{\varphi}{\int \vec{j} \cdot d\vec{S}} = \frac{\varphi}{\int \sigma E_n dS}; \text{ as } \vec{j} \uparrow \uparrow \vec{E}$$

and

$$C = \frac{q}{\varphi} = \frac{\epsilon \epsilon_0 \int E_n dS}{\varphi}$$

So,

$$RC = \frac{\epsilon \epsilon_0}{\sigma} = \rho \epsilon \epsilon_0$$

- 3.162** The dielectric ends in a conductor. It is given that on one side (the dielectric side) the electric displacement  $D$  is as shown. Within the conductor, at any point  $A$ , there can be no normal component of electric field. For if there were such a field, a current will flow towards depositing charge there which in turn will set up countering electric field causing the normal component to vanish. Then by Gauss theorem, we easily derive  $\sigma = D_n = D \cos \alpha$  where  $\sigma$  is the surface charge density at  $A$ .

The tangential component is determined from the circulation theorem

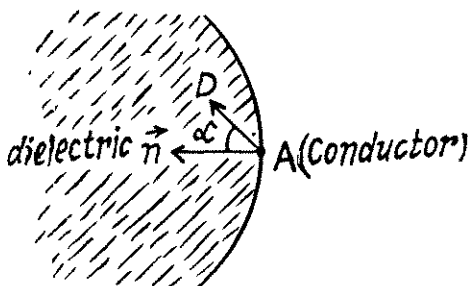
$$\oint \vec{E} \cdot d\vec{r} = 0$$

It must be continuous across the surface of the conductor. Thus, inside the conductor there is a tangential electric field of magnitude,

$$\frac{D \sin \alpha}{\epsilon_0 \epsilon} \text{ at } A.$$

This implies a current, by Ohm's law, of

$$j = \frac{D \sin \alpha}{\epsilon_0 \epsilon \rho}$$



- 3.163** The resistance of a layer of the medium, of thickness  $dx$  and at a distance  $x$  from the first plate of the capacitor is given by,

$$dR = \frac{1}{\sigma(x)} \frac{dx}{S} \quad (1)$$

Now, since  $\sigma$  varies linearly with the distance from the plate. It may be represented as,

$$\sigma = \sigma_1 + \left( \frac{\sigma_2 - \sigma_1}{d} \right) x, \text{ at a distance } x \text{ from any one of the plate.}$$

From Eq. (1)

$$dR = \frac{1}{\sigma_1 + \left( \frac{\sigma_2 - \sigma_1}{d} \right) x} \frac{dx}{S}$$

$$\text{or, } R = \frac{1}{S} \int_0^d \frac{dx}{\sigma_1 + \left( \frac{\sigma_2 - \sigma_1}{d} \right) x} = \frac{d}{S(\sigma_2 - \sigma_1)} \ln \frac{\sigma_2}{\sigma_1}$$

$$\text{Hence, } i = \frac{V}{R} = \frac{S V (\sigma_2 - \sigma_1)}{d \ln \frac{\sigma_2}{\sigma_1}} = 5 \text{ nA}$$

- 3.164** By charge conservation, current  $j$ , leaving the medium (1) must enter the medium (2). Thus

$$j_1 \cos \alpha_1 = j_2 \cos \alpha_2$$

Another relation follows from

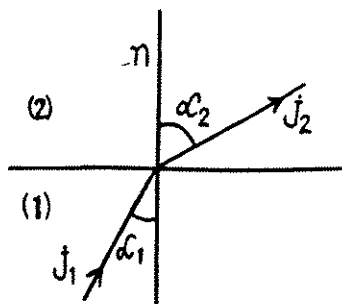
$$E_{1t} = E_{2t},$$

which is a consequence of  $\oint \vec{E} \cdot d\vec{r} = 0$

Thus  $\frac{1}{\sigma_1} j_1 \sin \alpha_1 = \frac{1}{\sigma_2} j_2 \sin \alpha_2$

or,  $\frac{\tan \alpha_1}{\sigma_1} = \frac{\tan \alpha_2}{\sigma_2}$

or,  $\frac{\tan \alpha_1}{\tan \alpha_2} = \frac{\sigma_1}{\sigma_2}$



**3.165** The electric field in conductor 1 is

$$E_1 = \frac{\rho_1 I}{\pi R^2}$$

and that in 2 is  $E_2 = \frac{\rho_2 I}{\pi R^2}$

Applying Gauss' theorem to a small cylindrical pill-box at the boundary.

$$-\frac{\rho_1 I}{\pi R^2} dS + \frac{\rho_2 I}{\pi R^2} dS = \frac{\sigma dS}{\epsilon_0}$$

Thus,  $\sigma = \epsilon_0 (\rho_2 - \rho_1) \frac{1}{\pi R^2}$

and charge at the boundary =  $\epsilon_0 (\rho_2 - \rho_1) I$

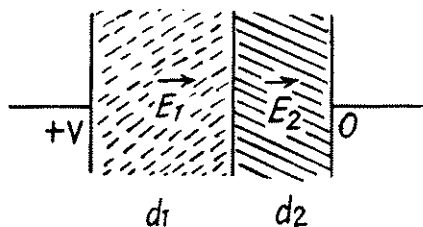
**3.166** We have,  $E_1 d_1 + E_2 d_2 = V$

and by current conservation

$$\frac{1}{\rho_1} E_1 = \frac{1}{\rho_2} E_2$$

Thus,  $E_1 = \frac{\rho_1 V}{\rho_1 d_1 + \rho_2 d_2}$ ,

$$E_2 = \frac{\rho_2 V}{\rho_1 d_1 + \rho_2 d_2}$$



At the boundary between the two dielectrics,

$$\sigma = D_2 - D_1 = \epsilon_0 \epsilon_2 E_2 - \epsilon_0 \epsilon_1 E_1$$

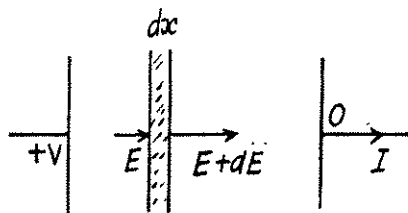
$$\frac{\epsilon_0 V}{\rho_1 d_1 + \rho_2 d_2} (\epsilon_2 \rho_2 - \epsilon_1 \rho_1)$$

**3.167** By current conservation

$$\frac{E(x)}{\rho(x)} = \frac{E(x) + dE(x)}{\rho(x) + d\rho(x)} = \frac{dE(x)}{d\rho(x)}$$

This has the solution,

$$E(x) = C \rho(x) = \frac{I \rho(x)}{A}$$





Hence charge induced in the slice per unit area

$$d\sigma = \epsilon_0 \frac{I}{A} [ \{ \epsilon(x) + d\epsilon(x) \} \{ \rho(x) + d\rho(x) \} - \epsilon(x) \rho(x) ] = \epsilon_0 \frac{I}{A} d[ \epsilon(x) \rho(x) ]$$

Thus, 
$$dQ = \epsilon_0 I d[ \epsilon(x) \rho(x) ]$$

Hence total charge induced, is by integration,

$$Q = \epsilon_0 I (\epsilon_2 \rho_2 - \epsilon_1 \rho_1)$$

**3.168** As in the previous problem

$$E(x) = C \rho(x) = C(\rho_0 + \rho_1 x)$$

where 
$$\rho_0 + \rho_1 d = \eta \rho_0 \quad \text{or,} \quad \rho_1 = \frac{(\eta - 1) \rho_0}{d}$$

By integration 
$$V = \int_0^d C \rho(x) dx = C \rho_0 d \left( 1 + \frac{\eta - 1}{2} \right) = \frac{1}{2} C \rho_0 d (\eta + 1)$$

Thus 
$$C = \frac{2V}{\rho_0 d (\eta + 1)}$$

Thus volume density of charge present in the medium

$$\begin{aligned} &= \frac{dQ}{S dx} = \epsilon_0 dE(x)/dx \\ &= \frac{2\epsilon_0 V}{\rho_0 d (\eta + 1)} \times \frac{(\eta - 1) \rho_0}{d} = \frac{2\epsilon_0 V (\eta - 1)}{(\eta + 1) d^2} \end{aligned}$$

**3.169** (a) Consider a cylinder of unit length and divide it into shells of radius  $r$  and thickness  $dr$ . Different sections are in parallel. For a typical section,

$$d\left(\frac{1}{R_1}\right) = \frac{2\pi r dr}{(\alpha/r^2)} = \frac{2\pi r^3 dr}{\alpha}$$

Integrating, 
$$\frac{1}{R_1} = \frac{\pi R^4}{2\alpha} = \frac{S^2}{2\pi\alpha}$$

or, 
$$R_1 = \frac{2\pi\alpha}{S^2}, \quad \text{where } S = \pi R^2$$

(b) Suppose the electric field inside is  $E_z = E_0$  ( $Z$  axis is along the axis of the conductor). This electric field cannot depend on  $r$  in steady conditions when other components of  $E$  are absent, otherwise one violates the circulation theorem

$$\oint \vec{E} \cdot d\vec{r} = 0$$

The current through a section between radii  $(r + dr, r)$  is

$$2\pi r dr \frac{1}{\alpha/r^2} E = 2\pi r^3 dr \frac{E}{\alpha}$$

Thus 
$$I = \int_0^R 2\pi r^3 dr \frac{E}{\alpha} = \frac{\pi R^4 E}{2\alpha}$$

Hence 
$$E = \frac{2\alpha\pi I}{S^2} \quad \text{when } S = \pi R^2$$

3.170 The formula is,

$$q = C V_0 (1 - e^{-t/RC})$$

$$\text{or, } V = \frac{q}{C} = V_0 (1 - e^{-t/RC}) \quad \text{or, } \frac{V}{V_0} = 1 - e^{-t/RC}$$

$$\text{or, } e^{-t/RC} = 1 - \frac{V}{V_0} = \frac{V_0 - V}{V_0}$$

$$\text{Hence, } t = RC \ln \frac{V_0}{V_0 - V} = RC \ln 10, \text{ if } V = 0.9 V_0.$$

Thus  $t = 0.6 \mu\text{S}$ .

3.171 The charge decays according to the formula

$$q = q_0 e^{-t/RC}$$

Here,  $RC = \text{mean life} = \text{Half-life} / \ln 2$

So, half life =  $T = RC \ln 2$

$$\text{But, } C = \frac{\epsilon \epsilon_0 A}{d}, R = \frac{\rho d}{A}$$

$$\text{Hence, } \rho = \frac{T}{\epsilon \epsilon_0 \ln 2} = 1.4 \times 10^{13} \Omega \cdot \text{m}$$

3.172 Suppose  $q$  is the charge at time  $t$ . Initially  $q = C \xi$ , at  $t = 0$ .

Then at time  $t$ ,

$$\frac{\eta q}{C} - iR - \xi = 0$$

But,  $i = -\frac{dq}{dt}$  (- sign because charge decreases)

$$\text{So } \frac{\eta q}{C} + R \frac{dq}{dt} = \xi$$

$$\frac{dq}{dt} + \frac{\eta}{RC} q = \frac{\xi}{R}$$

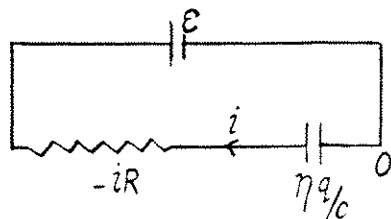
$$\text{or, } \frac{d}{dt} q e^{t\eta/RC} = \frac{\xi}{R} e^{t\eta/RC}$$

$$\text{or, } q = \frac{C \xi}{\eta} + A e^{-t\eta/RC}$$

$$A = C \xi \left( 1 - \frac{1}{\eta} \right), \text{ from } q = C \xi \text{ at } t = 0$$

$$\text{Hence, } q = C \xi \left( \frac{1}{\eta} + \left( 1 - \frac{1}{\eta} \right) e^{-t\eta/RC} \right)$$

$$\text{Finally, } i = -\frac{dq}{dt} = \frac{\xi (\eta - 1)}{R} e^{-t\eta/RC}$$



3.173 Let  $r$  = internal resistance of the battery. We shall take the resistance of the ammeter to be = 0 and that of voltmeter to be  $G$ .

$$\text{Initially, } V = \xi - Ir, I = \frac{\xi}{r + G}$$

$$\text{So, } V = \xi \frac{G}{r+G} \quad (1)$$

After the voltmeter is shunted

$$\frac{V}{\eta} = \xi - \frac{\xi r}{r + \frac{RG}{R+G}} \quad (\text{Voltmeter}) \quad (2)$$

$$\text{and } \frac{\xi}{r + \frac{RG}{R+G}} = \eta \frac{\xi}{r+G} \quad (\text{Ammeter}) \quad (3)$$

From (2) and (3) we have

$$\frac{V}{\eta} = \xi - \frac{\eta r \xi}{r+G} \quad (4)$$

From (1) and (4)

$$\frac{G}{\eta} = r + G - \eta r \text{ or } G = \eta r$$

Then (1) gives the required reading

$$\frac{V}{\eta} = \frac{\xi}{\eta + 1}$$

**3.174** Assume the current flow, as shown. Then potentials are as shown. Thus,

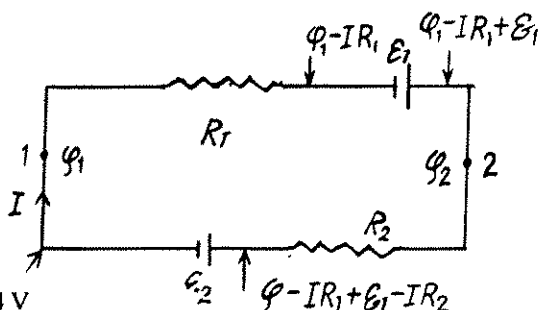
$$\varphi_1 = \varphi_1 - IR_1 + \xi_1 - IR_2 - \xi_2$$

$$\text{or, } I = \frac{\xi_1 - \xi_2}{R_1 + R_2}$$

$$\text{And } \varphi_2 = \varphi_1 - IR_1 + \xi_1$$

$$\text{So, } \varphi_1 - \varphi_2 = -\xi_1 + \frac{\xi_1 - \xi_2}{R_1 + R_2} R_1$$

$$= -(\xi_1 R_2 + \xi_2 R_1) / (R_1 + R_2) = -4 \text{ V}$$



**3.175** Let, us consider the current  $i$ , flowing through the circuit, as shown in the figure. Applying loop rule for the circuit,  $-\Delta\varphi = 0$

$$-2\xi + iR_1 + iR_2 + iR = 0$$

$$\text{or, } i(R_1 + R_2 + R) = 2\xi$$

$$\text{or, } i = \frac{2\xi}{R + R_1 + R_2}$$

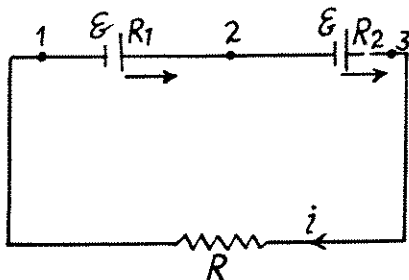
$$\text{Now, if } \varphi_1 - \varphi_2 = 0$$

$$-\xi + iR_1 = 0$$

$$\text{or, } \frac{2\xi R_1}{R + R_1 + R_2} = \xi \text{ and } 2R_1 = R_2 + R + R_1$$

$$\text{or, } R = R_1 - R_2, \text{ which is not possible as } R_2 > R_1$$

$$\text{Thus, } \varphi_2 - \varphi_3 = -\xi + iR_2 = 0$$



or, 
$$\frac{2\xi R_2}{R + R_1 + R_2} = \xi$$

So,  $R = R_2 - R_1$ , which is the required resistance.

3.176 (a) Current,  $i = \frac{N\xi}{NR} = \frac{N\alpha R}{NR} = \alpha$ , as  $\xi = \alpha R$  (given)

(b)  $\varphi_A - \varphi_B = n\xi - niR = n\alpha R - n\alpha R = 0$

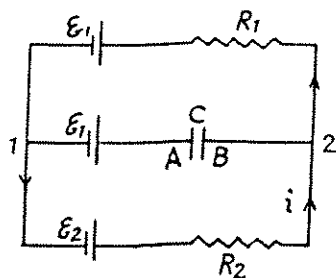
3.177 As the capacitor is fully charged, no current flows through it. So, current

$$i = \frac{\xi_2 - \xi_1}{R_1 + R_2} \text{ (as } \xi_2 > \xi_1 \text{)}$$

And hence,  $\varphi_A - \varphi_B = \xi_1 - \xi_2 + iR_2$

$$= \xi_1 - \xi_2 + \frac{\xi_2 - \xi_1}{R_1 + R_2} R_2$$

$$= \frac{(\xi_1 - \xi_2)R_1}{R_1 + R_2} = -0.5 \text{ V}$$



3.178 Let us make the current distribution, as shown in the figure.

Current  $i = \frac{\xi}{R + \frac{R_1 R_2}{R_1 + R_2}}$  (using loop rule)

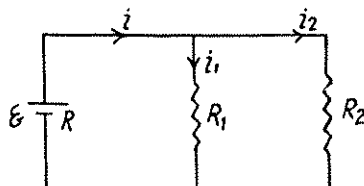
So, current through the resistor  $R_1$ ,

$$i_1 = \frac{\xi}{R + \frac{R_1 R_2}{R_1 + R_2}} \frac{R_2}{R_1 + R_2}$$

$$= \frac{\xi R_2}{R R_1 + R R_2 + R_1 R_2} = 1.2 \text{ A}$$

and similarly, current through the resistor  $R_2$ ,

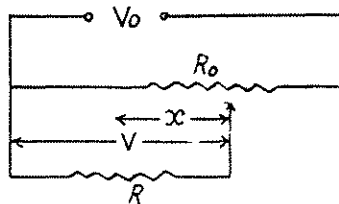
$$i_2 = \frac{\xi}{R + \frac{R_1 R_2}{R_1 + R_2}} \frac{R_1}{R_1 + R_2} = \frac{\xi R_1}{R R_1 + R R_2 + R_1 R_2} = 0.8 \text{ A}$$



3.179 Total resistance =  $\frac{l-x}{l} R_0 + \frac{R \cdot \frac{x R_0}{l}}{R + \frac{x R_0}{l}}$

$$= \frac{l-x}{l} R_0 + \frac{x R R_0}{l R + x R_0}$$

$$= R_0 \left[ \frac{l-x}{l} + \frac{x R}{l R + x R_0} \right]$$



$$\text{Then } V = V_0 \frac{xR}{lR + xR_0} \bigg/ \left( 1 - \frac{x}{l} + \frac{xR}{xR_0 + lR} \right) = V_0 R x \bigg/ \left\{ lR + R_0 x \left( 1 - \frac{x}{l} \right) \right\}$$

$$\text{For } R \gg R_0, V \approx V_0 \frac{x}{l}$$

**3.180** Let us connect a load of resistance  $R$  between the points  $A$  and  $B$  (Fig.)

From the loop rule,  $\Delta \varphi = 0$ , we obtain

$$iR = \xi_1 - i_1 R_1 \quad (1)$$

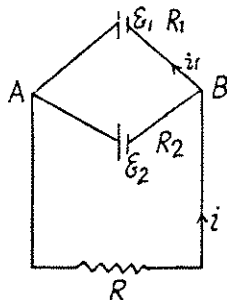
$$\text{and } iR = \xi_2 - (i - i_1) R_2$$

$$\text{or } i(R + R_2) = \xi_2 + i_1 R_2 \quad (2)$$

Solving Eqs. (1) and (2), we get

$$i = \frac{\xi_1 R_1 + \xi_2 R_2}{R_1 + R_2} \bigg/ R + \frac{R_1 R_2}{R_1 + R_2} = \frac{\xi_0}{R + R_0} \quad (3)$$

$$\text{where } \xi_0 = \frac{\xi_1 R_1 + \xi_2 R_2}{R_1 + R_2} \quad \text{and} \quad R_0 = \frac{R_1 R_2}{R_1 + R_2}$$



Thus one can replace the given arrangement of the cells by a single cell having the emf  $\xi_0$  and internal resistance  $R_0$ .

**3.181** Make the current distribution, as shown in the diagram.

Now, in the loop 12341, applying  $-\Delta \varphi = 0$

$$iR + i_1 R_1 + \xi_1 = 0 \quad (1)$$

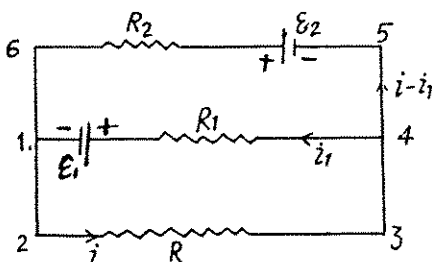
and in the loop 23562,

$$iR - \xi_2 + (i - i_1) R_2 = 0 \quad (2)$$

Solving (1) and (2), we obtain current through the resistance  $R$ ,

$$i = \frac{(\xi_2 R_1 - \xi_1 R_2)}{R R_1 + R R_2 + R_1 R_2} = 0.02 \text{ A}$$

and it is directed from left to the right



**3.182** At first indicate the currents in the branches using charge conservation (which also includes the point rule).

In the loops 1BA61 and B34AB from the loop rule,  $-\Delta \varphi = 0$ , we get, respectively

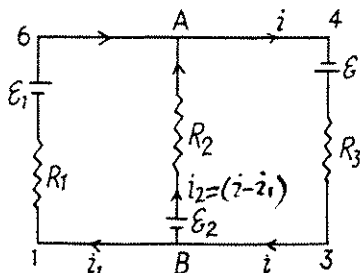
$$-\xi_2 + (i - i_1) R_2 + \xi_1 - i_1 R_1 = 0 \quad (1)$$

$$i R_3 + \xi_3 - (i - i_1) R_2 + \xi_2 = 0 \quad (2)$$

On solving Eqs (1) and (2), we obtain

$$i_1 = \frac{(\xi_1 - \xi_2) R_3 + R_2 (\xi_1 + \xi_3)}{R_1 R_2 + R_2 R_3 + R_3 R_1} = 0.06 \text{ A}$$

$$\text{Thus } \varphi_A - \varphi_B = \xi_2 - i_2 R_2 \approx 0.9 \text{ V}$$



- 3.183** Indicate the currents in all the branches using charge conservation as shown in the figure. Applying loop rule,  $-\Delta\varphi = 0$  in the loops 1A781, 1B681 and B456B, respectively, we get

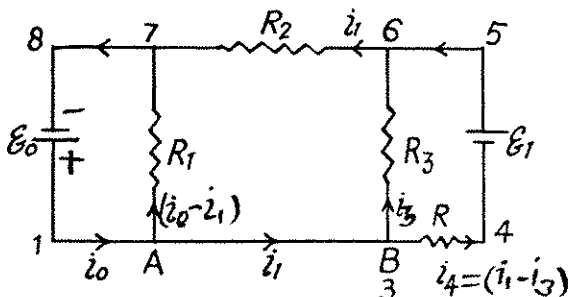
$$\xi_0 = (i_0 - i_1) R_1 \quad (1)$$

$$i_3 R_3 + i_1 R_2 - \xi_0 = 0 \quad (2) \text{ and}$$

$$(i_1 - i_3) R - \xi - i_3 R_3 = 0 \quad (3)$$

Solving Eqs. (1), (2) and (3), we get the sought current

$$(i_1 - i_3) = \frac{\xi (R_2 + R_3) + \xi_0 R_3}{R (R_2 + R_3) + R_2 R_3}$$



- 3.184** Indicate the currents in all the branches using charge conservation as shown in the figure. Applying the loop rule ( $-\Delta\varphi = 0$ ) in the loops 12341 and 15781, we get

$$-\xi_1 + i_3 R_1 - (i_1 - i_3) R_2 = 0 \quad (1)$$

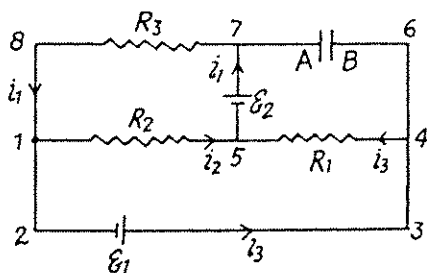
$$\text{and } (i_1 - i_3) R_2 - \xi_2 + i_1 R_3 = 0 \quad (2)$$

Solving Eqs. (1) and (2), we get

$$i_3 = \frac{\xi_1 (R_2 + R_3) + \xi_2 R_2}{R_1 R_2 + R_2 R_3 + R_3 R_1}$$

Hence, the sought p.d.

$$\begin{aligned} \varphi_A - \varphi_B &= \xi_2 - i_3 R_1 \\ &= \frac{\xi_2 R_3 (R_1 + R_2) - \xi_1 R_1 (R_2 + R_3)}{R_1 R_2 + R_2 R_3 + R_3 R_1} = -1 \text{ V} \end{aligned}$$



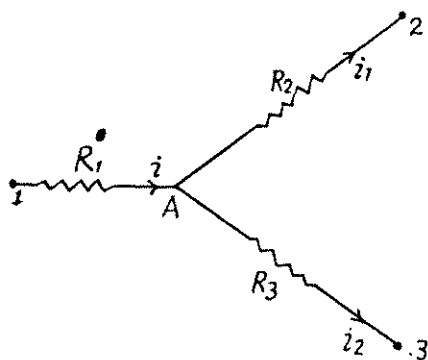
- 3.185** Let us distribute the currents in the paths as shown in the figure.

$$\text{Now, } \varphi_1 - \varphi_2 = i R_1 + i_1 R_2 \quad (1)$$

$$\text{and } \varphi_1 - \varphi_3 = i R_1 + (i - i_1) R_3 \quad (2)$$

Simplifying Eqs. (1) and (2) we get

$$i = \frac{R_3 (\varphi_1 - \varphi_2) + R_2 (\varphi_1 - \varphi_3)}{R_1 R_2 + R_2 R_3 + R_3 R_1} = 0.2 \text{ A}$$

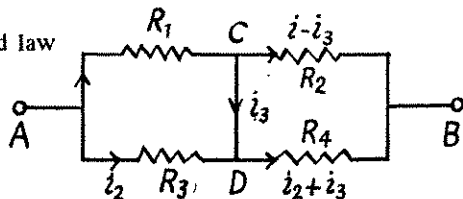


- 3.186** Current is as shown. From Kirchhoff's Second law

$$i_1 R_1 = i_2 R_3,$$

$$i_1 R_1 + (i_1 - i_3) R_2 = V,$$

$$i_2 R_3 + (i_3 + i_2) R_4 = V$$



Eliminating  $i_2$

$$i_1 (R_1 + R_2) - i_3 R_2 = V$$

$$i_1 \frac{R_1}{R_3} (R_3 + R_4) + i_3 R_4 = V$$

Hence

$$i_3 \left[ R_4 (R_1 + R_2) + \frac{R_1 R_2}{R_3} (R_3 + R_4) \right] = V \left[ (R_1 + R_2) - \frac{R_1}{R_3} (R_3 + R_4) \right]$$

or,

$$i_3 = \frac{R_3 (R_1 + R_2) - R_1 (R_3 + R_4)}{R_3 R_4 (R_1 + R_2) + R_1 R_2 (R_3 + R_4)}$$

On substitution we get  $i_3 = 1.0$  A from C to D

**3.187** From the symmetry of the problem, current flow is indicated, as shown in the figure.

Now,  $\varphi_A - \varphi_B = i_1 r + (i - i_1) R$  (1)

In the loop 12561, from  $-\Delta\varphi = 0$

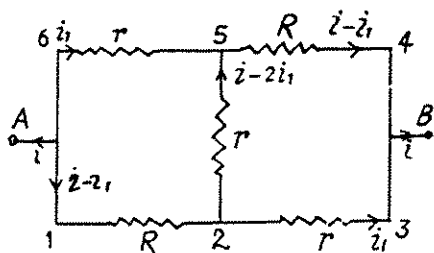
$$(i - i_1) R + (i - 2i_1) r - i_1 r = 0$$

or,

$$i_1 = \frac{(R + r)}{3r + R} i$$
 (2)

Equivalent resistance between the terminals A and B using (1) and (2),

$$R_0 = \frac{\varphi_A - \varphi_B}{i} = \frac{\left[ \frac{R + r}{3r + R} (r - R) + R \right] i}{i} = \frac{r(3R + r)}{3r + R}$$



**3.188** Let, at any moment of time, charge on the plates be  $+q$  and  $-q$  respectively, then voltage across the capacitor,  $\varphi = q/C$  (1)

Now, from charge conservation,

$$i = i_1 + i_2, \text{ where } i_2 = \frac{dq}{dt}$$
 (2)

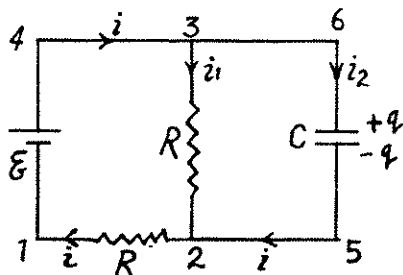
In the loop 65146, using  $-\Delta\varphi = 0$ .

$$\frac{q}{C} + \left( i_1 + \frac{dq}{dt} \right) R - \xi = 0$$
 (3)

[using (1) and (2)]

In the loop 25632, using  $-\Delta\varphi = 0$

$$-\frac{q}{C} + i_1 R = 0 \quad \text{or, } i_1 R = \frac{q}{C}$$
 (4)



From (1) and (2),

$$\frac{dq}{dt} R = \xi_1 - \frac{2q}{C} \quad \text{or,} \quad \frac{dq}{\xi_1 - \frac{2q}{C}} = \frac{dt}{R} \quad (5)$$

On integrating the expression (5) between suitable limits,

$$\int_0^q \frac{dq}{\xi_1 - \frac{2q}{C}} = \frac{1}{R} \int_0^t dt \quad \text{or,} \quad -\frac{C}{2} \ln \frac{\xi_1 - \frac{2q}{C}}{\xi_1} = \frac{t}{R}$$

Thus 
$$\frac{q}{C} = V = \frac{1}{2} \xi_1 \left( 1 - e^{-2t/RC} \right)$$

**3.189** (a) As current  $i$  is linear function of time, and at  $t = 0$  and  $\Delta t$ , it equals  $i_0$  and zero respectively, it may be represented as,

$$i = i_0 \left( 1 - \frac{t}{\Delta t} \right)$$

Thus

$$q = \int_0^{\Delta t} i dt = \int_0^{\Delta t} i_0 \left( 1 - \frac{t}{\Delta t} \right) dt = \frac{i_0 \Delta t}{2}$$

So,

$$i_0 = \frac{2q}{\Delta t}$$

Hence,

$$i = \frac{2q}{\Delta t} \left( 1 - \frac{t}{\Delta t} \right)$$

The heat generated.

$$H = \int_0^{\Delta t} i^2 R dt = \int_0^{\Delta t} \left[ \frac{2q}{\Delta t} \left( 1 - \frac{t}{\Delta t} \right) \right]^2 R dt = \frac{4q^2 R}{3 \Delta t}$$

(b) Obviously the current through the coil is given by

$$i = i_0 \left( \frac{1}{2} \right)^{t/\Delta t}$$

Then charge

$$q = \int_0^{\infty} i dt = \int_0^{\infty} i_0 2^{-t/\Delta t} dt = \frac{i_0 \Delta t}{\ln 2}$$

So,

$$i_0 = \frac{q \ln 2}{\Delta t}$$

And hence, heat generated in the circuit in the time interval  $t \in [0, \infty]$ ,

$$H = \int_0^{\infty} i^2 R dt = \int_0^{\infty} \left[ \frac{q \ln 2}{\Delta t} 2^{-t/\Delta t} \right]^2 R dt = -\frac{q^2 \ln 2}{2 \Delta t} R$$



1.190 The equivalent circuit may be drawn as in the figure.

Resistance of the network =  $R_0 + (R/3)$

Let, us assume that e.m.f. of the cell is  $\xi$ , then current

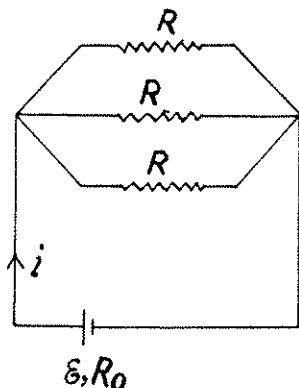
$$i = \frac{\xi}{R_0 + (R/3)}$$

Now, thermal power, generated in the circuit

$$P = i^2 R/3 = \frac{\xi^2}{(R_0 + (R/3))^2} (R/3)$$

For  $P$  to be maximum,  $\frac{dP}{dR} = 0$ , which yields

$$R = 3R_0$$

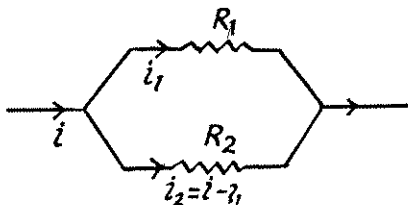


3.191 We assume current conservation but not Kirchhoff's second law. Then thermal power dissipated is

$$P(i_1) = i_1^2 R_1 + (i - i_1)^2 R_2$$

$$= i_1^2 (R_1 + R_2) - 2i i_1 R_2 + i^2 R_2$$

$$= [R_1 + R_2] \left[ i_1 - \frac{R_2}{R_1 + R_2} i \right]^2 + i^2 \frac{R_1 R_2}{R_1 + R_2}$$



The resistances being positive we see that the power dissipated is minimum when

$$i_1 = i \frac{R_2}{R_1 + R_2}$$

This corresponds to usual distribution of currents over resistance joined in parallel.

3.192 Let, internal resistance of the cell be  $r$ , then

$$V = \xi - ir \quad (1)$$

where  $i$  is the current in the circuit. We know that thermal power generated in the battery.

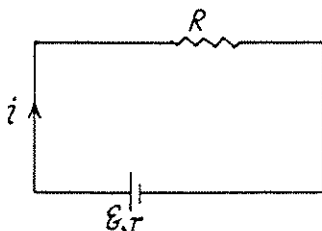
$$Q = i^2 r \quad (2)$$

Putting  $r$  from (1) in (2), we obtain,

$$Q = (\xi - V) i = 0.6 \text{ W}$$

In a battery work is done by electric forces (whose origin lies in the chemical processes going on inside the cell). The work so done is stored and used in the electric circuit outside. Its magnitude just equals the power used in the electric circuit. We can say that net power developed by the electric forces is

$$P = -IV = -2.0 \text{ W}$$



Minus sign means that this is generated not consumed.

- 3.193 As far as motor is concerned the power delivered is dissipated and can be represented by a load,  $R_0$ . Thus

$$I = \frac{V}{R + R_0}$$

and 
$$P = I^2 R_0 = \frac{V^2 R_0}{(R_0 + R)^2}$$

This is maximum when  $R_0 = R$  and the current  $I$  is then

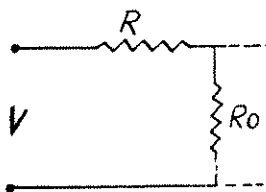
$$I = \frac{V}{2R}$$

The maximum power delivered is

$$\frac{V^2}{4R} = P_{\max}$$

The power input is  $\frac{V^2}{R + R_0}$  and its value when  $P$  is maximum is  $\frac{V^2}{2R}$

The efficiency then is  $\frac{1}{2} = 50\%$



- 3.194 If the wire diameter decreases by  $\delta$  then by the information given

$$P = \text{Power input} = \frac{V^2}{R} = \text{heat lost through the surface, } H.$$

Now,  $H \propto (1 - \delta)$  like the surface area and

$$R \propto (1 - \delta)^{-2}$$

So, 
$$\frac{V^2}{R_0} (1 - \delta)^2 = A (1 - \delta) \quad \text{or,} \quad V^2 (1 - \delta) = \text{constant}$$

But  $V \propto 1 + \eta$  so  $(1 + \eta)^2 (1 - \delta) = \text{Const} = 1$

Thus 
$$\delta = 2\eta = 2\%$$

- 3.195 The equation of heat balance is

$$\frac{V^2}{R} - k(T - T_0) = C \frac{dT}{dt}$$

Put 
$$T - T_0 = \xi$$

So, 
$$C \xi + k \xi = \frac{V^2}{R} \quad \text{or,} \quad \xi + \frac{k}{C} \xi = \frac{V^2}{CR}$$

or, 
$$\frac{d}{dt} (\xi e^{kt/C}) = \frac{V^2}{CR} e^{kt/C}$$

or, 
$$\xi e^{kt/C} = \frac{V^2}{kR} e^{kt/C} + A$$

where  $A$  is a constant. Clearly

$$\xi = 0 \text{ at } t = 0, \text{ so } A = -\frac{V^2}{kR} \text{ and hence,}$$

$$T = T_0 + \frac{V^2}{kR} (1 - e^{-kt/C})$$

3.196 Let,  $\varphi_A - \varphi_B = \varphi$

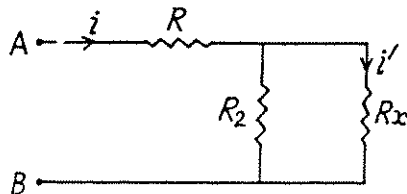
Now, thermal power generated in the resistance  $R_x$ ,

$$P = i'^2 R_x = \left[ \frac{\frac{\varphi}{R_1 + \frac{R_2 R_x}{R_2 + R_x}}}{\frac{R_2}{R_2 + R_x}} \right]^2 R_x$$

For  $P$  to be independent of  $R_x$ ,

$$\frac{dP}{dR_x} = 0, \text{ which yields}$$

$$R_x = \frac{R_1 R_2}{R_1 + R_2} = 12 \Omega$$



3.197 Indicate the currents in the circuit as shown in the figure.

Applying loop rule in the closed loop 12561,  $-\Delta\varphi = 0$  we get

$$i_1 R - \xi_1 + i R_1 = 0 \quad (1)$$

and in the loop 23452,

$$(i - i_1) R_2 + \xi_2 - i_1 R = 0 \quad (2)$$

Solving (1) and (2), we get,

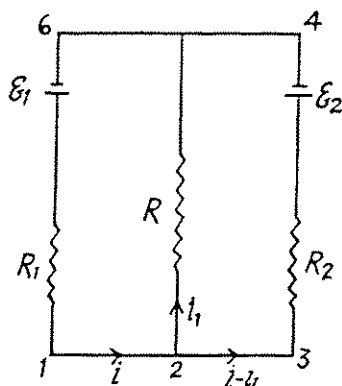
$$i_1 = \frac{\xi_1 R_2 + \xi_2 R_1}{R R_1 + R_1 R_2 + R R_2}$$

So, thermal power, generated in the resistance  $R$ ,

$$P = i_1^2 R = \left[ \frac{\xi_1 R_2 + \xi_2 R_1}{R R_1 + R_1 R_2 + R R_2} \right]^2 R$$

For  $P$  to be maximum,  $\frac{dP}{dR} = 0$ , which fields

$$R = \frac{R_1 R_2}{R_1 + R_2}$$



Hence,

$$P_{\max} = \frac{(\xi_1 R_2 + \xi_2 R_1)^2}{4 R_1 R_2 (R_1 + R_2)}$$

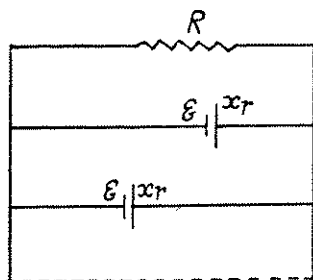
3.198 Let, there are  $x$  number of cells, connected in series in each of the  $n$  parallel groups

then,  $n x = N$  or,  $x = \frac{N}{n}$  (1)

Now, for any one of the loop, consisting of  $x$  cells and the resistor  $R$ , from loop rule

$$i R + \frac{i}{n} x r - x \xi = 0$$

$$\text{So, } i = \frac{x \xi}{R + \frac{x r}{n}} = \frac{\frac{N}{n} \xi}{R + \frac{N r}{n^2}}, \text{ using (1)}$$



Heat generated in the resistor  $R$ ,

$$Q = i^2 R = \left( \frac{N n \xi}{n^2 R + N R} \right)^2 R \quad (2)$$

and for  $Q$  to be maximum,  $\frac{dQ}{dn} = 0$ , which yields

$$n = \sqrt{\frac{N r}{R}} = 3$$

**3.199** When switch 1 is closed, maximum charge accumulated on the capacitor,

$$q_{\max} = C \xi, \quad (1)$$

and when switch 2 is closed, at any arbitrary instant of time,

$$(R_1 + R_2) \left( -\frac{dq}{dt} \right) = q/C,$$

because capacitor is discharging.

$$\text{or, } \int_{q_{\max}}^q \frac{1}{q} dq = -\frac{1}{(R_1 + R_2) C} \int_0^t dt$$

Integrating, we get

$$\ln \frac{q}{q_{\max}} = \frac{-t}{(R_1 + R_2) C} \quad \text{or, } q = q_{\max} e^{\frac{-t}{(R_1 + R_2) C}} \quad (2)$$

Differentiating with respect to time,

$$i(t) = \frac{dq}{dt} = q_{\max} e^{\frac{-t}{(R_1 + R_2) C}} \left( -\frac{1}{(R_1 + R_2) C} \right)$$

$$\text{or, } i(t) = \frac{C \xi}{(R_1 + R_2) C} e^{\frac{-t}{(R_1 + R_2) C}}$$

Negative sign is ignored, as we are not interested in the direction of the current.

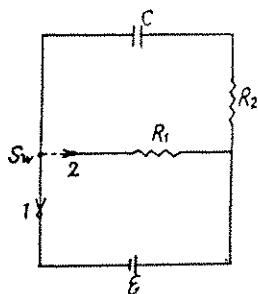
$$\text{thus, } i(t) = \frac{\xi}{(R_1 + R_2)} e^{\frac{-1}{(R_1 + R_2) C}} \quad (3)$$

When the switch ( $Sw$ ) is at the position 1, the charge (maximum) accumulated on the capacitor is,

$$q = C \xi$$

When the  $Sw$  is thrown to position 2, the capacitor starts discharging and as a result the electric energy stored in the capacitor totally turns into heat energy tho' the resistors  $R_1$  and  $R_2$  (during a very long interval of time). Thus from the energy conservation, the total heat liberated tho' the resistors.

$$H = U_i = \frac{q^2}{2C} = \frac{1}{2} C \xi^2$$



During the process of discharging of the capacitor, the current thro' the resistors  $R_1$  and  $R_2$  is the same at all the moments of time, thus

$$H_1 \propto R_1 \text{ and } H_2 \propto R_2$$

So, 
$$H_1 = \frac{H R_1}{(R_1 + R_2)} \quad (\text{as } H = H_1 + H_2)$$

Hence 
$$H_1 = \frac{1}{2} \frac{C R_1}{R_1 + R_2} \xi^2$$

**3.200** When the plate is absent the capacity of the condenser is

$$C = \frac{\epsilon_0 S}{d}$$

When it is present, the capacity is

$$C' = \frac{\epsilon_0 S}{d(1-\eta)} = \frac{C}{1-\eta}$$

(a) The energy increment is clearly.

$$\Delta U = \frac{1}{2} C V^2 - \frac{1}{2} C' V^2 = \frac{C \eta}{2(1-\eta)} V^2$$

(b) The charge on the plate is

$$q_i = \frac{C V}{1-\eta} \text{ initially and } q_f = C V \text{ finally.}$$

A charge  $\frac{C V \eta}{1-\eta}$  has flown through the battery charging it and withdrawing  $\frac{C V^2 \eta}{1-\eta}$  units of energy from the system into the battery. The energy of the capacitor has decreased by just half of this. The remaining half i.e.  $\frac{1}{2} \frac{C V^2 \eta}{1-\eta}$  must be the work done by the external agent in withdrawing the plate. This ensures conservation of energy.

**3.201** Initially, capacitance of the system =  $C \epsilon$ .

So, initial energy of the system :  $U_i = \frac{1}{2} (C \epsilon) V^2$

and finally, energy of the capacitor :  $U_f = \frac{1}{2} C V^2$

Hence capacitance energy increment,

$$\Delta U = \frac{1}{2} C V^2 - \frac{1}{2} (C \epsilon) V^2 = -\frac{1}{2} C V^2 (\epsilon - 1) = -0.5 \text{ mJ}$$

From energy conservation

$$\Delta U = A_{\text{cell}} + A_{\text{agent}}$$

(as there is no heat liberation)

But  $A_{\text{cell}} = (C_f - C_i) V^2 = (C - C \epsilon) V^2$

Hence  $A_{\text{agent}} = \Delta U - A_{\text{cell}}$

$$= \frac{1}{2} C (1 - \epsilon) V^2 = 0.5 \text{ m J}$$

**3.202** If  $C_0$  is the initial capacitance of the condenser before water rises in it then

$$U_i = \frac{1}{2} C_0 V^2, \quad \text{where } C_0 = \frac{\epsilon_0 2l\pi R}{d}$$

( $R$  is the mean radius and  $l$  is the length of the capacitor plates.)

Suppose the liquid rises to a height  $h$  in it. Then the capacitance of the condenser is

$$C = \frac{\epsilon\epsilon_0 h 2\pi R}{d} + \frac{\epsilon(l-h) 2\pi R}{d} = \frac{\epsilon_0 2\pi R}{d} (l + (\epsilon - 1)h)$$

and energy of the capacitor and the liquid (including both gravitational and electrostatic contributions) is

$$\frac{1}{2} \frac{\epsilon_0 2\pi R}{d} (l + (\epsilon - 1)h) V^2 + \rho g (2\pi R h d) \frac{h}{2}$$

If the capacitor were not connected to a battery this energy would have to be minimized. But the capacitor is connected to the battery and, in effect, the potential energy of the whole system has to be minimized. Suppose we increase  $h$  by  $\delta h$ . Then the energy of the capacitor and the liquid increases by

$$\delta h \left( \frac{\epsilon_0 2\pi R}{2d} (\epsilon - 1) V^2 + \rho g (2\pi R d) h \right)$$

and that of the cell diminishes by the quantity  $A_{\text{cell}}$  which is the product of charge flown and  $V$

$$\delta h \frac{\epsilon_0 (2\pi R)}{d} (\epsilon - 1) V^2$$

In equilibrium, the two must balance; so

$$\rho g d h = \frac{\epsilon_0 (\epsilon - 1) V^2}{2d}$$

Hence

$$h = \frac{\epsilon_0 (\epsilon - 1) V^2}{2\rho g d^2}$$

**3.203** (a) Let us mentally isolate a thin spherical layer with inner and outer radii  $r$  and  $r + dr$  respectively. Lines of current at all the points of this layer are perpendicular to it and therefore such a layer can be treated as a spherical conductor of thickness  $dr$  and cross sectional area  $4\pi r^2$ . Now, we know that resistance,

$$dR = \rho \frac{dr}{S(r)} = \rho \frac{dr}{4\pi r^2} \quad (1)$$

Integrating expression (1) between the limits,

$$\int_0^R dR = \int_a^b \rho \frac{dr}{4\pi r^2} \quad \text{or,} \quad R = \frac{\rho}{4\pi} \left[ \frac{1}{a} - \frac{1}{b} \right] \quad (2)$$

$$\text{Capacitance of the network, } C = \frac{4\pi\epsilon_0\epsilon}{\left[ \frac{1}{a} - \frac{1}{b} \right]} \quad (3)$$

$$\text{and} \quad q = C\varphi \left[ \begin{array}{l} \text{where } q \text{ is the charge} \\ \text{at any arbitrary moment} \end{array} \right] \quad (4)$$

$$\text{also,} \quad \varphi = \left( \frac{-dq}{dt} \right) R, \text{ as capacitor is discharging.} \quad (5)$$

From Eqs. (2), (3), (4) and (5) we get,

$$q = \frac{4\pi\epsilon_0\epsilon}{\left[ \frac{1}{a} - \frac{1}{b} \right]} \frac{\left[ -\frac{dq}{dt} \right] \rho \left[ \frac{1}{a} - \frac{1}{b} \right]}{4\pi} \quad \text{or,} \quad \frac{dq}{q} = \frac{dt}{\rho\epsilon\epsilon_0}$$

$$\text{Integrating} \quad \int_{q_0}^q -\frac{dq}{q} = \frac{1}{\rho\epsilon_0\epsilon} \int_0^t dt = \frac{dt}{\rho\epsilon\epsilon_0}$$

$$\text{Hence} \quad q = q_0 e^{\frac{-t}{\rho\epsilon_0\epsilon}}$$

(b) From energy conservation heat generated, during the spreading of the charge,

$$\begin{aligned} H &= U_i - U_f \text{ [because } A_{\text{cell}} = 0] \\ &= \frac{1}{2} \frac{q_0^2}{4\pi\epsilon_0\epsilon} \left[ \frac{1}{a} - \frac{1}{b} \right] - 0 = \frac{q_0^2}{8\pi\epsilon_0\epsilon} \frac{b-a}{ab} \end{aligned}$$

**3.204** (a) Let, at any moment of time, charge on the plates be  $(q_0 - q)$  then current through

the resistor,  $i = -\frac{d(q_0 - q)}{dt}$ , because the capacitor is discharging.

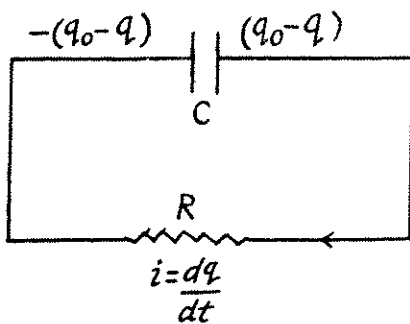
$$\text{or,} \quad i = \frac{dq}{dt}$$

Now, applying loop rule in the circuit,

$$iR - \frac{q_0 - q}{C} = 0$$

$$\text{or,} \quad \frac{dq}{dt} R = \frac{q_0 - q}{C}$$

$$\text{or,} \quad \frac{dq}{q_0 - q} = \frac{1}{RC} dt$$



At  $t = 0$ ,  $q = 0$  and at  $t = \tau$ ,  $q = q$

So, 
$$\ln \frac{q_0 - q}{q_0} = \frac{-\tau}{RC}$$

Thus 
$$q = q_0 (1 - e^{-\tau/RC}) = 0.18 \text{ mC}$$

(b) Amount of heat generated = decrement in capacitance energy

$$\begin{aligned} &= \frac{1}{2} \frac{q_0^2}{C} - \frac{1}{2} \frac{\left[ q_0 - q_0 (1 - e^{-\tau/RC}) \right]^2}{C} \\ &= \frac{1}{2} \frac{q_0^2}{C} \left[ 1 - e^{-\frac{2\tau}{RC}} \right] = 82 \text{ mJ} \end{aligned}$$

**3.205** Let, at any moment of time, charge flown be  $q$  then current  $i = \frac{dq}{dt}$

Applying loop rule in the circuit,  $-\Delta\phi = 0$ , we get :

$$\frac{dq}{dt} IR - \frac{(CV_0 - q)}{C} + \frac{q}{C} = 0$$

or, 
$$\frac{dq}{CV_0 - 2q} = \frac{1}{RC} dt$$

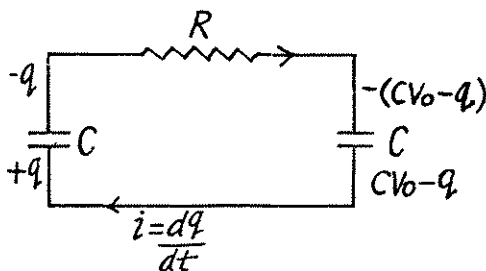
So, 
$$\ln \frac{CV_0 - 2q}{CV_0} = -2 \frac{t}{RC} \text{ for } 0 \leq t \leq \tau$$

or, 
$$q = \frac{CV_0}{2} \left( 1 - e^{-\frac{2t}{RC}} \right)$$

Hence, 
$$i = \frac{dq}{dt} = \frac{CV_0}{2} \frac{2}{RC} e^{-2t/RC} = \frac{V_0}{R} e^{-2t/RC}$$

Now, heat liberated,

$$Q = \int_0^\infty i^2 R dt = \frac{V_0^2}{R^2} R \int_0^\infty e^{-\frac{4t}{RC}} dt = \frac{1}{4} CV_0^2$$



**3.206** In a rotating frame, to first order in  $\omega$ , the main effect is a coriolis force  $2m \vec{v}' \times \vec{\omega}$ .

This unbalanced force will cause electrons to react by setting up a magnetic field  $\vec{B}$  so that the magnetic force  $e \vec{v} \times \vec{B}$  balances the coriolis force.

Thus 
$$-\frac{e}{2m} \vec{B} = \vec{\omega} \text{ or, } \vec{B} = -\frac{2m}{e} \vec{\omega}$$

The flux associated with this is

$$\Phi = N \pi r^2 B = N \pi r^2 \frac{2m}{e} \omega$$



where  $N = \frac{l}{2\pi r}$  is the number of turns of the ring. If  $\omega$  changes (and there is time for the electron to rearrange) then  $B$  also changes and so does  $\Phi$ . An emf will be induced and a current will flow. This is

$$I = N \pi r^2 \frac{2m}{e} \omega / R$$

The total charge flowing through the ballistic galvanometer, as the ring is stopped, is

$$q = N \pi r^2 / \frac{2m}{e} \omega / R$$

So,

$$\frac{e}{m} = \frac{2N\pi r^2 \omega}{qR} = \frac{l\omega r}{qR}$$

**3.207** Let,  $n_0$  be the total number of electrons then, total momentum of electrons,

$$p = n_0 m_e v_d \quad (1)$$

Now,

$$I = \rho S_x v_d = \frac{n_0 e}{V} S_x v_d = \frac{ne}{l} v_d \quad (2)$$

Here  $S_x$  = Cross sectional area,  $\rho$  = electron charge density,  $V$  = volume of sample  
From (1) and (2)

$$p = \frac{m_e}{e} Il = 0.40 \mu \text{Ns}$$

**3.208** By definition

$ne v_d = j$  (where  $v_d$  is the drift velocity,  $n$  is number density of electrons.)

Then

$$\tau = \frac{l}{v_d} = \frac{nel}{j}$$

So distance actually travelled

$$S = \langle v \rangle \tau = \frac{nel \langle v \rangle}{j}$$

( $\langle v \rangle$  = mean velocity of thermal motion of an electron)

**3.209** Let,  $n$  be the volume density of electrons, then from  $I = \rho S_x v_d$

$$I = ne S_x | \langle \vec{v} \rangle | = ne S_x \frac{l}{t}$$

So,

$$t = \frac{ne S_x l}{I} = 3 \mu\text{s}.$$

(b) Sum of electric forces

$$= |(nv) e \vec{E}| = |n S l e \rho \vec{j}|, \text{ where } \rho \text{ is resistivity of the material.}$$

$$= n S l e \rho \frac{I}{S} = n e l \rho I = 1.0 \mu\text{N}$$

**3.210** From Gauss theorem field strength at a surface of a cylindrical shape equals,

$\frac{\lambda}{2\pi\epsilon_0 r}$ , where  $\lambda$  is the linear charge density.

$$\text{Now,} \quad eV = \frac{1}{2} m_e v^2 \quad \text{or,} \quad v = \sqrt{\frac{2eV}{m_e}} \quad (1)$$

$$\text{Also,} \quad dq = \lambda dx \quad \text{so,} \quad \frac{dq}{dt} = \lambda \frac{dx}{dt}$$

$$\text{or,} \quad I = \lambda v \quad \text{or,} \quad \lambda = \frac{I}{v} = \frac{I}{\sqrt{\frac{2eV}{m_e}}}, \text{ using (1)}$$

$$\text{Hence} \quad E = \frac{I}{2\pi\epsilon_0 r} \sqrt{\frac{m_e}{2eV}} = 32 \text{ V/m}$$

(b) For the point, inside the solid charged cylinder, applying Gauss' theorem,

$$2\pi r h E = \pi r^2 h \frac{q}{\epsilon_0 \pi R^2 l}$$

$$\text{or,} \quad E = \frac{q/l}{2\pi\epsilon_0 R^2} r = \frac{\lambda r}{2\pi\epsilon_0 R^2}$$

$$\text{So, from} \quad E = -\frac{d\varphi}{dr},$$

$$\int_{\varphi_1}^{\varphi_2} -d\varphi = \int_0^R \frac{\lambda}{2\pi\epsilon_0 R^2} r dr$$

$$\text{or,} \quad \varphi_1 - \varphi_2 = \frac{\lambda}{2\pi\epsilon_0 R^2} \left[ \frac{r^2}{2} \right]_0^R = \frac{\lambda}{4\pi\epsilon_0}$$

$$\text{Hence,} \quad \varphi_1 - \varphi_2 = \frac{VI}{4\pi\epsilon_0} \sqrt{\frac{m_e}{2eV}} = 0.80 \text{ V}$$

**3.211** Between the plates  $\varphi = ax^{4/3}$

$$\text{or,} \quad \frac{\partial\varphi}{\partial x} = a \times \frac{4}{3} x^{1/3}$$

$$\frac{d^2\varphi}{dx^2} = \frac{4}{9} ax^{-2/3} = -\rho/\epsilon_0$$

$$\text{or,} \quad \rho = -\frac{4\epsilon_0 a}{9} x^{-2/3}$$

Let the charge on the electron be  $-e$ ,

then 
$$\frac{1}{2} m v^2 - e \varphi = \text{Const.} = 0,$$

as the electron is initially emitted with negligible energy.

$$v^2 = \frac{2 e \varphi}{m}, \quad v = \sqrt{\frac{2 e \varphi}{m}}$$

So, 
$$j = - \rho v = \frac{4 \epsilon_0 a}{9} \sqrt{\frac{2 \varphi}{m}} x^{-2/3}.$$

( $j$  is measured from the anode to cathode, so the - ve sign.)

**3.212**  $E = \frac{V}{d}$

So by the definition of the mobility

$$v^+ = u_0^+ \frac{V}{d}, \quad v^- = u_0^- \frac{V}{d}$$

and

$$j = (n_+ u_0^+ + n_- u_0^-) \frac{eV}{d}$$

(The negative ions move towards the anode and the positive ion towards the cathode and the total current is the sum of the currents due to them.)

On the other hand, in equilibrium  $n_+ = n_-$

$$\begin{aligned} \text{So, } n_+ = n_- &= \frac{I}{S} \bigg/ (u_0^+ + u_0^-) \frac{eV}{d} \\ &= \frac{I d}{e V S (u_0^+ + u_0^-)} = 2.3 \times 10^8 \text{ cm}^{-3} \end{aligned}$$

**3.213** Velocity = mobility  $\times$  field

or,  $v = u \frac{V_0}{l} \sin \omega t$ , which is positive for  $0 \leq \omega t \leq \pi$

So, maximum displacement in one direction is

$$x_{\max} = \int_0^{\pi} u \frac{V_0}{l} \sin \omega t \, dt = \frac{2 u V_0}{l \omega}$$

At  $\omega = \omega_0$ ,  $x_{\max} = l$ , so,  $\frac{2 u V_0}{l \omega} = l$

Thus 
$$u = \frac{\omega l^2}{2 V_0}$$

**3.214** When the current is saturated, all the ions, produced, reach the plate.

Then, 
$$\dot{n}_i = \frac{I_{\text{sat}}}{eV} = 6 \times 10^9 \text{ cm}^{-3} \text{ s}^{-1}$$

(Both positive ions and negative ions are counted here)

The equation of balance is, 
$$\frac{dn}{dt} = \dot{n}_i - rn^2$$

The first term on the right is the production rate and the second term is the recombination rate which by the usual statistical arguments is proportional to  $n^2$  (= no of positive ions  $\times$  no. of  $-ve$  ion). In equilibrium,

$$\frac{dn}{dt} = 0$$

so, 
$$n_{eq} = \sqrt{\frac{\dot{n}_i}{r}} = 6 \times 10^7 \text{ cm}^{-3}$$

**3.215** Initially  $n = n_0 = \sqrt{\dot{n}_i}/r$

Since we can assume that the long exposure to the ionizer has caused equilibrium to be set up. After the ionizer is switched off,

$$\frac{dn}{dt} = -rn^2$$

or 
$$r dt = -\frac{dn}{n^2}, \quad \text{or,} \quad rt = \frac{1}{n} + \text{constant}$$

But 
$$n = n_0 \text{ at } t = 0, \text{ so, } rt = \frac{1}{n} - \frac{1}{n_0}$$

The concentration will decrease by a factor  $\eta$  when

$$rt_0 = \frac{1}{n_0/\eta} - \frac{1}{n_0} = \frac{\eta - 1}{n_0}$$

or, 
$$t_0 = \frac{\eta - 1}{\sqrt{r \dot{n}_i}} = 13 \text{ ms}$$

**3.216** Ions produced will cause charge to decay. Clearly,

$$\eta CV = \text{decrease of charge} = \dot{n}_i e A dt = \frac{\epsilon_0 A}{d} V \eta$$

or, 
$$t = \frac{\epsilon_0 V \eta}{\dot{n}_i e d^2} = 4.6 \text{ days}$$

Note, that  $n_p$  here, is the number of ion pairs produced.

**3.217** If  $v$  = number of electrons moving to the anode at distance  $x$ , then

$$\frac{dv}{dx} = \alpha v \quad \text{or} \quad v = v_0 e^{\alpha x}$$

Assuming saturation,  $I = e v_0 e^{\alpha d}$

**3.218** Since the electrons are produced uniformly through the volume, the total current attaining saturation is clearly,

$$I = \int_0^d e (\dot{n}_i A dx) e^{\alpha x} = e \dot{n}_i A \left( \frac{e^{\alpha d} - 1}{\alpha} \right)$$

Thus, 
$$j = \frac{I}{A} = e \dot{n}_i \left( \frac{e^{\alpha d} - 1}{\alpha} \right)$$

### 3.5 CONSTANT MAGNETIC FIELD. MAGNETICS

3.219 (a) From the Biot - Savart law,

$$d\vec{B} = \frac{\mu_0}{4\pi} i \frac{d\vec{l} \times \vec{r}}{r^3}, \text{ so}$$

$$dB = \frac{\mu_0}{4\pi} i \frac{(R d\theta) R}{R^3} \text{ (as } d\vec{l} \perp \vec{r} \text{)}$$

From the symmetry

$$B = \int dB = \int_0^{2\pi} \frac{\mu_0}{4\pi} \frac{i}{R} d\theta = \frac{\mu_0}{2} \frac{i}{R} = 6.3 \mu \text{ T}$$

(b) From Biot-Savart's law :

$$\vec{B} = \frac{\mu_0}{4\pi} i \int \frac{d\vec{l} \times \vec{r}}{r^3} \text{ (here } \vec{r} = \vec{R} + \vec{x} \text{)}$$

$$\text{So, } \vec{B} = \frac{\mu_0}{4\pi} i \left[ \oint d\vec{l} \times \vec{R} + \oint d\vec{l} \times \vec{x} \right]$$

Since  $\vec{x}$  is a constant vector and  $|\vec{R}|$  is also constant

$$\text{So, } \oint d\vec{l} \times \vec{x} = \left( \oint d\vec{l} \right) \times \vec{x} = 0 \text{ (because } \oint d\vec{l} = 0 \text{)}$$

and

$$\begin{aligned} \oint d\vec{l} \times \vec{R} &= \oint R d\vec{l} \times \vec{n} \\ &= \vec{n} R \oint d\vec{l} = 2\pi R^2 \vec{n} \end{aligned}$$

Here  $\vec{n}$  is a unit vector perpendicular to the plane containing the current loop (Fig.) and in the direction of  $\vec{x}$

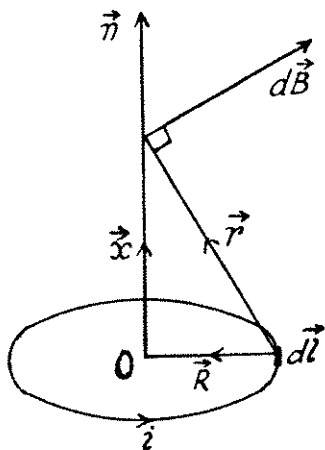
$$\text{Thus we get } \vec{B} = \frac{\mu_0}{4\pi} \frac{2\pi R^2 i}{(x^2 + R^2)^{3/2}} \vec{n}$$

3.220 As  $\angle AOB = \frac{2\pi}{n}$ ,  $OC$  or perpendicular distance of any segment from centre equals

$R \cos \frac{\pi}{n}$ . Now magnetic induction at  $O$ , due to the right current carrying element  $AB$

$$= \frac{\mu_0}{4\pi} \frac{i}{R \cos \frac{\pi}{n}} 2 \sin \frac{\pi}{n}$$

(From Biot-Savart's law, the magnetic field at  $O$  due to any section such as  $AB$  is perpendicular to the plane of the figure and has the magnitude.)



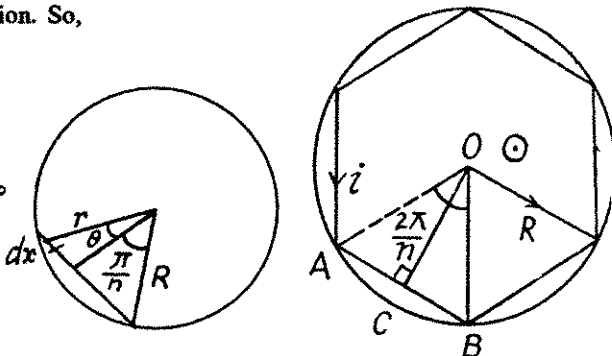
$$B = \int \frac{\mu_0}{4\pi} i \frac{dx}{r^2} \cos\theta = \int_{-\frac{\pi}{n}}^{\frac{\pi}{n}} \frac{\mu_0 i}{4\pi} \frac{R \cos \frac{\pi}{n} \sec^2 \theta d\theta}{R^2 \cos \frac{2\pi}{n} \sec^2 \theta} \cos\theta = \frac{\mu_0 i}{4\pi} \frac{1}{R \cos \frac{\pi}{n}} 2 \sin \frac{\pi}{n}$$

As there are  $n$  number of sides and magnetic induction vectors, due to each side at  $O$ , are equal in magnitude and direction. So,

$$B_0 = \frac{\mu_0}{4\pi} \frac{ni}{R \cos \frac{\pi}{n}} 2 \sin \frac{\pi}{n} \cdot n$$

$$= \frac{\mu_0}{2\pi R} \tan \frac{\pi}{n} \text{ and for } n \rightarrow \infty$$

$$B_0 = \frac{\mu_0}{2\pi R} \lim_{n \rightarrow \infty} \left( \frac{\tan \frac{\pi}{n}}{\pi/n} \right) = \frac{\mu_0}{2\pi R} i$$



**3.221** We know that magnetic induction due to a straight current carrying wire at any point, at a perpendicular distance from it is given by :

$$B = \frac{\mu_0}{4\pi r} i (\sin \theta_1 + \sin \theta_2),$$

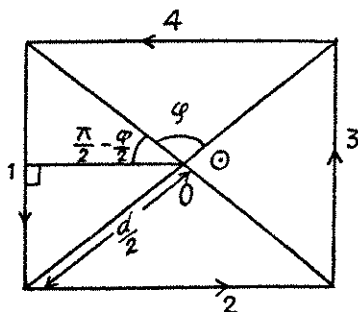
where  $r$  is the perpendicular distance of the wire from the point, considered, and  $\theta_1$  is the angle between the line, joining the upper point of straight wire to the considered point and the perpendicular drawn to the wire and  $\theta_2$  that from the lower point of the straight wire.

Here, 
$$B_1 = B_3 = \frac{\mu_0}{4\pi} \frac{i}{(d/2) \sin \frac{\varphi}{2}} \left\{ \cos \frac{\varphi}{2} + \cos \frac{\varphi}{2} \right\}$$

and 
$$B_2 = B_4 = \frac{\mu_0}{4\pi} \frac{i}{(d/2) \cos \frac{\varphi}{2}} \left( \sin \frac{\varphi}{2} + \sin \frac{\varphi}{2} \right)$$

Hence, the magnitude of total magnetic induction at  $O$ ,

$$\begin{aligned} B_0 &= B_1 + B_2 + B_3 + B_4 \\ &= \frac{\mu_0}{4\pi} \frac{4i}{d/2} \left[ \frac{\cos \frac{\varphi}{2}}{\sin \frac{\varphi}{2}} + \frac{\sin \frac{\varphi}{2}}{\cos \frac{\varphi}{2}} \right] \\ &= \frac{4\mu_0 i}{\pi d \sin \varphi} = 0.10 \text{ mT} \end{aligned}$$



3.222 Magnetic induction due to the arc segment at  $O$ ,

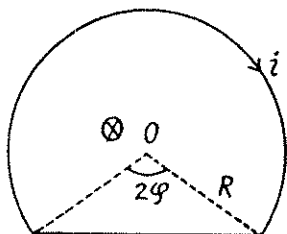
$$B_{\text{arc}} = \frac{\mu_0}{4\pi} \frac{i}{R} (2\pi - 2\varphi)$$

and magnetic induction due to the line segment at  $O$ ,

$$B_{\text{line}} = \frac{\mu_0}{4\pi} \frac{i}{R \cos \varphi} [2 \sin \varphi]$$

So, total magnetic induction at  $O$ ,

$$B_0 = B_{\text{arc}} + B_{\text{line}} = \frac{\mu_0}{2\pi} \frac{i}{R} [\pi - \varphi + \tan \varphi] = 28 \mu \text{ T}$$



3.223 (a) From the Biot-Savart law,

$$dB = \frac{\mu_0}{4\pi} i \frac{d\vec{l} \times \vec{r}}{r^3}$$

So, magnetic field induction due to the segment 1 at  $O$ ,

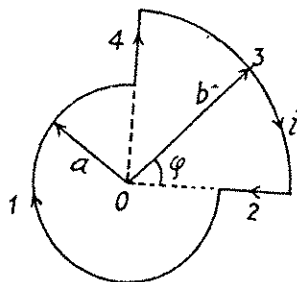
$$B_1 = \frac{\mu_0}{4\pi} \frac{i}{a} (2\pi - \varphi)$$

also  $B_2 = B_4 = 0$ , as  $d\vec{l} \parallel \vec{r}$

and  $B_3 = \frac{\mu_0}{4\pi} \frac{i}{b} \varphi$

Hence,  $B_0 = B_1 + B_2 + B_3 + B_4$

$$= \frac{\mu_0}{4\pi} i \left[ \frac{2\pi - \varphi}{a} + \frac{\varphi}{b} \right]$$



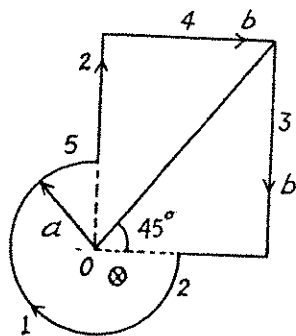
(b) Here,  $B_1 = \frac{\mu_0}{4\pi} \frac{i}{a} \frac{3\pi}{a}$ ,  $B_2 = 0$ ,

$$B_3 = \frac{\mu_0}{4\pi} \frac{i}{b} \sin 45^\circ,$$

$$B_4 = \frac{\mu_0}{4\pi} \frac{i}{b} \sin 45^\circ,$$

and  $B_5 = 0$

So,  $B_0 = B_1 + B_2 + B_3 + B_4 + B_5$



$$= \frac{\mu_0}{4\pi} \frac{i}{a} \frac{3\pi}{2} + 0 + \frac{\mu_0}{4\pi} \frac{i}{b} \sin 45^\circ + \frac{\mu_0}{4\pi} \frac{i}{b} \sin 45^\circ + 0$$

$$= \frac{\mu_0}{4\pi} i \left[ \frac{3\pi}{2a} + \frac{\sqrt{2}}{b} \right]$$

- 3.224 The thin walled tube with a longitudinal slit can be considered equivalent to a full tube and a strip carrying the same current density in the opposite direction. Inside the tube, the former does not contribute so the total magnetic field is simply that due to the strip. It is

$$B = \frac{\mu_0 (I/2 \pi R) h}{2 \pi r} = \frac{\mu_0 I h}{4 \pi^2 R r}$$

where  $r$  is the distance of the field point from the strip.

- 3.225 First of all let us find out the direction of vector  $\vec{B}$  at point  $O$ . For this purpose, we divide the entire conductor into elementary fragments with current  $di$ . It is obvious that the sum of any two symmetric fragments gives a resultant along  $\vec{B}$  shown in the figure and consequently, vector  $\vec{B}$  will also be directed as shown

$$\text{So, } |\vec{B}| = \int dB \sin \varphi \quad (1)$$

$$= \int \frac{\mu_0}{2 \pi R} di \sin \varphi$$

$$= \int_0^\pi \frac{\mu_0}{2 \pi^2 R} i \sin \varphi d\varphi, \left( \text{as } di = \frac{i}{\pi} d\varphi \right)$$

$$\text{Hence } B = \mu_0 i / \pi^2 R$$

- 3.226 (a) From symmetry

$$B_0 = B_1 + B_2 + B_3$$

$$= 0 + \frac{\mu_0}{4 \pi R} i \pi + 0 = \frac{\mu_0}{4 \pi R} i$$

- (b) From symmetry

$$B_0 = B_1 + B_2 + B_3$$

$$= \frac{\mu_0}{4 \pi R} i + \frac{\mu_0}{2 \pi R} i \frac{3\pi}{2} + 0 = \frac{\mu_0}{4 \pi R} i \left[ 1 + \frac{3\pi}{2} \right]$$

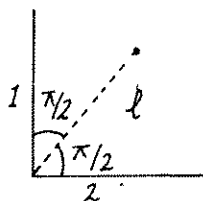
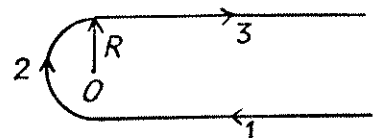
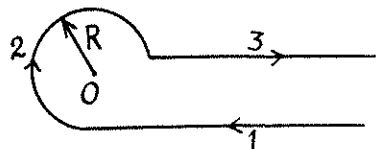
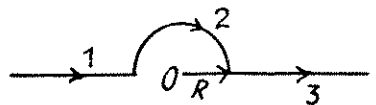
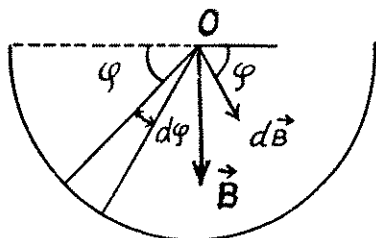
- (c) From symmetry

$$B_0 = B_1 + B_2 + B_3$$

$$= \frac{\mu_0}{4 \pi R} i + \frac{\mu_0}{4 \pi R} i \pi + \frac{\mu_0}{4 \pi R} i = \frac{\mu_0}{4 \pi R} i (2 + \pi)$$

$$3.227 \quad \vec{B}_0 = \vec{B}_1 + \vec{B}_2$$

$$\text{or, } |\vec{B}_0| = \frac{\mu_0 i}{4 \pi l} \sqrt{2} = 2.0 \mu \text{ T, (using 3.221)}$$





$$\begin{aligned}
 3.228 \quad (a) \quad \vec{B}_0 &= \vec{B}_1 + \vec{B}_2 + \vec{B}_3 \\
 &= \frac{\mu_0 i}{4\pi R} (-\vec{k}) + \frac{\mu_0 i}{4\pi R} \pi (-\vec{i}) + \frac{\mu_0 i}{4\pi R} (-\vec{k}) \\
 &= -\frac{\mu_0 i}{4\pi R} [2\vec{k} + \pi\vec{i}]
 \end{aligned}$$

So,  $|\vec{B}_0| = \frac{\mu_0 i}{4\pi R} \sqrt{\pi^2 + 4} = 0.30 \mu\text{T}$

$$\begin{aligned}
 (b) \quad \vec{B}_0 &= \vec{B}_1 + \vec{B}_2 + \vec{B}_3 \\
 &= \frac{\mu_0 i}{4\pi R} (-\vec{k}) + \frac{\mu_0 i}{4\pi R} \pi (-\vec{i}) + \frac{\mu_0 i}{4\pi R} (-\vec{i}) \\
 &= -\frac{\mu_0 i}{4\pi R} [\vec{k} + (\pi + 1)\vec{i}]
 \end{aligned}$$

So,

$$|\vec{B}_0| = \frac{\mu_0 i}{4\pi R} \sqrt{1 + (\pi + 1)^2} = 0.34 \mu\text{T}$$

(c) Here using the law of parallel resistances

$$i_1 + i_2 = i \text{ and } \frac{i_1}{i_2} = \frac{1}{3},$$

So,  $\frac{i_1 + i_2}{i_2} = \frac{4}{3}$

Hence  $i_2 = \frac{3}{4}i$ , and  $i_1 = \frac{1}{4}i$

$$\begin{aligned}
 \text{Thus } \vec{B}_0 &= \frac{\mu_0 i}{4\pi R} (-\vec{k}) + \frac{\mu_0 i}{4\pi R} (-\vec{j}) + \left[ \frac{\mu_0}{4\pi} \left( \frac{3\pi}{2} \right) \frac{i_1}{R} (-\vec{i}) + \frac{\mu_0}{4\pi} \frac{(\pi/2) i_2}{R} \vec{i} \right] \\
 &= -\frac{\mu_0 i}{4\pi R} (\vec{j} + \vec{k}) + 0
 \end{aligned}$$

Thus,  $|\vec{B}_0| = \frac{\mu_0 \sqrt{2} i}{4\pi R} = 0.11 \mu\text{T}$

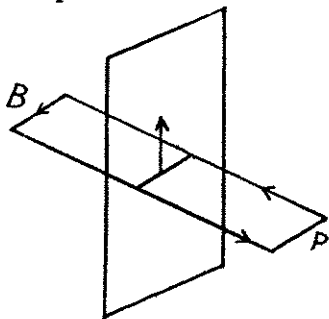
3.229 (a) We apply circulation theorem as shown. The current is vertically upwards in the plane and the magnetic field is horizontal and parallel to the plane.

$$\oint \vec{B} \cdot d\vec{l} = 2Bl = \mu_0 il \quad \text{or, } B = \frac{\mu_0 i}{2}$$

(b) Each plane contributes  $\mu_0 \frac{i}{2}$  between the planes and outside the plane that cancel.

Thus

$$B = \begin{cases} \mu_0 i \text{ between the plane} \\ 0 \text{ outside.} \end{cases}$$



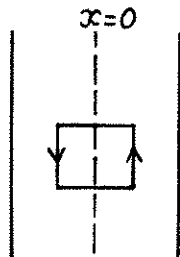
**3.230** We assume that the current flows perpendicular to the plane of the paper, by circulation theorem,

$$2B dl = \mu_0 (2x dl) j$$

or,  $B = \mu_0 x j, |x| \leq d$

Outside,  $2B dl = \mu_0 (2d dl) j$

or,  $B = \mu_0 d j, |x| \geq d.$

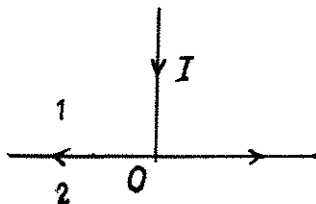


**3.231** It is easy to convince oneself that both in the regions. 1 and 2, there can only be a circular magnetic field (i.e. the component  $B_\phi$ ). Any radial field in region 1 or any  $B_z$  away from the current plane will imply a violation of Gauss' law of magnetostatics,  $B_\phi$  must obviously be symmetrical about the straight wire. Then in 1,

$$B_\phi 2\pi r = \mu_0 I$$

or,  $B_\phi = \frac{\mu_0 I}{2\pi r}$

In 2,  $B_\phi \cdot 2\pi r = 0$ , or  $B_\phi = 0$



**3.232** On the axis,  $B = \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}} = B_x$  along the axis.

$$\begin{aligned} \text{Thus, } \int \vec{B} \cdot d\vec{r} &= \int_{-\infty}^{\infty} B_x dx = \frac{\mu_0 I R^2}{2} \int_{-\infty}^{\infty} \frac{dx}{(R^2 + x^2)^{3/2}} \\ &= \frac{\mu_0 I R^2}{2} \int_{-\pi/2}^{\pi/2} \frac{R \sec^2 \theta d\theta}{R^3 \sec^3 \theta}, \text{ on putting } x = R \tan \theta \\ &= \mu_0 I \frac{1}{2} \int_{-\pi/2}^{\pi/2} \cos \theta d\theta = \mu_0 I \end{aligned}$$

The physical interpretation of this result is that  $\int_{-\infty}^{\infty} B_x dx$  can be thought of as the circulation of  $B$  over a closed loop by imaging that the two ends of the axis are connected, by a line at infinity (e.g. a semicircle of infinite radius).

**3.233** By circulation theorem inside the conductor

$$B_\phi 2\pi r = \mu_0 j_z \pi r^2 \text{ or, } B_\phi = \mu_0 j_z r/2$$

i.e.,  $\vec{B} = \frac{1}{2} \mu_0 \vec{j} \times \vec{r}$

Similarly outside the conductor,

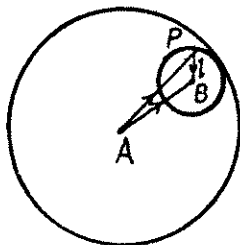
$$B_{\varphi} 2 \pi r = \mu_0 j_z \pi R^2 \quad \text{or,} \quad B_{\varphi} = \frac{1}{2} \mu_0 j_z \frac{R^2}{r}$$

So, 
$$\vec{B} = \frac{1}{2} \mu_0 (\vec{j} \times \vec{r}) \frac{R^2}{r^2}$$

**2.234** We can think of the given current which will be assumed uniform, as arising due to a negative current, flowing in the cavity, superimposed on the true current, everywhere including the cavity. Then from the previous problem, by superposition.

$$\vec{B} = \frac{1}{2} \mu_0 \vec{j} \times (A \vec{P} - B \vec{P}) = \frac{1}{2} \mu_0 \vec{j} \times \vec{l}$$

If  $\vec{l}$  vanishes so that the cavity is concentric with the conductor, there is no magnetic field in the cavity.



**3.235** By Circulation theorem,

$$B_{\varphi} \cdot 2 \pi r = \mu_0 \int_0^r j(r') \times 2 \pi r' dr'$$

or using  $B_{\varphi} = br^{\alpha}$  inside the stream,

$$br^{\alpha+1} = \mu_0 \int_0^r j(r') r' dr'$$

So by differentiation,

$$(\alpha + 1) br^{\alpha} = \mu_0 j(r) r$$

Hence, 
$$j(r) = \frac{b(\alpha + 1)}{\mu_0} r^{\alpha-1}$$

**3.236** On the surface of the solenoid there is a surface current density

$$\vec{j}_s = n I \hat{e}_{\varphi}$$

Then, 
$$\vec{B} = -\frac{\mu_0}{4\pi} n I \int R d\varphi dz \frac{\hat{e}_{\varphi} \times \vec{r}_0}{r_0^3}$$

where  $\vec{r}_0$  is the vector from the current element to the field point, which is the centre of the solenoid,

Now, 
$$-\hat{e}_{\varphi} \times \vec{r}_0 = R \hat{e}_z$$

$$r_0 = (z^2 + R^2)^{1/2}$$

Thus, 
$$B = B_z = \frac{\mu_0 n I}{4\pi} \times 2\pi R^2 \int_{-1/2}^{1/2} \frac{dz}{(R^2 + z^2)^{3/2}}$$

$$\begin{aligned}
& + \tan^{-1} \frac{l}{2R} \\
& = \frac{1}{2} \mu_0 n I \int_{-\tan^{-1} \frac{l}{2R}}^{+\tan^{-1} \frac{l}{2R}} \cos \alpha \, d\alpha \quad (\text{on putting } z = R \tan \alpha) \\
& = \mu_0 n I \sin \alpha = \mu_0 n I \frac{l/2}{\sqrt{(l/2)^2 + R^2}} = \mu_0 n I / \sqrt{1 + \left(\frac{2R}{l}\right)^2}
\end{aligned}$$

3.237 We proceed exactly as in the previous problem. Then (a) the magnetic induction on the axis at a distance  $x$  from one end is clearly,

$$\begin{aligned}
B &= \frac{\mu_0 n I}{4\pi} \times 2\pi R^2 \int_0^\infty \frac{dz}{[R^2 + (z-x)^2]^{3/2}} = \frac{1}{2} \mu_0 n I R^2 \int_x^\infty \frac{dz}{(z^2 + R^2)^{3/2}} \\
&= \frac{1}{2} \mu_0 n I \int_{\tan^{-1} \frac{x}{R}}^{\pi/2} \cos \theta \, d\theta = \frac{1}{2} \mu_0 n I \left( 1 - \frac{x}{\sqrt{x^2 + R^2}} \right)
\end{aligned}$$

$x > 0$  means that the field point is outside the solenoid.  $B$  then falls with  $x$ .  $x < 0$  means that the field point gets more and more inside the solenoid.  $B$  then increases with  $(x)$  and eventually becomes constant, equal to  $\mu_0 n I$ . The  $B-x$  graph is as given in the answer script.

$$(b) \text{ We have, } \frac{B_0 - \delta B}{B_0} = \frac{1}{2} \left[ 1 - \frac{x_0}{\sqrt{R^2 + x_0^2}} \right] = 1 - \eta$$

$$\text{or, } -\frac{x_0}{\sqrt{R^2 + x_0^2}} = 1 - 2\eta$$

Since  $\eta$  is small ( $\approx 1\%$ ),  $x_0$  must be negative. Thus  $x_0 = -|x_0|$

$$\text{and } \frac{|x_0|}{\sqrt{R^2 + |x_0|^2}} = 1 - 2\eta$$

$$\begin{aligned}
|x_0|^2 &= (1 - 4\eta + 4\eta^2)(R^2 + |x_0|^2) \\
0 &= (1 - 2\eta)^2 R^2 - 4\eta(1 - \eta)|x_0|^2
\end{aligned}$$

$$\text{or, } |x_0| = \frac{(1 - 2\eta)R}{2\sqrt{\eta(1 - \eta)}}$$

3.238 If the strip is tightly wound, it must have a pitch of  $h$ . This means that the current will flow obliquely, partly along  $\hat{e}_\varphi$  and partly along  $\hat{e}_z$ . Obviously, the surface current density is,

$$\vec{J}_s = \frac{I}{h} \left[ \sqrt{1 - (h/2\pi R)^2} \hat{e}_\varphi + \frac{h}{2\pi R} \hat{e}_z \right].$$

By comparison with the case of a solenoid and a hollow straight conductor, we see that field inside the coil

$$= \mu_0 \frac{I}{h} \sqrt{1 - (h/2\pi R)^2}$$

(Cf.  $B = \mu_0 nI$ ).

Outside, only the other term contributes, so

$$B_\varphi \times 2\pi r = \mu_0 \frac{I}{h} \times \frac{h}{2\pi R} \times 2\pi R$$

or, 
$$B_\varphi = \frac{\mu_0}{4\pi} \cdot \frac{2I}{r}.$$

**Note** - Surface current density is defined as current flowing normally across a unit length over a surface.

**3.239** Suppose  $a$  is the radius of cross section of the core. The winding has a pitch  $2\pi R/N$ , so the surface current density is

$$\vec{J}_s = \frac{I}{2\pi R/N} \vec{e}_1 + \frac{I}{2\pi a} \vec{e}_2$$

where  $\vec{e}_1$  is a unit vector along the cross section of the core and  $\vec{e}_2$  is a unit vector along its length.

The magnetic field inside the cross section of the core is due to first term above, and is given by

$$B_\varphi \cdot 2\pi R = \mu_0 NI$$

( $NI$  is total current due to the above surface current (first term.))

Thus, 
$$B_\varphi = \mu_0 NI/2\pi R.$$

The magnetic field at the centre of the core can be obtained from the basic formula.

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{\vec{J}_s \times \vec{r}_0}{r_0^3} dS \text{ and is due to the second term.}$$

So, 
$$\vec{B} = B_z \vec{e}_z = \vec{e}_z \frac{\mu_0}{4\pi} \frac{I}{2\pi a} \int \frac{1}{R^3} R d\varphi \times 2\pi a$$

or, 
$$B_z = \frac{\mu_0 I}{2R}$$

The ratio of the two magnetic field, is  $= \frac{N}{\pi}$

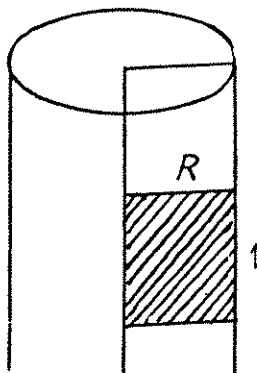
**3.240** We need the flux through the shaded area.

Now by Ampere's theorem,

$$B_\varphi 2\pi r = \mu_0 \frac{I}{\pi R^2} \cdot \pi r^2$$

or, 
$$B_\varphi = \frac{\mu_0}{2\pi} I \frac{r}{R^2}$$

The flux through the shaded region is,



$$\begin{aligned}\Phi_1 &= \int_0^R 1 \cdot dr \cdot B_\varphi(r) \\ &= \int_0^R dr \frac{\mu_0}{2\pi} I \frac{r}{R^2} = \frac{\mu_0}{4\pi} I.\end{aligned}$$

3.241 Using 3.237, the magnetic field is given by,

$$B = \frac{1}{2} \mu_0 n I \left( 1 - \frac{x}{\sqrt{x^2 + R^2}} \right)$$

At the end,  $B = \frac{1}{2} \mu_0 n I = \frac{1}{2} B_0$ , where  $B_0 = \mu_0 n I$ ,

is the field deep inside the solenoid. Thus,

$$\Phi = \frac{1}{2} \mu_0 n I S = \Phi_0/2, \text{ where } \Phi = \mu_0 n I S$$

is the flux of the vector  $B$  through the cross section deep inside the solenoid.

3.242  $B_\varphi 2\pi r = \mu_0 N I$

or,  $B_\varphi = \frac{\mu_0 N I}{2\pi r}$

Then,  $\Phi = \int_a^b B_\varphi h dr, a \leq r \leq b = \frac{\mu_0}{4\pi} 2N I h \ln \eta$ , where  $\eta = b/a$

3.243 Magnetic moment of a current loop is given by  $p_m = n i S$  (where  $n$  is the number of turns and  $S$ , the cross sectional area.) In our problem,  $n = 1$ ,  $S = \pi R^2$  and  $B = \frac{\mu_0 i}{2 R}$

So,  $p_m = \frac{2 B R}{\mu_0} \pi R^2 = \frac{2\pi B R^3}{\mu_0}$

3.244 Take an element of length  $r d\theta$  containing  $\frac{N}{\pi r} \cdot r d\theta$  turns. Its magnetic moment is

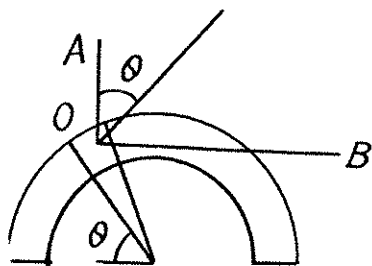
$$\frac{N}{\pi} d\theta \cdot \frac{\pi}{4} d^2 I$$

normal to the plane of cross section. We resolve it along  $OA$  and  $OB$ . The moment along  $OA$  integrates to

$$\int_0^\pi \frac{N}{4} d^2 I d\theta \cos \theta = 0$$

while that along  $OB$  gives

$$p_m = \int_0^\pi \frac{N d^2 I}{4} \sin \theta d\theta = \frac{1}{2} N d^2 I$$



- 3.245 (a) From Biot-Savart's law, the magnetic induction due to a circular current carrying wire loop at its centre is given by,

$$B_r = \frac{\mu_0}{2r} i$$

The plane spiral is made up of concentric circular loops, having different radii, varying from  $a$  to  $b$ . Therefore, the total magnetic induction at the centre,

$$B_0 = \int \frac{\mu_0}{2r} dN \quad (1)$$

where  $\frac{\mu_0}{2r} i$  is the contribution of one turn of radius  $r$  and  $dN$  is the number of turns in the interval  $(r, r + dr)$

i.e. 
$$dN = \frac{N}{b-a} dr$$

Substituting in equation (1) and integrating the result over  $r$  between  $a$  and  $b$ , we obtain,

$$B_0 = \int_a^b \frac{\mu_0 i}{2r} \frac{N}{(b-a)} dr = \frac{\mu_0 i N}{2(b-a)} \ln \frac{b}{a}$$

- (b) The magnetic moment of a turn of radius  $r$  is  $p_m = i \pi r^2$  and of all turns,

$$p = \int p_m dN = \int_a^b i \pi r^2 \frac{N}{b-a} dr = \frac{\pi i N (b^3 - a^3)}{3(b-a)}$$

- 3.246 (a) Let us take a ring element of radius  $r$  and thickness  $dr$ , then charge on the ring element.,  $dq = \sigma 2 \pi r dr$

and current, due to this element,  $di = \frac{(\sigma 2 \pi r dr) \omega}{2 \pi} = \sigma \omega r dr$

So, magnetic induction at the centre, due to this element :  $dB = \frac{\mu_0 di}{2r}$

and hence, from symmetry :  $B = \int dB = \int_0^R \frac{\mu_0 \sigma \omega r dr}{r} = \frac{\mu_0}{2} \sigma \omega R$

- (b) Magnetic moment of the element, considered,

$$dp_m = (di) \pi r^2 = \sigma \omega dr \pi r^2 = \sigma \pi \omega r^3 dr$$

Hence, the sought magnetic moment,

$$p_m = \int dp_m = \int_0^R \sigma \pi \omega r^3 dr = \sigma \pi \omega \frac{R^4}{4}$$

**3.247** As only the outer surface of the sphere is charged, consider the element as a ring, as shown in the figure.

The equivalent current due to the ring element,

$$di = \frac{\omega}{2\pi} (2\pi r \sin \theta r d\theta) \sigma \quad (1)$$

and magnetic induction due to this loop element at the centre of the sphere,  $O$ ,

$$dB = \frac{\mu_0}{4\pi} di \frac{2\pi r \sin \theta r \sin \theta}{r^3} = \frac{\mu_0}{4\pi} di \frac{\sin^2 \theta}{r}$$

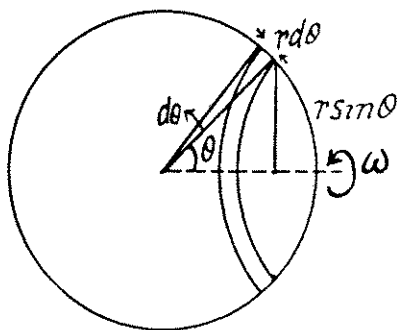
[Using 3.219 (b)]

Hence, the total magnetic induction due to the sphere at the centre,  $O$ ,

$$B = \int dB = \int_0^{\pi/2} \frac{\mu_0 \omega}{4\pi 2\pi} \frac{2\pi r^2 \sin \theta d\theta \sin^2 \theta}{r} \quad [\text{using (1)}]$$

Hence,

$$B = \int_0^{\pi/2} \frac{\mu_0 \sigma \omega r}{4\pi} \sin^3 \theta d\theta = \frac{2}{3} \mu_0 \sigma \omega r = 29 \text{ pT}$$



**3.248** The magnetic moment must clearly be along the axis of rotation. Consider a volume element  $dV$ . It contains a charge  $\frac{q}{4\pi/3 R^3} dV$ . The rotation of the sphere causes this charge to revolve around the axis and constitute a current.

$$\frac{3q}{4\pi R^3} dV \times \frac{\omega}{2\pi}$$

Its magnetic moment will be

$$\frac{3q}{4\pi R^3} dV \times \frac{\omega}{2\pi} \times \pi r^2 \sin^2 \theta$$

So the total magnetic moment is

$$P_m = \int_0^R \int_0^\pi \frac{3q}{2R^3} r^2 \sin \theta d\theta \times \frac{\omega r^2 \sin^2 \theta}{2} dr = \frac{3q}{2R^3} \times \frac{\omega}{2} \times \frac{R^5}{5} \times \frac{4}{3} = \frac{1}{5} q R^2 \omega$$

The mechanical moment is

$$M = \frac{2}{5} m R^2 \omega, \quad \text{So,} \quad \frac{P_m}{M} = \frac{q}{2m}.$$

**3.249** Because of polarization a space charge is present within the cylinder. It's density is

$$\rho_p = -\text{div } \vec{P} = -2\alpha$$

Since the cylinder as a whole is neutral a surface charge density  $\sigma_p$  must be present on the surface of the cylinder also. This has the magnitude (algebraically)



$$\sigma_p \times 2\pi R = 2\alpha \pi R^2 \quad \text{or,} \quad \sigma_p = \alpha R$$

When the cylinder rotates, currents are set up which give rise to magnetic fields. The contribution of  $\rho_p$  and  $\sigma_p$  can be calculated separately and then added.

For the surface charge the current is (for a particular element)

$$\alpha R \times 2\pi R \, dx \times \frac{\omega}{2\pi} = \alpha R^2 \omega \, dx$$

Its contribution to the magnetic field at the centre is

$$\frac{\mu_0 R^2 (\alpha R^2 \omega \, dx)}{2 (x^2 + R^2)^{3/2}}$$

and the total magnetic field is

$$B_s = \int_{-\infty}^{\infty} \frac{\mu_0 R^2 (\alpha R^2 \omega \, dx)}{2 (x^2 + R^2)^{3/2}} = \frac{\mu_0 \alpha R^4 \omega}{2} \int_{-\infty}^{\infty} \frac{dx}{(x^2 + R^2)^{3/2}} = \frac{\mu_0 \alpha R^4 \omega}{2} \times \frac{2}{R^2} = \mu_0 \alpha R^2 \omega$$

As for the volume charge density consider a circle of radius  $r$ , radial thickness  $dr$  and length  $dx$ .

The current is  $-2\alpha \times 2\pi r \, dr \, dx \times \frac{\omega}{2\pi} = -2\alpha r \, dr \, \omega \, dx$

The total magnetic field due to the volume charge distribution is

$$\begin{aligned} B_v &= - \int_0^R dr \int_{-\infty}^{\infty} dx \, 2\pi r \omega \frac{\mu_0 r^2}{2 (x^2 + r^2)^{3/2}} = - \int_0^R \alpha \mu_0 \omega r^3 \, dr \int_{-\infty}^{\infty} \frac{dx}{(x^2 + r^2)^{3/2}} \\ &= - \int_0^R \alpha \mu_0 \omega r \, dr \times 2 = -\mu_0 \alpha \omega R^2 \quad \text{so,} \quad B = B_s + B_v = 0 \end{aligned}$$

**3.250** Force of magnetic interaction,  $\vec{F}_{mag} = e (\vec{v} \times \vec{B})$

Where, 
$$\vec{B} = \frac{\mu_0 e (\vec{v} \times \vec{r})}{4\pi r^3}$$

So, 
$$\vec{F}_{mag} = \frac{\mu_0 e^2}{4\pi r^3} [\vec{v} \times (\vec{v} \times \vec{r})]$$

$$= \frac{\mu_0}{4\pi} \frac{e^2}{r^3} [(\vec{v} \times \vec{r}) \times \vec{v} - (\vec{v} \cdot \vec{v}) \times \vec{r}] = \frac{\mu_0}{4\pi} \frac{e^2}{r^3} (-v^2 \vec{r})$$

And 
$$\vec{F}_{ele} = e\vec{E} = e \frac{1}{4\pi \epsilon_0} \frac{e\vec{r}}{r^3}$$

Hence, 
$$\frac{|\vec{F}_{mag}|}{|\vec{F}_{electric}|} = -v^2 \mu_0 \epsilon_0 = \left(\frac{v}{c}\right)^2 = 1.00 \times 10^{-6}$$

- 3.251 (a) The magnetic field at  $O$  is only due to the curved path, as for the line element,  $d\vec{l} \uparrow \uparrow \vec{r}$ .

$$\text{Hence, } \vec{B} = \frac{\mu_0 i}{4\pi R} \pi (-\vec{k}) = \frac{\mu_0 i}{4R} (-\vec{k})$$

$$\text{Thus } \vec{F}_u = i\vec{B} (-\vec{j}) = \frac{\mu_0 i^2}{4R} (-\vec{j})$$

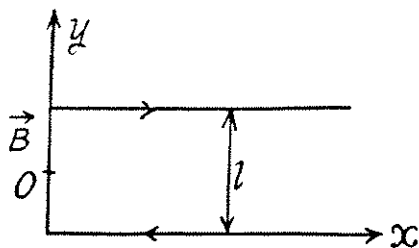
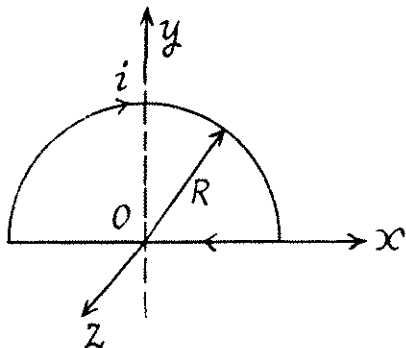
$$\text{So, } F_u = \frac{\pi_0 i^2}{4R} = 0.20 \text{ N/m}$$

- (b) In this part, magnetic induction  $\vec{B}$  at  $O$  will be effective only due to the two semi infinite segments of wire. Hence

$$\begin{aligned} \vec{B} &= 2 \cdot \frac{\mu_0 i}{4\pi \left(\frac{l}{2}\right)} \sin \frac{\pi}{2} (-\vec{k}) \\ &= \frac{\mu_0 i}{\pi l} (-\vec{k}) \end{aligned}$$

Thus force per unit length,

$$\vec{F}_u = \frac{\mu_0 l^2}{\pi l} (-\vec{i})$$



- 3.252 Each element of length  $dl$  experiences a force  $BI dl$ . This causes a tension  $T$  in the wire. For equilibrium,

$$T d\alpha = BI dl,$$

where  $d\alpha$  is the angle subtended by the element at the centre.

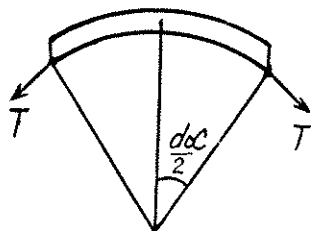
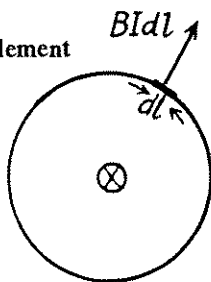
$$\text{Then, } T = BI \frac{dl}{d\alpha} = BIR$$

The wire experiences a stress

$$\frac{BIR}{\pi d^2/4}$$

This must equals the breaking stress  $\sigma_m$  for rupture. Thus,

$$B_{\max} = \frac{\pi d^2 \sigma_m}{4 IR}$$



- 3.253 The Ampere forces on the sides  $OP$  and  $O'P'$  are directed along the same line, in opposite directions and have equal values, hence the net force as well as the net torque of these forces about the axis  $OO'$  is zero. The Ampere-force on the segment  $PP'$  and the corresponding moment of this force about the axis  $OO'$  is effective and is deflecting in nature.

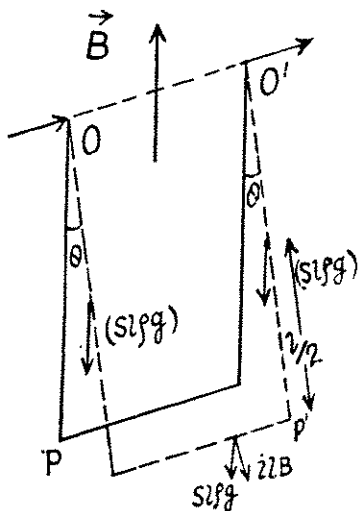
In equilibrium (in the dotted position) the deflecting torque must be equal to the restoring torque, developed due to the weight of the shape.

Let, the length of each side be  $l$  and  $\rho$  be the density of the material then,

$$ilB (l \cos \theta) = (Sl\rho) g \frac{l}{2} \sin \theta + (Sl\rho) g \frac{l}{2} \sin \theta + (Sl\rho) gl \sin \theta$$

$$\text{or, } il^2 B \cos \theta = 2S\rho gl^2 \sin \theta$$

$$\text{Hence, } B = \frac{2S\rho g}{i} \tan \theta$$



3.254 We know that the torque acting on a magnetic dipole.

$$\vec{N} = \vec{p}_m \times \vec{B}$$

But,  $\vec{p}_m = iS\hat{n}$ , where  $\hat{n}$  is the normal on the plane of the loop and is directed in the direction of advancement of a right handed screw, if we rotate the screw in the sense of current in the loop.

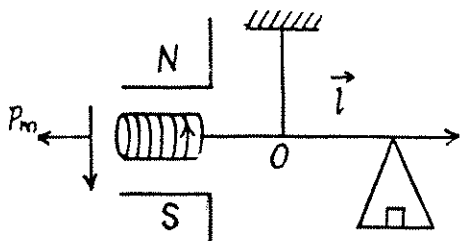
On passing a current through the coil, this torque acting on the magnetic dipole, is counterbalanced by the moment of additional weight, about  $O$ .

Hence, the direction of current in the loop must be in the direction, shown in the figure.

$$\vec{p}_m \times \vec{B} = -\vec{l} \times \Delta m \vec{g}$$

$$\text{or, } NiSB = \Delta mgl$$

$$\text{So, } B = \frac{\Delta mgl}{NiS} = 0.4 \text{ T on putting the values.}$$



3.255 (a) As is clear from the condition, Ampere's forces on the sides (2) and (4) are equal in magnitude but opposite in direction. Hence the net effective force on the frame is the resultant of the forces, experienced by the sides (1) and (3).

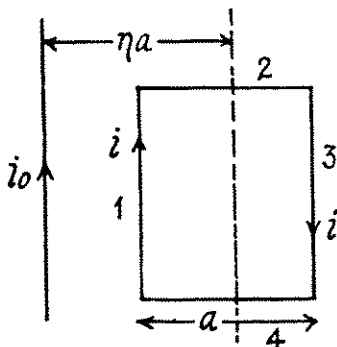
Now, the Ampere force on (1),

$$F_1 = \frac{\mu_0}{2\pi} \frac{i_0 i}{\left(\eta - \frac{1}{2}\right)}$$

and that on (3),

$$F_3 = \frac{\mu_0}{2\pi} \frac{i_0 i}{\left(\eta + \frac{1}{2}\right)}$$

So, the resultant force on the frame  
 $= F_1 - F_3$ , (as they are opposite in nature.)



$$= \frac{2 \mu_0 \ddot{u}_0}{\pi (4 \eta^2 - 1)} = 0.40 \mu \text{ N.}$$

(b) Work done in turning the frame through some angle,  $A = \int i d\Phi = i(\Phi_f - \Phi_i)$ , where  $\Phi_f$  is the flux through the frame in final position, and  $\Phi_i$  that in the initial position.

Here,  $|\Phi_f| = |\Phi_i| = \Phi$  and  $\Phi_i = -\Phi_f$

so,  $\Delta\Phi = 2\Phi$  and  $A = i 2\Phi$

Hence,

$$A = 2i \int \vec{B} \cdot d\vec{S}$$

$$= 2i \int_{a(\eta - \frac{1}{2})}^{a(\eta + \frac{1}{2})} \frac{\mu_0 i_0 a}{2\pi r} dr = \frac{\mu_0 \ddot{u}_0 a}{\pi} \ln \left( \frac{2\eta + 1}{2\eta - 1} \right)$$

**3.256** There are excess surface charges on each wire (irrespective of whether the current is flowing through them or not). Hence in addition to the magnetic force  $\vec{F}_m$ , we must take into account the electric force  $\vec{F}_e$ . Suppose that an excess charge  $\lambda$  corresponds to a unit length of the wire, then electric force exerted per unit length of the wire by other wire can be found with the help of Gauss's theorem.

$$F_e = \lambda E = \lambda \frac{1}{4\pi\epsilon_0} \frac{2\lambda}{l} = \frac{2\lambda^2}{4\pi\epsilon_0 l}, \quad (1)$$

where  $l$  is the distance between the axes of the wires. The magnetic force acting per unit length of the wire can be found with the help of the theorem on circulation of vector  $\vec{B}$

$$F_m = \frac{\mu_0 2i^2}{4\pi l},$$

where  $i$  is the current in the wire. (2)

Now, from the relation,

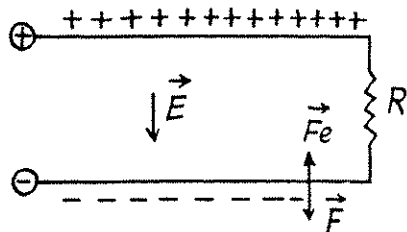
$\lambda = C\varphi$ , where  $C$  is the capacitance of the wires per unit lengths and is given in problem 3.108 and  $\varphi = iR$

$$\lambda = \frac{\pi\epsilon_0}{\ln \eta} iR \quad \text{or,} \quad \frac{i}{\lambda} = \frac{\ln \eta}{\pi\epsilon_0 R} \quad (3)$$

Dividing (2) by (1) and then substituting the value of  $\frac{i}{\lambda}$  from (3), we get,

$$\frac{F_m}{F_e} = \frac{\mu_0 (\ln \eta)^2}{\epsilon_0 \pi^2 R^2}$$

The resultant force of interaction vanishes when this ratio equals unity. This is possible when  $R = R_0$  where



$$R_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \frac{\ln \eta}{\pi} = 0.36 \text{ k}\Omega$$

3.257 Use 3.225

The magnetic field due to the conductor with semicircular cross section is

$$B = \frac{\mu_0 I}{\pi^2 R}$$

Then

$$\frac{\partial F}{\partial l} = BI = \frac{\mu_0 I^2}{\pi^2 R}$$

3.258 We know that Ampere's force per unit length on a wire element in a magnetic field is given by,

$$d\vec{F}_n = i(\hat{n} \times \vec{B}) \text{ where } \hat{n} \text{ is the unit vector along the direction of current.} \quad (1)$$

Now, let us take an element of the conductor  $i_2$ , as shown in the figure. This wire element is in the magnetic field, produced by the current  $i_1$ , which is directed normally into the sheet of the paper and its magnitude is given by,

$$|\vec{B}| = \frac{\mu_0 I_1}{2\pi r} \quad (2)$$

From Eqs. (1) and (2)

$$d\vec{F}_n = \frac{I_2}{b} dr (\hat{n} \times \vec{B}), \text{ (because the current through the element equals } \frac{I_2}{b} dr \text{)}$$

$$\text{So, } d\vec{F}_n = \frac{\mu_0 I_1 I_2}{2\pi b} \frac{dr}{r}, \text{ towards left (as } \hat{n} \perp \vec{B} \text{)}.$$

Hence the magnetic force on the conductor :

$$\vec{F}_n = \frac{\mu_0 I_1 I_2}{2\pi b} \int_a^{a+b} \frac{dr}{r} \text{ (towards left)} = \frac{\mu_0 I_1 I_2}{2\pi b} \ln \frac{a+b}{a} \text{ (towards left).}$$

Then according to the Newton's third law the magnitude of sought magnetic interaction force

$$= \frac{\mu_0 I_1 I_2}{2\pi b} \ln \frac{a+b}{a}$$

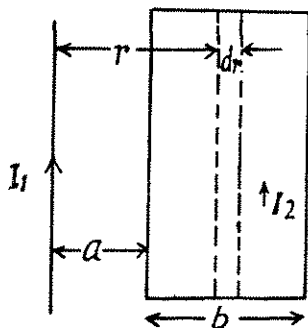
3.259 By the circulation theorem  $B = \mu_0 i$ ,

where  $i$  = current per unit length flowing along the plane perpendicular to the paper. Currents flow in the opposite sense in the two planes and produce the given field  $B$  by superposition.

The field due to one of the plates is just  $\frac{1}{2}B$ . The force on the plate is,

$$\frac{1}{2}B \times i \times \text{Length} \times \text{Breadth} = \frac{B^2}{2\mu_0} \text{ per unit area.}$$

(Recall the formula  $F = BIl$  on a straight wire)

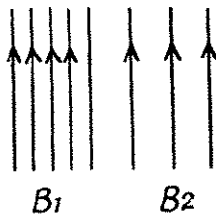


- 3.260 (a) The external field must be  $\frac{B_1 + B_2}{2}$ , which when superposed with the internal field  $\frac{B_1 - B_2}{2}$  (of opposite sign on the two sides of the plate) must give actual field. Now

$$\frac{B_1 - B_2}{2} = \frac{1}{2} \mu_0 i$$

or, 
$$i = \frac{B_1 - B_2}{\mu_0}$$

Thus, 
$$F = \frac{B_1^2 - B_2^2}{2\mu_0}$$

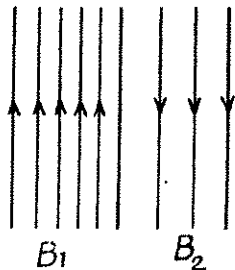


- (b) Here, the external field must be  $\frac{B_1 - B_2}{2}$  upward with an internal field,  $\frac{B_1 + B_2}{2}$ , upward on the left and downward on the right. Thus,

$$i = \frac{B_1 + B_2}{\mu_0} \text{ and } F = \frac{B_1^2 - B_2^2}{2\mu_0}.$$

- (c) Our boundary condition following from Gauss' law is,  $B_1 \cos \theta_1 = B_2 \cos \theta_2$ .

Also,  $(B_1 \sin \theta_1 + B_2 \sin \theta_2) = \mu_0 i$  where  $i$  = current per unit length.

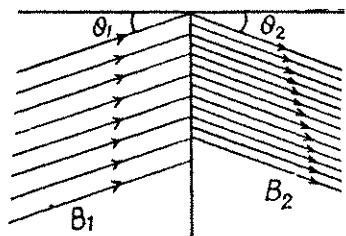


The external field parallel to the plate must be  $\frac{B_1 \sin \theta_1 - B_2 \sin \theta_2}{2}$

(The perpendicular component  $B_1 \cos \theta_1$ , does not matter since the corresponding force is tangential)

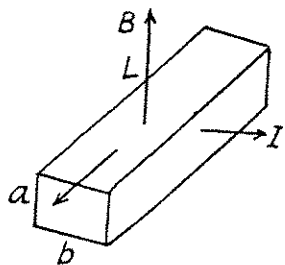
$$\begin{aligned} \text{Thus, } F &= \frac{B_1^2 \sin^2 \theta_1 - B_2^2 \sin^2 \theta_2}{2\mu_0} \text{ per unit area} \\ &= \frac{B_1^2 - B_2^2}{2\mu_0} \text{ per unit area.} \end{aligned}$$

The direction of the current in the plane conductor is perpendicular to the paper and beyond the drawing.



- 3.261 The Current density is  $\frac{I}{aL}$ , where  $L$  is the length of the section. The difference in pressure produced must be,

$$\Delta p = \frac{1}{aL} \times B \times (abL)/ab = \frac{IB}{a}$$



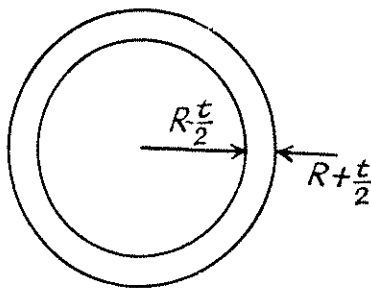
**3.262** Let  $t$  = thickness of the wall of the cylinder. Then,

$J = I/2\pi R t$  along  $z$  axis. The magnetic field due to this at a distance  $r$

$\left(R - \frac{t}{2} < r < R + \frac{t}{2}\right)$ , is given by,

$$B_{\phi}(2\pi r) = \mu_0 \frac{I}{2\pi R t} \pi \left\{ r^2 - \left(R - \frac{t}{2}\right)^2 \right\}$$

$$\text{or, } B_{\phi} = \frac{\mu_0 I}{4\pi R t} \left\{ r^2 - \left(R - \frac{t}{2}\right)^2 \right\}$$



$$\text{Now, } \vec{F} = \int \vec{J} \times \vec{B} dV$$

$$\text{and } p = \frac{F_r}{2\pi R L} = \frac{1}{2\pi R L} \int_{R - \frac{t}{2}}^{R + \frac{t}{2}} \frac{\mu_0 I^2}{8\pi^2 R^2 t^2 r} \left\{ r^2 - \left(R - \frac{t}{2}\right)^2 \right\} \times 2\pi r L dr$$

$$\begin{aligned} &= \frac{\mu_0 I^2}{8\pi^2 R^3 t^2} \int_{R - \frac{t}{2}}^{R + \frac{t}{2}} \left\{ r^2 - \left(R - \frac{t}{2}\right)^2 \right\} dr = \frac{\mu_0 I^2}{8\pi^2 R^3 t^2} \left[ \frac{\left(R + \frac{t}{2}\right)^3}{3} - \left(R - \frac{t}{2}\right)^3 - \left(R - \frac{t}{2}\right)^2 t \right] \\ &= \frac{\mu_0 I^2}{8\pi^2 R^3 t} [Rt + 0(t^2)] = \frac{\mu_0 I^2}{8\pi^2 R^2} \end{aligned}$$

**3.263** When self-forces are involved, a typical factor of  $\frac{1}{2}$  comes into play. For example, the force on a current carrying straight wire in a magnetic induction  $B$  is  $BIl$ . If the magnetic induction  $B$  is due to the current itself then the force can be written as,

$$F = \int_0^l B(l') dl'$$

If  $B(l') \propto l'$ , then this becomes,  $F = \frac{1}{2} B(l) Il$ .

In the present case,  $B(l) = \mu_0 n I$  and this acts on  $nI$  ampere turns per unit length, so,

$$\text{pressure } p = \frac{F}{\text{Area}} = \frac{1}{2} \mu_0 n \frac{I \times nI \times 1 \times l}{1 \times l} = \frac{1}{2} \mu_0 n^2 I^2$$

**3.264** The magnetic induction  $B$  in the solenoid is given by  $B = \mu_0 nI$ . The force on an element  $dl$  of the current carrying conductor is,

$$dF = \frac{1}{2} \mu_0 n I dl = \frac{1}{2} \mu_0 n I^2 dl$$

This is radially outwards. The factor  $\frac{1}{2}$  is explained above.

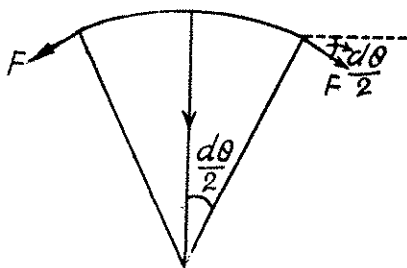
To relate  $dF$  to the tensile strength  $F_{\text{lim}}$  we proceed as follows. Consider the equilibrium of the element  $dl$ . The longitudinal forces  $F$  have a radial component equal to,

$$dF = 2F \sin \frac{d\theta}{2} = F d\theta$$

Thus using  $dl = R d\theta$ ,  $F = \frac{1}{2} \mu_0 n I^2 R$

This equals  $F_{\text{lim}}$  when,  $I = I_{\text{lim}} = \sqrt{\frac{2 F_{\text{lim}}}{\mu_0 n R}}$

Note that  $F_{\text{lim}}$ , here, is actually a force and not a stress.



**3.265** Resistance of the liquid between the plates =  $\frac{\rho d}{S}$

Voltage between the plates =  $Ed = v Bd$ ,

Current through the plates =  $\frac{v Bd}{R + \frac{\rho d}{S}}$

Power, generated, in the external resistance  $R$ ,

$$P = \frac{v^2 B^2 d^2 R}{\left(R + \frac{\rho d}{S}\right)^2} = \frac{v^2 B^2 d^2}{\left(\sqrt{R} + \frac{\rho d}{S \sqrt{R}}\right)^2} = \frac{v^2 B^2 d^2}{\left[\left(R^{1/4} - \left(\frac{\rho d}{S \sqrt{R}}\right)^{1/2}\right)^2 + 2 \sqrt{\frac{\rho d}{S}}\right]^2}$$

This is maximum when  $R = \frac{\rho d}{S}$  and  $P_{\text{max}} = \frac{v^2 B^2 S d}{4 \rho}$

**3.266** The electrons in the conductor are drifting with a speed of,

$$v_d = \frac{J}{ne} = \frac{I}{\pi R^2 ne},$$

where  $e$  = magnitude of the charge on the electron,  $n$  = concentration of the conduction electrons.

The magnetic field inside the conductor due to this current is given by,

$$B_\phi (2\pi r) = \pi r^2 \frac{I}{\pi R^2} \mu_0 \quad \text{or,} \quad B_\phi = \frac{\mu_0 I r}{2\pi R^2}$$

A radial electric field  $v B_\phi$  must come into being in equilibrium. Its P.D. is,

$$\Delta\phi = \int_0^R \frac{I}{\pi R^2 ne} \frac{\mu_0 I r}{2\pi R^2} dr = \frac{I}{\pi R^2 ne} \left( \frac{\mu_0}{4\pi} I \right) = \frac{\mu_0 I^2}{4 \pi R^2 ne}$$



3.267 Here,  $v_d = \frac{E}{B}$  and  $j = ne v_d$

$$\begin{aligned}\text{so, } n &= \frac{jB}{eE} = \frac{200 \times 10^4 \frac{\text{A}}{\text{m}^2} \times 1 \text{ T}}{1.6 \times 10^{-19} \text{ C} \times 5 \times 10^{-4} \text{ V/m}} \\ &= 2.5 \times 10^{28} \text{ per m}^3 = 2.5 \times 10^{22} \text{ per c.c.}\end{aligned}$$

Atomic weight of Na being 23 and its density  $\approx 1$ , molar volume is 23 c.c. Thus number of atoms per unit volume is  $\frac{6 \times 10^{23}}{23} = 2.6 \times 10^{22}$  per c.c.

Thus there is almost one conduction electron per atom.

3.268 By definition, mobility =  $\frac{\text{drift velocity}}{\text{Electric field component causing this drift}}$  or  $\mu = \frac{v}{E_L}$

On other hand,

$$E_T = vB = \frac{E_L}{\eta}, \text{ as given so, } \mu = \frac{1}{\eta B} = 3.2 \times 10^{-3} \text{ m}^2/(\text{V} \cdot \text{s})$$

3.269 Due to the straight conductor,  $B_\phi = \frac{\mu_0 I}{2\pi r}$

We use the formula,  $\vec{F} = (\vec{p}_m \cdot \vec{\nabla}) \vec{B}$

(a) The vector  $\vec{p}_m$  is parallel to the straight conductor.

$$\vec{F} = p_m \frac{\partial}{\partial z} \vec{B} = 0,$$

because neither the direction nor the magnitude of  $\vec{B}$  depends on  $z$

(b) The vector  $\vec{p}_m$  is oriented along the radius vector  $\vec{r}$

$$\vec{F} = p_m \frac{\partial}{\partial r} \vec{B}$$

The direction of  $\vec{B}$  at  $r + dr$  is parallel to the direction at  $r$ . Thus only the  $\phi$  component of  $\vec{F}$  will survive.

$$F_\phi = p_m \frac{\partial}{\partial r} \frac{\mu_0 I}{2\pi r} = -\frac{\mu_0 I p_m}{2\pi r^2}$$

(c) The vector  $\vec{p}_m$  coincides in direction with the magnetic field, produced by the conductor carrying current  $I$

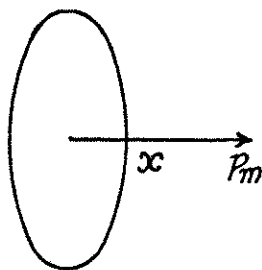
$$\vec{F} = p_m \frac{\partial}{\partial \phi} \frac{\mu_0 I}{2\pi} \vec{e}_\phi = \frac{\mu_0 I p_m}{2\pi r^2} \frac{\partial \vec{e}_\phi}{\partial \phi}$$

$$\text{So, } \vec{F} = -\frac{\mu_0 I p_m}{2\pi r^2} \vec{e}_r \quad \text{As, } \frac{\partial \vec{e}_\phi}{\partial \phi} = -\vec{e}_r$$

$$3.270 \quad F_x = p_m \frac{\partial}{\partial x} B_x$$

$$\text{But, } B_x = \frac{\mu_0 I}{4\pi} \int \frac{R dl}{(x^2 + R^2)^{3/2}} = \frac{\mu_0 I R^2}{2 (x^2 + R^2)^{3/2}}$$

$$\begin{aligned} \text{So, } F &= \frac{\mu_0}{4\pi} \frac{I \cdot 2\pi R^2}{(x^2 + R^2)^{5/2}} \cdot \frac{3}{2} \cdot 2x \cdot p_m \\ &= \frac{\mu_0}{4\pi} \frac{6\pi R^2 I p_m x}{(x^2 + R^2)^{5/2}} \end{aligned}$$



3.271

$$\begin{aligned} F &= P_{2m} \frac{\partial}{\partial l} \left[ \frac{\mu_0}{4\pi} \frac{3 \vec{p}_{1m} \cdot \vec{r} \vec{r} - \vec{p}_{1m} r^2}{r^5} \right] \\ &= P_{2m} \frac{\partial}{\partial l} \left[ \frac{\mu_0}{2\pi} \frac{p_{1m}}{l^3} \right] = \frac{-3}{2} \frac{\mu_0 p_{1m} P_{2m}}{\pi l^4} = 9 \text{ nN} \end{aligned}$$

3.272 From 3.270, for  $x \gg R$ ,

$$B_x \approx \frac{\mu_0 I' R^2}{2x^3}$$

$$\text{or, } I' \approx \frac{2B_x x^3}{\mu_0 R^2} = \frac{2 \times 3 \times 10^{-5} \text{ T} \times (10^{-1} \text{ m})^3}{1.26 \times 10^{-6} \times (10^{-2} \text{ m})^4} \approx 0.5 \text{ kA}$$

3.273

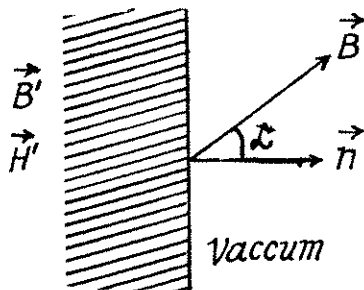
$$B'_n = B \cos \alpha,$$

$$H'_t = \frac{1}{\mu_0} B \sin \alpha,$$

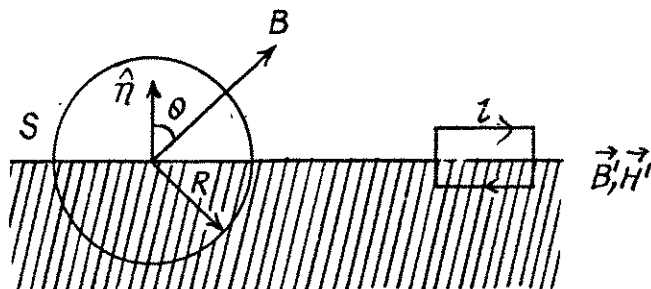
$$B'_t = \mu B \sin \alpha$$

so,

$$B' = B \sqrt{\mu^2 \sin^2 \alpha + \cos^2 \alpha}$$



$$3.274 \quad (a) \oint \vec{H} \cdot d\vec{S} = \oint \left( \frac{\vec{B}}{\mu_0} - \vec{J} \right) \cdot d\vec{S} = - \oint \vec{J} \cdot d\vec{S}, \text{ since } \oint \vec{B} \cdot d\vec{S} = 0$$

Now  $\vec{J}$  is nonvanishing only in the bottom half of the sphere.

Here,  $B'_n = B \cos \theta$ ,  $H'_t = \frac{1}{\mu_0} B \sin \theta$ ,  $B'_t = \mu B \sin \theta$ ,  $H'_n = \frac{B}{\mu \mu_0} \cos \theta$

$$J_n = \frac{B \cos \theta}{\mu_0} \left(1 - \frac{1}{\mu}\right) \text{ and } J_t = \frac{\mu - 1}{\mu_0} B \sin \theta.$$

Only  $J_n$  contributes the surface integral and

$$-\oint \vec{J} \cdot d\vec{S} = -\oint_{\text{lower}} \vec{J} \cdot d\vec{S} = \oint_{\text{lower}} J_n dS = \frac{\pi R^2 B \cos \theta}{\mu_0} \left(1 - \frac{1}{\mu}\right)$$

$$(b) \oint_{\Gamma} \vec{B} \cdot d\vec{r} = (B_t - B'_t) l = (1 - \mu) B l \sin \theta$$

**3.275** Inside the cylindrical wire there is an external current of density  $\frac{I}{\pi R^2}$ . This gives a magnetic field  $H_\varphi$  with

$$H_\varphi 2\pi r = I \frac{r^2}{R^2} \quad \text{or,} \quad H_\varphi = \frac{Ir}{2\pi R^2}$$

From this  $B_\varphi = \frac{\mu \mu_0 Ir}{2\pi R^2}$  and  $J_\varphi = \frac{\mu - 1}{2\pi} \frac{Ir}{R^2} = \frac{\chi Ir}{2\pi R^2} = \text{Magnetization.}$

Hence total volume molecular current is,

$$\oint_{r=R} \vec{J}_\varphi \cdot d\vec{r} = \int \frac{\chi I}{2\pi R} dl = \chi I$$

The surface current is obtained by using the equivalence of the surface current density to  $\vec{J} \times \vec{n}$ , this gives rise to a surface current density in the  $z$ -direction of  $-\frac{\chi I}{2\pi R}$

The total molecular surface current is,

$$I'_s = -\frac{\chi I}{2\pi R} (2\pi R) = -\chi I.$$

The two currents have opposite signs.

**3.276** We can obtain the form of the curves, required here, by qualitative arguments.

$$\text{From} \quad \oint \vec{H} \cdot d\vec{l} = I,$$

$$\text{we get} \quad H(x \gg 0) = H(x \ll 0) = nI$$

$$\text{Then} \quad B(x \gg 0) = \mu \mu_0 nI$$

$$B(x \ll 0) = \mu_0 nI$$

Also,

$$B(x < 0) = \mu_0 H(x < 0)$$

$$J(x < 0) = 0$$

$B$  is continuous at  $x = 0$ ,  $H$  is not. These give the required curves as shown in the answer-sheet.

3.277 The lines of the  $B$  as well as  $H$  field are circles around the wire. Thus

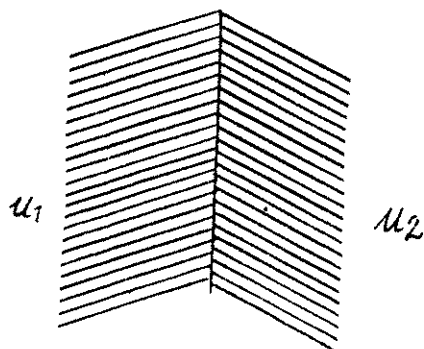
$$H_1 \pi r + H_2 \pi r = I \quad \text{or,} \quad H_1 + H_2 = \frac{I}{\pi r}$$

$$\text{Also } \mu_0 \mu_1 H_1 = \mu_2 H_2 \mu_0 = B_1 = B_2 = B$$

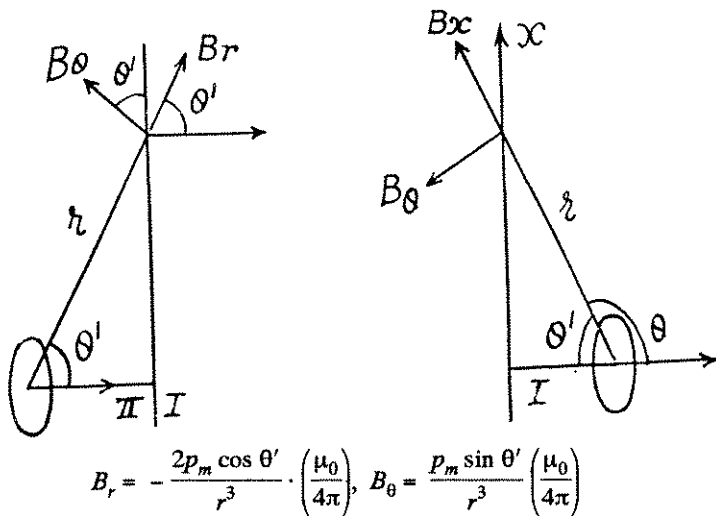
$$\text{Thus } H_1 = \frac{\mu_2}{\mu_1 + \mu_2} \frac{I}{\pi r},$$

$$H_2 = \frac{\mu_1}{\mu_1 + \mu_2} \frac{I}{\pi r}$$

$$\text{and } B = \mu_0 \frac{\mu_1 \mu_2}{\mu_1 + \mu_2} \frac{I}{\pi r}.$$



3.278 The medium I is vacuum and contains a circular current carrying coil with current  $I$ . The medium II is a magnetic with permeability  $\mu$ . The boundary is the plane  $z = 0$  and the coil is in the plane  $z = l$ . To find the magnetic induction, we note that the effect of the magnetic medium can be written as due to an image coil in II as far as the medium I is concerned. On the other hand, the induction in II can be written as due to the coil in I, carrying a different current. It is sufficient to consider the far away fields and ensure that the boundary conditions are satisfied there. Now for actual coil in medium I,



$$\text{so, } B_z = \frac{\mu_0 p_m}{4\pi} (2 \cos^2 \theta' - \sin^2 \theta') \quad \text{and} \quad B_x = \frac{\mu_0 p_m}{4\pi} (-3 \sin \theta' \cos \theta')$$

where  $p_m = I (\pi a^2)$ ,  $a$  = radius of the coil.

Similarly due to the image coil,

$$B_z = \frac{\mu_0 p'_m}{4\pi} (2 \cos^2 \theta' - \sin^2 \theta'), \quad B_x = \frac{\mu_0 p'_m}{4\pi} (3 \sin \theta' \cos \theta'), \quad p'_m = I' (\pi a^2)$$

As far as the medium II is concerned, we write similarly

$$B_z = \frac{\mu_0 p''_m}{4\pi} (2 \cos^2 \theta' - \sin^2 \theta'), \quad B_x = \frac{\mu_0 p''_m}{4\pi} (-3 \sin \theta' \cos \theta'), \quad p''_m = I'' (\pi a^2)$$

The boundary conditions are,  $p_m + p'_m = p''_m$  (from  $B_{1n} = B_{2n}$ )

$$-p_m + p'_m = -\frac{1}{\mu} p''_m \text{ (from } H_{1t} = H_{2t}\text{)}$$

Thus, 
$$I'' = \frac{2\mu}{\mu+1} I, \quad I' = \frac{\mu-1}{\mu+1} I$$

In the limit, when the coil is on the boundary, the magnetic field everywhere can be obtained by taking the current to be  $\frac{2\mu}{\mu+1} I$ . Thus,  $\vec{B} = \frac{2\mu}{\mu+1} \vec{B}_0$

**3.279** We use the fact that within an isolated uniformly magnetized ball,

$\vec{H}' = -\vec{J}/3$ ,  $\vec{B}' = \frac{2\mu_0 \vec{J}}{3}$ , where  $\vec{J}$  is the magnetization vector. Then in a uniform magnetic field with induction  $B_0$ , we have by superposition,

$$\vec{B}_{in} = \vec{B}_0 + \frac{2\mu_0 \vec{J}}{3}, \quad \vec{H}_{in} = \frac{\vec{B}_0}{\mu_0} - \vec{J}/3$$

or, 
$$\vec{B}_{in} + 2\mu_0 \vec{H}_{in} = 3\vec{B}_0$$

also, 
$$\vec{B}_{in} = \mu \mu_0 \vec{H}_{in}$$

Thus, 
$$\vec{H}_{in} = \frac{3\vec{B}_0}{\mu_0(\mu+2)} \text{ and } \vec{B}_{in} = \frac{3\mu\vec{B}_0}{\mu+2}$$

**3.280** The coercive force  $H_c$  is just the magnetic field within the cylinder. This is by circulation theorem,  $H_c = \frac{NI}{l} = 6 \text{ kA/m}$

(from  $\oint \vec{H} \cdot d\vec{r} = I$ , total current, considering a rectangular contour.)

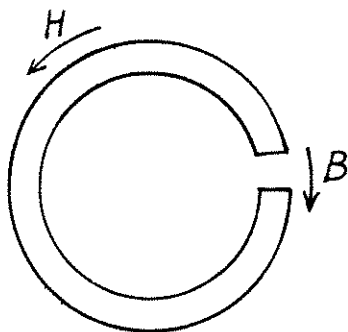
**3.281** We use,  $\oint \vec{H} \cdot d\vec{l} = 0$

Neglecting the fringing of the lines of force, we write this as

$$H(\pi d - b) + \frac{B}{\mu_0} b = 0$$

or, 
$$H = \frac{-Bb}{\mu_0 \pi d} = 101 \text{ A/m}$$

The sense of  $H$  is opposite to  $B$



**3.282** Here,  $\oint \vec{H} \cdot d\vec{l} = NI$  or,  $H(2\pi R) + \frac{Bb}{\mu_0} = NI$ , so,  $H = \frac{NI\mu_0 - Bb}{2\pi R\mu_0}$

Hence, 
$$\mu = \frac{B}{\mu_0 H} = \frac{2\pi RB}{\mu_0 NI - Bb} = 3700$$

**3.283** One has to draw the graph of  $\mu = \frac{B}{\mu_0 H}$  versus  $H$  from the given graph. The  $\mu - H$  graph starts out horizontally, and then rises steeply at about  $H = 0.04 \text{ kA/m}$  before falling again. It is easy to check that  $\mu_{\max} \approx 10,000$ .

3.284 From the theorem on circulation of vector  $\vec{H}$ .

$$H \pi d + \frac{B b}{\mu_0} = NI \quad \text{or, } B = \frac{\mu_0 N I}{b} - \frac{\mu_0 \pi d}{b} H = (1.51 - 0.987) H,$$

where  $B$  is in Tesla and  $H$  in kA/m. Besides,  $B$  and  $H$  are interrelated as in the Fig. 3.76 of the text. Thus we have to solve for  $B$ ,  $H$  graphically by simultaneously drawing the two curves (the hysteresis curve and the straight line, given above) and find the point of intersection. It is at

$$H \approx 0.26 \text{ kA/m, } B = 1.25 \text{ T}$$

Then,

$$\mu = \frac{B}{\mu_0 H} \approx 4000.$$

3.285 From the formula,

$$\vec{F} = (\vec{p}_m \cdot \vec{\nabla}) \vec{B} \rightarrow \vec{F} = P \int (\vec{J} \cdot \vec{\nabla}) \vec{B} dV,$$

Thus

$$\vec{F} = \frac{\chi}{\mu \mu_0} \int (\vec{B} \cdot \vec{\nabla}) \vec{B} dV$$

or since  $\vec{B}$  is predominantly along the  $x$ -axis,

$$F_x = \frac{\chi}{\mu \mu_0} \int B_x \frac{\partial B_x}{\partial x} S dx = \frac{\chi S}{2 \mu \mu_0} \int_{x=0}^{x=L} dB_x^2 = -\frac{\chi S B^2}{2 \mu \mu_0} \approx \frac{\chi S B^2}{2 \mu_0}$$

3.286 The force in question is,

$$\vec{F} = (\vec{p}_m \cdot \vec{\nabla}) \vec{B} = \frac{\chi B V}{\mu \mu_0} \frac{dB}{dx}$$

since  $B$  is essentially in the  $x$ -direction.

$$\text{So, } F_x \approx \frac{\chi V}{2 \mu_0} \frac{dB^2}{dx} = \frac{\chi B_0^2 V}{2 \mu_0} \frac{d}{dx} (e^{-2ax^2}) = -4ax e^{-2ax^2} \frac{\chi B_0^2}{2 \mu_0} V$$

This is maximum when its derivative vanishes

$$\text{i.e. } 16a^2 x^2 - 4a = 0, \quad \text{or, } x_m = \frac{1}{\sqrt{4a}}$$

The maximum force is,

$$F_{\max} = 4a \frac{1}{\sqrt{4a}} e^{-1/2} \frac{\chi B_0^2 V}{2 \mu_0} = \frac{\chi B_0^2 V}{\mu_0} \sqrt{\frac{a}{e}}$$

$$\text{So, } \chi = \left( \mu_0 F_{\max} \sqrt{\frac{e}{a}} \right) / V B_0^2 = 3.6 \times 10^{-4}$$

$$3.287 \quad F_x = (\vec{p}_m \cdot \vec{\nabla}) B_x = \frac{\chi B V}{\mu \mu_0} \frac{dB}{dx} \approx \frac{\chi V}{2 \mu_0} \frac{dB^2}{dx}$$

This force is attractive and an equal force must be applied for balance. The work done by applied forces is,

$$A = \int_{x=0}^{x=L} -F_x dx = \frac{\chi V}{2 \mu_0} (-B^2)_{x=0}^{x=L} \approx \frac{\chi V B^2}{2 \mu_0}$$

### 3.6 ELECTROMAGNETIC INDUCTION. MAXWELL'S EQUATIONS

**3.288** Obviously, from Lenz's law, the induced current and hence the induced e.m.f. in the loop is anticlockwise.

From Faraday's law of electromagnetic induction,

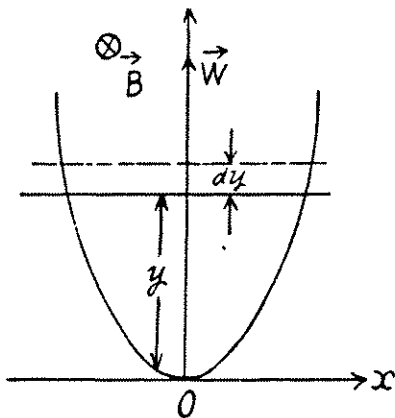
$$\xi_{in} = \left| \frac{d\Phi}{dt} \right|$$

Here,  $d\Phi = \vec{B} \cdot d\vec{S} = -2Bx dy$ ,

and from  $y = ax^2, x = \sqrt{\frac{y}{a}}$

Hence,  $\xi_{in} = 2B \sqrt{\frac{y}{a}} \frac{dy}{dt}$

$$= By \sqrt{\frac{8w}{a}}, \text{ using } \frac{dy}{dt} = \sqrt{2wy}$$

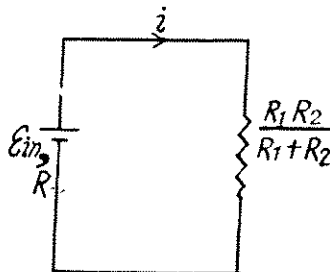


**3.289** Let us assume,  $\vec{B}$  is directed into the plane of the loop. Then the motional e.m.f.

$$\xi_{in} = \left| \int -(\vec{v} \times \vec{B}) \cdot d\vec{l} \right| = vBl$$

and directed in the same of  $(\vec{v} \times \vec{B})$  (Fig.)

So,  $i = \frac{\xi_{in}}{R + \frac{R_1 R_2}{R_1 + R_2}} = \frac{Bvl}{R + \frac{R_1 R_2}{R_1 + R_2}}$



As  $R_1$  and  $R_2$  are in parallel connections.

**3.290** (a) As the metal disc rotates, any free electron also rotates with it with same angular velocity  $\omega$ , and that's why an electron must have an acceleration  $\omega^2 r$  directed towards the disc's centre, where  $r$  is separation of the electron from the centre of the disc. We know from Newton's second law that if a particle has some acceleration then there must be a net effective force on it in the direction of acceleration. We also know that a charged particle can be influenced by two fields electric and magnetic. In our problem magnetic field is absent hence we reach at the conclusion that there is an electric field near any electron and is directed opposite to the acceleration of the electron.

If  $E$  be the electric field strength at a distance  $r$  from the centre of the disc, we have from Newton's second law.

$$F_n = m \omega_n^2 r$$

$$eE = m r \omega^2, \text{ or, } E = \frac{m \omega^2 r}{e},$$

and the potential difference,

$$\varphi_{cen} - \varphi_{rim} = \int_0^a \vec{E} \cdot d\vec{r} = \int_0^a \frac{m \omega^2 r}{e} dr, \text{ as } \vec{E} \uparrow \downarrow d\vec{r}$$

Thus  $\varphi_{cen} - \varphi_{rim} = \Delta \varphi = \frac{m \omega^2 a^2}{e} = 3.0 \text{ nV}$

(b) When field  $\vec{B}$  is present, by definition, of motional e.m.f. :

$$\varphi_1 - \varphi_2 = \int_1^2 -(\vec{v} \times \vec{B}) \cdot d\vec{r}$$

Hence the sought potential difference,

$$\varphi_{cen} - \varphi_{rim} = \int_0^a -v B dr = \int_0^a -\omega r B dr, \text{ (as } v = \omega r)$$

Thus  $\varphi_{rim} - \varphi_{cen} = \varphi = \frac{1}{2} \omega B a^2 = 20 \text{ mV}$

(In general  $\omega < \frac{eB}{m}$  so we can neglect the effect discussed in (1) here).

**3.291** By definition,

$$\vec{E} = -(\vec{v} \times \vec{B})$$

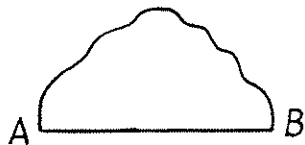
So, 
$$\int_A^C \vec{E} \cdot d\vec{r} = \int_A^C -(\vec{v} \times \vec{B}) \cdot d\vec{r} = \int_0^d -v B dr$$

But,  $v = \omega r$ , where  $r$  is the perpendicular distance of the point from A.

Hence, 
$$\int_A^C \vec{E} \cdot d\vec{r} = \int_0^d -\omega B r dr = -\frac{1}{2} \omega B d^2 = -10 \text{ mV}$$

This result can be generalized to a wire AC of arbitrary planar shape. We have

$$\begin{aligned} \int_A^C \vec{E} \cdot d\vec{r} &= - \int_A^C (\vec{v} \times \vec{B}) \cdot d\vec{r} = - \int_A^C ((\omega \times \vec{r}) \times \vec{B}) \cdot d\vec{r} \\ &= - \int_A^C (\vec{B} \cdot \vec{r} \omega - \vec{B} \cdot \omega \vec{r}) \cdot d\vec{r} \\ &= -\frac{1}{2} B \omega d^2, \end{aligned}$$



$d$  being AC and  $\vec{r}$  being measured from A.

**3.292** Flux at any moment of time,

$$|\Phi_t| = |\vec{B} \cdot d\vec{S}| = B \left( \frac{1}{2} R^2 \varphi \right)$$

where  $\varphi$  is the sector angle, enclosed by the field.

Now, magnitude of induced e.m.f. is given by,



$$\xi_{in} = \left| \frac{d\Phi_t}{dt} \right| = \left| \frac{BR^2}{2} \frac{d\varphi}{dt} \right| = \frac{BR^2}{2} \omega,$$

where  $\omega$  is the angular velocity of the disc. But as it starts rotating from rest at  $t = 0$  with an angular acceleration  $\beta$  its angular velocity  $\omega(t) = \beta t$ . So,

$$\xi_{in} = \frac{BR^2}{2} \beta t.$$

According to Lenz law the first half cycle current in the loop is in anticlockwise sense, and in subsequent half cycle it is in clockwise sense.

Thus in general,  $\xi_{in} = (-1)^n \frac{BR^2}{2} \beta t$ , where  $n$  is number of half revolutions.

The plot  $\xi_{in}(t)$ , where  $t_n = \sqrt{2\pi n/\beta}$  is shown in the answer sheet.

- 3.293** Field, due to the current carrying wire in the region, right to it, is directed into the plane of the paper and its magnitude is given by,

$$B = \frac{\mu_0 i}{2\pi r} \text{ where } r \text{ is the perpendicular distance from the wire.}$$

As  $B$  is same along the length of the rod thus motional e.m.f.

$$\xi_{in} = \left| - \int_1^2 (\vec{v} \times \vec{B}) \cdot d\vec{l} \right| = vBl$$

and it is directed in the sense of  $(\vec{v} \times \vec{B})$

So, current (induced) in the loop,

$$i_{in} = \frac{\xi_{in}}{R} = \frac{1}{2} \frac{\mu_0 I v l}{\pi R r}$$

- 3.294** Field, due to the current carrying wire, at a perpendicular distance  $x$  from it is given by,

$$B(x) = \frac{\mu_0 i}{2\pi x}$$

Motional e.m.f is given by  $\left| \int -(\vec{v} \times \vec{B}) \cdot d\vec{l} \right|$

There will be no induced e.m.f. in the segments (2) and (4)

as,  $\vec{v} \uparrow d\vec{l}$  and magnitude of e.m.f. induced in 1 and 3, will be

$$\xi_1 = v \left( \frac{\mu_0 i}{2\pi x} \right) a \text{ and } \xi_2 = v \left( \frac{\mu_0 i}{2\pi (a+x)} \right) a,$$

respectively, and their sense will be in the direction of  $(\vec{v} \times \vec{B})$ .

So, e.m.f., induced in the network =  $\xi_1 - \xi_2$  [as  $\xi_1 > \xi_2$ ]

$$= \frac{a v \mu_0 i}{2\pi} \left[ \frac{1}{x} - \frac{1}{a+x} \right] = \frac{v a^2 \mu_0 i}{2\pi x (a+x)}$$

**3.295** As the rod rotates, an emf.

$$\frac{d}{dt} \frac{1}{2} a^2 \theta \cdot B = \frac{1}{2} a^2 B \omega$$

is induced in it. The net current in the conductor is then  $\frac{\xi(t) - \frac{1}{2} a^2 B \omega}{R}$

A magnetic force will then act on the conductor of magnitude  $BI$  per unit length. Its direction will be normal to  $B$  and the rod and its torque will be

$$\int_0^a \left( \frac{\xi(t) - \frac{1}{2} a^2 B \omega}{R} \right) dx B x$$

Obviously both magnetic and mechanical torque acting on the C.M. of the rod must be equal but opposite in sense. Then

for equilibrium at constant  $\omega$

$$\frac{\xi(t) - \frac{1}{2} a^2 B \omega}{R} \cdot \frac{B a^2}{2} = \frac{1}{2} m g a \sin \omega t$$

$$\text{or, } \xi(t) = \frac{1}{2} a^2 B \omega + \frac{mgR}{aB} \sin \omega t = \frac{1}{2 a B} (a^3 B^2 \omega + 2 mg R \sin \omega t)$$

(The answer given in the book is incorrect dimensionally.)

**3.296** From Lenz's law, the current through the connector is directed from  $A$  to  $B$ . Here  $\xi_{in} = vBl$  between  $A$  and  $B$

where  $v$  is the velocity of the rod at any moment.

For the rod, from  $F_x = mw_x$

$$\text{or, } mg \sin \alpha - i l B = m w$$

For steady state, acceleration of the rod must be equal to zero.

$$\text{Hence, } mg \sin \alpha = i l B \quad (1)$$

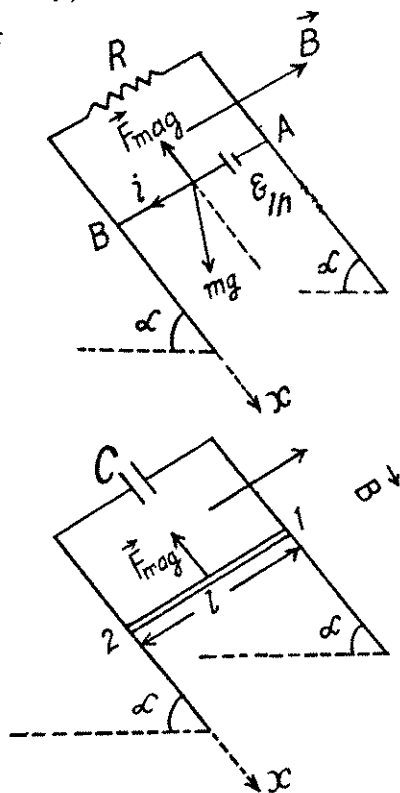
$$\text{But, } i = \frac{\xi_{in}}{R} = \frac{v B l}{R}$$

$$\text{From (1) and (2) } v = \frac{mg \sin \alpha R}{B^2 l^2}$$

**3.297** From Lenz's law, the current through the copper bar is directed from 1 to 2 or in other words, the induced current in the circuit is in clockwise sense.

Potential difference across the capacitor plates,

$$\frac{q}{C} = \xi_{in} \quad \text{or, } q = C \xi_{in}$$



Hence, the induced current in the loop,

$$i = \frac{dq}{dt} = C \frac{d\xi_{in}}{dt}$$

But the variation of magnetic flux through the loop is caused by the movement of the bar.

So, the induced e.m.f.  $\xi_{in} = B l v$

and, 
$$\frac{d\xi_{in}}{dt} = B l \frac{dv}{dt} = B l w$$

Hence, 
$$i = C \frac{d\xi}{dt} = C B l w$$

Now, the forces acting on the bars are the weight and the Ampere's force, where

$$F_{amp} = i l B (C B l w) \quad B = C l^2 B^2 w.$$

From Newton's second law, for the rod,  $F_x = m w_x$

or, 
$$mg \sin \alpha - C l^2 B^2 w = m w$$

Hence 
$$w = \frac{mg \sin \alpha}{C l^2 B^2 + m} = \frac{g \sin \alpha}{\frac{l^2 B^2 C}{1 + \frac{m}{C l^2 B^2}}}$$

1.298 Flux of  $\vec{B}$ , at an arbitrary moment of time  $t$  :

$$\Phi_t = \vec{B} \cdot \vec{S} = B \frac{\pi a^2}{2} \cos \omega t,$$

From Faraday's law, induced e.m.f.,  $\xi_{in} = - \frac{d\Phi}{dt}$

$$= - \frac{d \left( B \pi \frac{a^2}{2} \cos \omega t \right)}{dt} = \frac{B \pi a^2 \omega}{2} \sin \omega t.$$

and induced current, 
$$i_{in} = \frac{\xi_{in}}{R} = \frac{B \pi a^2 \omega}{2R} \sin \omega t.$$

Now thermal power, generated in the circuit, at the moment  $t = t$  :

$$P(t) = \xi_{in} \times i_{in} = \left( \frac{B \pi a^2 \omega}{2} \right)^2 \frac{1}{R} \sin^2 \omega t$$

and mean thermal power generated,

$$\langle P \rangle = \frac{\left[ \frac{B \pi a^2 \omega}{2} \right]^2 \frac{1}{R} \int_0^T \sin^2 \omega t \, dt}{\int_0^T dt} = \frac{1}{2R \left( \frac{\pi \omega a^2 B}{2} \right)^2}$$

**Note :** The calculation of  $\xi_{in}$  which can also be checked by using motional emf is correct even though the conductor is not a closed semicircle, for the flux linked to the rectangular part containing the resistance  $R$  is not changing. The answer given in the book is off by a factor  $1/4$ .

3.299 The flux through the coil changes sign. Initially it is  $BS$  per turn.

Finally it is  $-BS$  per turn. Now if flux is  $\Phi$  at an intermediate state then the current at that moment will be

$$i = \frac{-N \frac{d\Phi}{dt}}{R}$$

So charge that flows during a sudden turning of the coil is

$$q = \int i dt = -\frac{N}{R} [\Phi - (-\Phi)] = 2NBS/R$$

Hence,  $B = \frac{1}{2} \frac{qR}{NS} = 0.5 \text{ T}$  on putting the values.

3.300 According to Ohm's law and Faraday's law of induction, the current  $i_0$  appearing in the frame, during its rotation, is determined by the formula,

$$i_0 = -\frac{d\Phi}{dt} = -\frac{L di_0}{dt}$$

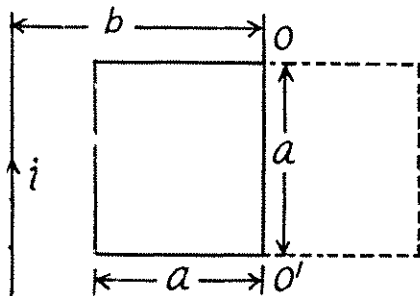
Hence, the required amount of electricity (charge) is,

$$q = \int i_0 dt = -\frac{1}{R} \int (d\Phi + L di_0) = -\frac{1}{R} (\Delta\Phi + L \Delta i_0)$$

Since the frame has been stopped after rotation, the current in it vanishes, and hence  $\Delta i_0 = 0$ .

It remains for us to find the increment of the flux  $\Delta\Phi$  through the frame ( $\Delta\Phi = \Phi_2 - \Phi_1$ ).

Let us choose the normal  $\vec{n}$  to the plane of the frame, for instance, so that in the final position,  $\vec{n}$  is directed behind the plane of the figure (along  $\vec{B}$ ).



Then it can be easily seen that in the final position,  $\Phi_2 > 0$ , while in the initial position,  $\Phi_1 < 0$  (the normal is opposite to  $\vec{B}$ ), and  $\Delta\Phi$  turns out to be simply equal to the flux through the surface bounded by the final and initial positions of the frame :

$$\Delta\Phi = \Phi_2 + |\Phi_1| = \int_{b-a}^{b+a} B a dr,$$

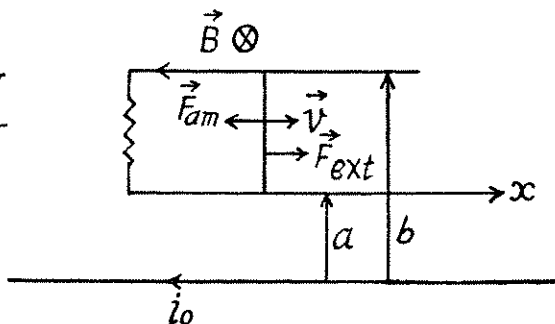
where  $B$  is a function of  $r$ , whose form can be easily found with the help of the theorem of circulation. Finally omitting the minus sign, we obtain,

$$q = \frac{\Delta\Phi}{R} = \frac{\mu_0 a i}{2\pi R} \ln \frac{b+a}{b-a}$$

3.301 As  $\vec{B}$ , due to the straight current carrying wire, varies along the rod (connector) and enters linearly so, to make the calculations simple,  $\vec{B}$  is made constant by taking its average value in the range  $[a, b]$ .

$$\langle B \rangle = \frac{\int_a^b B dr}{\int_a^b dr} = \frac{\int_a^b \frac{\mu_0 i_0}{2\pi r} dr}{\int_a^b dr}$$

$$\text{or, } \langle B \rangle = \frac{\mu_0}{2\pi} \frac{i_0}{(b-a)} \ln \frac{b}{a}$$



(a) The flux of  $\vec{B}$  changes through the loop due to the movement of the connector. According to Lenz's law, the current in the loop will be anticlockwise. The magnitude of motional e.m.f.,

$$\begin{aligned} \xi_{in} &= v \langle B \rangle (b-a) \\ &= \frac{\mu_0}{2\pi} \frac{i_0}{(b-a)} \ln \frac{b}{a} (b-a) \frac{dx}{dt} = \frac{\mu_0}{2\pi} i_0 \ln \frac{b}{a} v \end{aligned}$$

So, induced current

$$i_{in} = \frac{\xi_{in}}{R} = \frac{\mu_0}{2\pi} \frac{i_0 v}{R} \ln \frac{b}{a}$$

(b) The force required to maintain the constant velocity of the connector must be the magnitude equal to that of Ampere's acting on the connector, but in opposite direction.

$$\begin{aligned} \text{So, } F_{ext} &= i_{in} l \langle B \rangle = \left( \frac{\mu_0}{2\pi} \frac{i_0}{R} v \ln \frac{b}{a} \right) (b-a) \left( \frac{\mu_0}{2\pi} \frac{i_0}{(b-a)} \ln \frac{b}{a} \right) \\ &= \frac{v}{R} \left( \frac{\mu_0}{2\pi} i_0 \ln \frac{b}{a} \right)^2, \text{ and will be directed as shown in the (Fig.)} \end{aligned}$$

**3.302** (a) The flux through the loop changes due to the movement of the rod  $AB$ . According to Lenz's law current should be anticlockwise in sense as we have assumed  $\vec{B}$  is directed into the plane of the loop. The motion e.m.f  $\xi_{in}(t) = B l v$

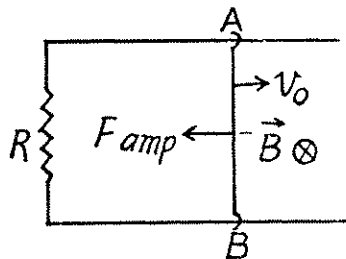
$$\text{and induced current } i_{in} = \frac{v B l}{R}$$

From Newton's law in projection form  $F_x = m w_x$

$$-F_{amp} = m \frac{v dv}{dx}$$

$$\text{But } F_{amp} = i_{in} l B = \frac{v B^2 l^2}{R}$$

$$\text{So, } -\frac{v B^2 l^2}{R} = m v \frac{dv}{dx}$$



or, 
$$\int_0^x dx = -\frac{mR}{B^2 l^2} \int_{v_0}^0 dv \quad \text{or, } x = \frac{mR v_0}{B^2 l^2}$$

(b) From equation of energy conservation;  $E_f - E_i + \text{Heat liberated} = A_{\text{cell}} + A_{\text{ext}}$

$$\left[ 0 - \frac{1}{2} m v_0^2 \right] + \text{Heat liberated} = 0 + 0$$

So, heat liberated =  $\frac{1}{2} m v_0^2$

**3.303** With the help of the calculation, done in the previous problem, Ampere's force on the connector,

$$\vec{F}_{\text{amp}} = \frac{v B^2 l^2}{R} \text{ directed towards left.}$$

Now from Newton's second law,

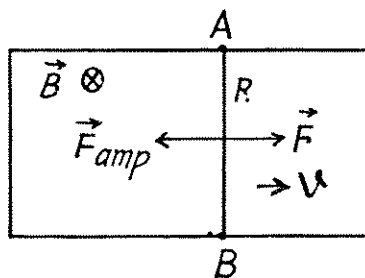
$$F - F_{\text{amp}} = m \frac{dv}{dt}$$

So, 
$$F = \frac{v B^2 l^2}{R} + m \frac{dv}{dt}$$

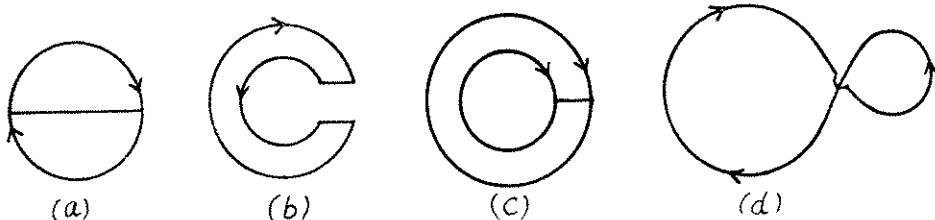
or, 
$$\int_0^t dt = m \int_0^v \frac{dv}{F - \frac{v B^2 l^2}{R}}$$

or, 
$$\frac{t}{m} = -\frac{R}{B^2 l^2} \ln \left( \frac{F - \frac{v B^2 l^2}{R}}{F} \right)$$

Thus 
$$v = \left( 1 - e^{-\frac{t B^2 l^2}{Rm}} \right) \frac{RF}{B^2 l^2}$$



**3.304** According to Lenz, the sense of induced e.m.f. is such that it opposes the cause of change of flux. In our problem, magnetic field is directed away from the reader and is diminishing.



So, in figure (a), in the round conductor, it is clockwise and there is no current in the connector

In figure (b) in the outside conductor, clockwise.

In figure (c) in both the conductor, clockwise; and there is no current in the connector to obey the charge conservation.

In figure (d) in the left side of the figure, clockwise.

- 3.305 The loops are connected in such a way that if the current is clockwise in one, it is anticlockwise in the other. Hence the e.m.f. in loop  $b$  opposes the e.m.f. in loop  $a$ .

$$\text{e.m.f. in loop } a = \frac{d}{dt}(a^2 B) = a^2 \frac{d}{dt}(B_0 \sin \omega t)$$

Similarly, e.m.f. in loop  $b = b^2 B_0 \omega \cos \omega t$ .

Hence, net e.m.f. in the circuit  $= (a^2 - b^2) B_0 \omega \cos \omega t$ , as both the e.m.f.'s are in opposite sense, and resistance of the circuit  $= 4(a + b) \rho$

Therefore, the amplitude of the current

$$= \frac{(a^2 - b^2) B_0 \omega}{4(a + b) \rho} = 0.5 \text{ A.}$$

- 3.306 The flat shape is made up of concentric loops, having different radii, varying from 0 to  $a$ .

Let us consider an elementary loop of radius  $r$ , then e.m.f. induced due to this loop

$$= \frac{-d(\vec{B} \cdot \vec{S})}{dt} = \pi r^2 B_0 \omega \cos \omega t.$$

and the total induced e.m.f.,

$$\xi_{ind} = \int_0^a (\pi r^2 B_0 \omega \cos \omega t) dN, \quad (1)$$

where  $\pi r^2 \omega \cos \omega t$  is the contribution of one turn of radius  $r$  and  $dN$  is the number of turns in the interval  $[r, r + dr]$ .

$$\text{So,} \quad dN = \left(\frac{N}{a}\right) dr \quad (2)$$

$$\text{From (1) and (2), } \xi = \int_0^a -(\pi r^2 B_0 \omega \cos \omega t) \frac{N}{a} dr = \frac{\pi B_0 \omega \cos \omega t N a^2}{3}$$

$$\text{Maximum value of e.m.f. amplitude } \xi_{max} = \frac{1}{3} \pi B_0 \omega N a^2$$

- 3.307 The flux through the loop changes due to the variation in  $\vec{B}$  with time and also due to the movement of the connector.

$$\text{So,} \quad \xi_{in} = \left| \frac{d(\vec{B} \cdot \vec{S})}{dt} \right| = \left| \frac{d(BS)}{dt} \right| \text{ as } \vec{S} \text{ and } \vec{B} \text{ are collinear}$$

But,  $B$ , after  $t$  sec. of beginning of motion  $= Bt$ , and  $S$  becomes  $= l \frac{1}{2} \omega t^2$ , as connector starts moving from rest with a constant acceleration  $\omega$ .

$$\text{So,} \quad \xi_{ind} = \frac{3}{2} B l \omega t^2$$

3.308 We use  $B = \mu_0 n I$

Then, from the law of electromagnetic induction

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi}{dt}$$

So, for  $r < a$

$$E_\varphi 2\pi r = -\pi r^2 \mu_0 n \dot{I} \quad \text{or,} \quad E_\varphi = -\frac{1}{2} \mu_0 n r \dot{I}. \quad (\text{where } I = dI/dt)$$

For  $r > a$

$$E_\varphi 2\pi r = -\pi a^2 \mu_0 n \dot{I} \quad \text{or,} \quad E_\varphi = -\mu_0 n \dot{I} a^2 / 2r$$

The meaning of minus sign can be deduced from Lenz's law.

3.309 The e.m.f. induced in the turn is  $\mu_0 n \dot{I} \pi \frac{d^2}{4}$

The resistance is  $\frac{\pi d}{S} \rho$ .

So, the current is  $\frac{\mu_0 n \dot{I} S d}{4 \rho} = 2 \text{ mA}$ , where  $\rho$  is the resistivity of copper.

3.310 The changing magnetic field will induce an e.m.f. in the ring, which is obviously equal, in the two parts by symmetry (the e.m.f. induced by electromagnetic induction does not depend on resistance). The current, that will flow due to this, will be different in the two parts. This will cause an acceleration of charge, leading to the setting up of an electric field  $E$  which has opposite sign in the two parts. Thus,

$$\frac{\xi}{2} - \pi a E = rI \quad \text{and} \quad \frac{\xi}{2} + \pi a E = \eta rI,$$

where  $\xi$  is the total induced e.m.f. From this,

$$\xi = (\eta + 1) rI,$$

and 
$$E = \frac{1}{2\pi a} (\eta - 1) rI = \frac{1}{2\pi a} \frac{\eta - 1}{\eta + 1} \xi$$

But by Faraday's law,  $\xi = \pi a^2 b$

so, 
$$E = \frac{1}{2} ab \frac{\eta - 1}{\eta + 1}$$

3.311 Go to the rotating frame with an instantaneous angular velocity  $\vec{\omega}(t)$ . In this frame, a Coriolis force,  $2m \vec{v}' \times \vec{\omega}(t)$

acts which must be balanced by the magnetic force,  $e \vec{v} \times \vec{B}(t)$

Thus, 
$$\vec{\omega}(t) = -\frac{e}{2m} \vec{B}(t).$$

(It is assumed that  $\vec{\omega}$  is small and varies slowly, so  $\omega^2$  and  $\dot{\omega}$  can be neglected.)



3.312 The solenoid has an inductance,

$$L = \mu_0 n^2 \pi b^2 l,$$

where  $n$  = number of turns of the solenoid per unit length. When the solenoid is connected to the source an e.m.f. is set up, which, because of the inductance and resistance, rises slowly, according to the equation,

$$RI + L \frac{dI}{dt} = V$$

This has the well known solution,

$$I = \frac{V}{R} (1 - e^{-tR/L}).$$

Corresponding to this current, an e.m.f. is induced in the ring. Its magnetic field

$B = \mu_0 n I$  in the solenoid, produces a force per unit length,  $\frac{dF}{dl} = B i = \mu_0^2 n^2 \pi a^2 I / r$

$$= \frac{\mu_0^2 \pi a^2 V^2}{r} \left( \frac{n^2}{RL} \right) e^{-tR/L} (1 - e^{-tR/L}),$$

acting on each segment of the ring. This force is zero initially and zero for large  $t$ . Its maximum value is for some finite  $t$ . The maximum value of

$$e^{-tR/L} (1 - e^{-tR/L}) = \frac{1}{4} - \left( \frac{1}{2} - e^{-tR/L} \right)^2 \text{ is } \frac{1}{4}.$$

So 
$$\frac{dF_{\max}}{dl} = \frac{\mu_0^2 \pi a^2 V^2}{r} \frac{n^2}{4RL} = \frac{\mu_0 a^2 V^2}{4rRlb^2}$$

3.313 The amount of heat generated in the loop during a small time interval  $dt$ ,

$$dQ = \xi^2 / R dt, \text{ but, } \xi = -\frac{d\Phi}{dt} = 2at - a\tau,$$

So, 
$$dQ = \frac{(2at - a\tau)^2}{R} dt$$

and hence, the amount of heat, generated in the loop during the time interval 0 to  $\tau$ .

$$Q = \int_0^\tau \frac{(2at - a\tau)^2}{R} dt = \frac{1}{3} \frac{a^2 \tau^3}{R}$$

3.314 Take an elementary ring of radius  $r$  and width  $dr$ .

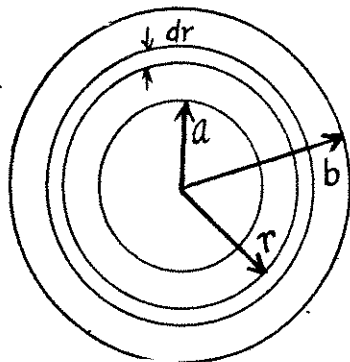
The e.m.f. induced in this elementary ring is  $\pi r^2 \beta$ .

Now the conductance of this ring is.

$$d\left(\frac{1}{R}\right) = \frac{h dr}{\rho 2 \pi r} \text{ so } dI = \frac{h r dr}{2 \rho} \beta$$

Integrating we get the total current,

$$I = \int_a^b \frac{h r dr}{2 \rho} \beta = \frac{h \beta (b^2 - a^2)}{4 \rho}$$



**3.315** Given  $L = \mu_0 n^2 V = \mu_0 n^2 l_0 \pi R^2$ , where  $R$  is the radius of the solenoid.

Thus, 
$$n = \sqrt{\frac{L}{\mu_0 l_0 \pi}} \frac{1}{R}.$$

So, length of the wire required is,

$$l = n l_0 2 \pi R = \sqrt{\frac{4 \pi L l_0}{\mu_0}} = 0.10 \text{ km}.$$

**3.316** From the previous problem, we know that,

$l' = \text{length of the wire needed} = \sqrt{\frac{L l 4 \pi}{\mu_0}}$ , where  $l = \text{length of solenoid here}.$

Now,  $R = \frac{\rho_0 l'}{S}$ , (where  $S = \text{area of cross section of the wire. Also } m = \rho S l')$

Thus, 
$$l' = \frac{R S}{\rho_0} = \frac{R m}{\rho \rho_0 l'} \quad \text{or} \quad l' = \sqrt{\frac{R m}{\rho \rho_0}}$$

where  $\rho_0 = \text{resistivity of copper and } \rho = \text{its density}.$

Equating, 
$$\frac{R m}{\rho \rho_0} = \frac{L l}{\mu_0 / 4 \pi}$$

or, 
$$L = \frac{\mu_0}{4 \pi} \frac{m R}{\rho \rho_0 l}$$

**3.317** The current at time  $t$  is given by,

$$I(t) = \frac{V}{R} (1 - e^{-tR/L})$$

The steady state value is,  $I_0 = \frac{V}{R}$

and 
$$\frac{I(t)}{I_0} = \eta = 1 - e^{-tR/L} \quad \text{or} \quad e^{-tR/L} = 1 - \eta$$

or, 
$$t_0 \frac{R}{L} = \ln \frac{1}{1 - \eta} \quad \text{or} \quad t_0 = \frac{L}{R} \ln \frac{1}{1 - \eta} = 1.49 \text{ s}$$

**3.318** The time constant  $\tau$  is given by

$$\tau = \frac{L}{R} = \frac{L}{\rho_0 \frac{S}{l_0}},$$

where,  $\rho_0 = \text{resistivity, } l_0 = \text{length of the winding wire, } S = \text{cross section of the wire}.$

But 
$$m = l \rho_0 S$$

So eliminating  $S, \tau = \frac{L}{\frac{\rho_0 l_0}{m/\rho l_0}} = \frac{mL}{\rho \rho_0 l_0^2}$

From problem 3.315  $l_0 = \frac{\sqrt{4\pi l L}}{\mu_0}$

(note the interchange of  $l$  and  $l_0$  because of difference in notation here.)

Thus, 
$$\tau = \frac{mL}{\rho \rho_0 \frac{4\pi}{\mu_0} L l} = \mu_0 4\pi \frac{m}{\rho \rho_0 l} = 0.7 \text{ ms,}$$

**3.319** Between the cables, where  $a < r < b$ , the magnetic field  $\vec{H}$  satisfies

$$H_\varphi 2\pi r = I \quad \text{or,} \quad H_\varphi = \frac{I}{2\pi r}$$

So 
$$B_\varphi = \frac{\mu \mu_0 I}{2\pi r}$$

The associated flux per unit length is, 
$$\Phi = \int_{r=a}^{r=b} \frac{\mu \mu_0 I}{2\pi r} \times 1 \times dr = \frac{\mu \mu_0 I}{2\pi} \ln \frac{b}{a}$$

Hence, the inductance per unit length  $L_1 = \frac{\Phi}{I} = \frac{\mu \mu_0}{2\pi} \ln \eta$ , where  $\eta = \frac{b}{a}$

We get  $L_1 = 0.26 \frac{\mu H}{m}$

**3.320** Within the solenoid,  $H_\varphi 2\pi r = NI$  or  $H_\varphi = \frac{NI}{2\pi r}$ ,  $B_\varphi = \mu \mu_0 \frac{NI}{2\pi r}$

and the flux,  $\Phi = N \Phi_1 = N \frac{\mu \mu_0}{2\pi} NI \int_b^{a+b} \frac{a dr}{r}$

Finally, 
$$L = \frac{\mu \mu_0}{2\pi} N^2 a \ln \left( 1 + \frac{a}{b} \right)$$

**3.321** Neglecting end effects the magnetic field  $B$ , between the plates, which is mainly parallel

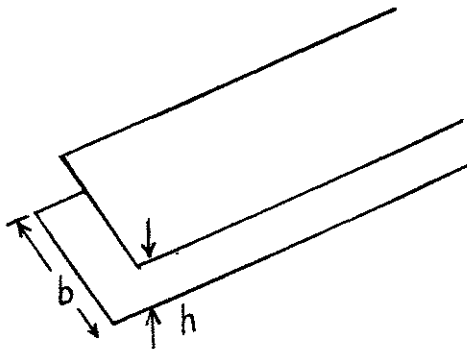
to the plates, is  $B = \mu_0 \frac{I}{b}$

(For a derivation see 3.229 b)

Thus, the associated flux per unit length of the plates is,

$$\Phi = \mu_0 \frac{I}{b} \times h \times 1 = \left( \mu_0 \frac{h}{b} \right) \times I.$$

So,  $L_1 = \text{inductance per unit length} = \mu_0 \frac{h}{b} = 25 \text{ nH/m.}$



**3.322** For a single current carrying wire,  $B_\varphi = \frac{\mu_0 I}{2\pi r}$  ( $r > a$ ). For the double line cable, with current, flowing in opposite directions, in the two conductors,

$B_\varphi \approx \frac{\mu_0 I}{\pi r}$ , between the cables, by superposition. The associated flux is,

$$\Phi = \int_a^{d-a} \frac{\mu_0 I}{\pi} \frac{dr \times 1}{r} \approx \frac{\mu_0 I}{\pi} \ln \frac{d}{a} = \frac{\mu_0}{\pi} \ln \eta \times I, \text{ per unit length}$$

Hence,  $L_1 = \frac{\mu_0}{\pi} \ln \eta$

is the inductance per unit length.

**3.323** In a superconductor there is no resistance, Hence,

$$L \frac{dI}{dt} = + \frac{d\Phi}{dt}$$

So integrating,  $I = \frac{\Delta\Phi}{L} = \frac{\pi a^2 B}{L}$

because  $\Delta\Phi = \Phi_f - \Phi_i$ ,  $\Phi_f = \pi a^2 B$ ,  $\Phi_i = 0$

Also, the work done is,  $A = \int \xi I dt = \int I dt \frac{d\Phi}{dt} = \frac{1}{2} L I^2 = \frac{1}{2} \frac{\pi^2 a^4 B^2}{L}$

**3.324** In a solenoid, the inductance  $L = \mu\mu_0 n^2 V = \mu\mu_0 \frac{N^2 S}{l}$ ,

where  $S$  = area of cross section of the solenoid,  $l$  = its length,  $V = Sl$ ,  $N = nl$  = total number of turns.

When the length of the solenoid is increased, for example, by pulling it, its inductance will decrease. If the current remains unchanged, the flux, linked to the solenoid, will also decrease. An induced e.m.f. will then come into play, which by Lenz's law will try to oppose the decrease of flux, for example, by increasing the current. In the superconducting state the flux will not change and so,

$$\frac{I}{l} = \text{constant}$$

Hence,  $\frac{I}{l} = \frac{I_0}{l_0}$ , or,  $I = I_0 \frac{l}{l_0} = I_0 (1 + \eta)$

**3.325** The flux linked to the ring can not change on transition to the superconduction state, for reasons, similar to that given above. Thus a current  $I$  must be induced in the ring, where,

$$I = \frac{\Phi}{L} = \frac{\pi a^2 B}{\mu_0 a \left( \ln \frac{8a}{b} - 2 \right)} = \frac{\pi a B}{\mu_0 \left( \ln \frac{8a}{b} - 2 \right)}$$

3.326 We write the equation of the circuit as,

$$Ri + \frac{L}{\eta} \frac{di}{dt} = \xi,$$

for  $t \geq 0$ . The current at  $t = 0$  just after inductance is changed, is

$i = \eta \frac{\xi}{R}$ , so that the flux through the inductance is unchanged.

We look for a solution of the above equation in the form

$$i = A + Be^{-\nu C}$$

Substituting  $C = \frac{L}{\eta R}$ ,  $B = \eta - 1$ ,  $A = \frac{\xi}{R}$

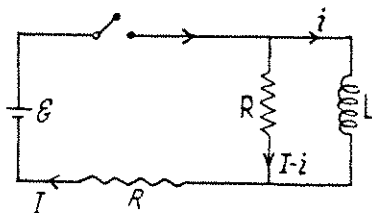
Thus, 
$$i = \frac{\xi}{R} (1 + (\eta - 1) e^{-\eta R/L})$$

3.327 Clearly,  $L \frac{di}{dt} = R(I - i) = \xi - Ri$

$$\text{So, } 2L \frac{di}{dt} = \xi - Ri$$

This equation has the solution (as in 3.312)

$$i = \frac{\xi}{R} (1 - e^{-tR/2L})$$



3.328 The equations are,

$$L_1 \frac{di_1}{dt} = L_2 \frac{di_2}{dt} = \xi - R(i_1 + i_2)$$

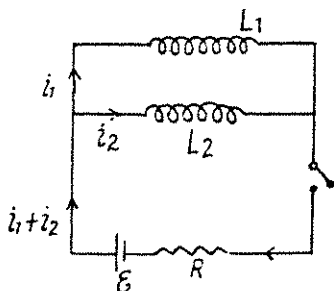
$$\text{Then, } \frac{d}{dt}(L_1 i_1 - L_2 i_2) = 0$$

$$\text{or, } L_1 i_1 - L_2 i_2 = \text{constant}$$

$$\text{But initially at } t = 0, i_1 = i_2 = 0$$

so constant must be zero and at all times,

$$L_1 i_1 = L_2 i_2$$



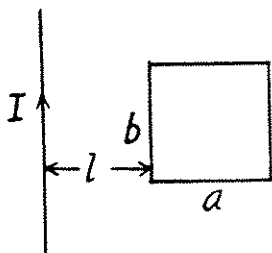
In the final steady state, current must obviously be  $i_1 + i_2 = \frac{\xi}{R}$ . Thus in steady state,

$$i_1 = \frac{\xi L_2}{R(L_1 + L_2)} \text{ and } i_2 = \frac{\xi L_1}{R(L_1 + L_2)}$$

3.329 Here,  $B = \frac{\mu_0 I}{2\pi r}$  at a distance  $r$  from the wire. The flux through the frame is obtained as,

$$\Phi_{12} = \int_l^{a+l} \frac{\mu_0 I}{2\pi r} b dr = \frac{\mu_0 b}{2\pi} I \ln\left(1 + \frac{a}{l}\right)$$

$$\text{Thus, } L_{12} = \frac{\Phi_{12}}{I} = \frac{\mu_0 b}{2\pi} \ln\left(1 + \frac{a}{l}\right)$$



3.330 Here also,  $B = \frac{\mu_0 I}{2 \pi r}$  and  $\Phi = \mu_0 \mu \frac{I}{2 \pi} \int_a^b \frac{h dr}{r} N$ .

Thus,  $L_{12} = \frac{\mu \mu_0 h N}{2 \pi} \ln \frac{b}{a}$

3.331 The direct calculation of the flux  $\Phi_2$  is a rather complicated problem, since the configuration of the field itself is complicated. However, the application of the reciprocity theorem simplifies the solution of the problem. Indeed, let the same current  $i$  flow through loop 2. Then the magnetic flux created by this current through loop 1 can be easily found.

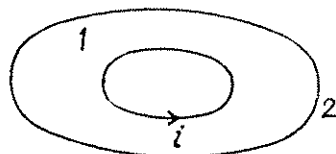
Magnetic induction at the centre of the loop, :  $B = \frac{\mu_0 i}{2b}$

So, flux through loop 1, :  $\Phi_{12} = \pi a^2 \frac{\mu_0 i}{2b}$

and from reciprocity theorem,

$$\Phi_{12} = \Phi_{21}, \quad \Phi_{21} = \frac{\mu_0 \pi a^2 i}{2b}$$

So,  $L_{12} = \frac{\Phi_{21}}{i} = \frac{1}{2} \mu_0 \pi a^2 / b$



3.332 Let  $\vec{p}_m$  be the magnetic moment of the magnet  $M$ . Then the magnetic field due to this magnet is,

$$\frac{\mu_0}{4\pi} \left[ \frac{3 (\vec{p}_m \cdot \vec{r}) \vec{r}}{r^5} - \frac{\vec{p}_m}{r^3} \right]$$

The flux associated with this, when the magnet is along the axis at a distance  $x$  from the centre, is

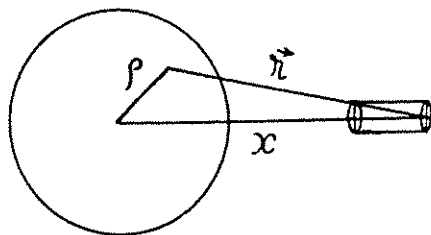
$$\Phi = \frac{\mu_0}{4\pi} \int \left[ \frac{3 (\vec{p}_m \cdot \vec{r}) \vec{r}}{r^5} - \frac{\vec{p}_m}{r^3} \right] \cdot d\vec{S} = \Phi_1 - \Phi_2$$

where,  $\Phi_2 = \frac{\mu_0}{4\pi} p_m \int_0^a \frac{2\pi \rho d\rho}{(x^2 + \rho^2)^{3/2}} = \frac{\mu_0 p_m}{2} \left( \frac{1}{x} - \frac{1}{\sqrt{x^2 + a^2}} \right)$

and  $\Phi_1 = \frac{3\mu_0 p_m x^2}{4\pi} \int_0^a \frac{2\pi \rho d\rho}{(x^2 + \rho^2)^{5/2}}$

$$= \frac{\mu_0 p_m x^2}{2} \left( \frac{1}{x^3} - \frac{1}{(x^2 + a^2)^{3/2}} \right)$$

So,  $\Phi = \frac{-\mu_0 p_m a^2}{2(x^2 + a^2)^{3/2}}$



When the flux changes, an e.m.f.  $-N \frac{d\Phi}{dt}$  is induced and a current  $-\frac{N}{R} \frac{d\Phi}{dt}$  flows. The total charge  $q$ , flowing, as the magnet is removed to infinity from  $x = 0$  is,

$$q = \frac{N}{R} \Phi(x=0) = \frac{N}{R} \cdot \frac{\mu_0 P_m}{2a}$$

or,

$$P_m = \frac{2aqR}{N\mu_0}$$

**3.333** If a current  $I$  flows in one of the coils, the magnetic field at the centre of the other coil is,

$$B = \frac{\mu_0 a^2 I}{2(l^2 + a^2)^{3/2}} = \frac{\mu_0 a^2 I}{2l^3}, \text{ as } l \gg a.$$

The flux associated with the second coil is then approximately  $\mu_0 \pi a^4 I / 2l^3$

Hence,

$$L_{12} = \frac{\mu_0 \pi a^4}{2l^3}$$

**3.334** When the current in one of the loop is  $I_1 = \alpha t$ , an e.m.f.  $L_{12} \frac{dI_1}{dt} = L_{12} \alpha$ , is induced in the other loop. Then if the current in the other loop is  $I_2$  we must have,

$$L_2 \frac{dI_2}{dt} + RI_2 = L_{12} \alpha$$

This familiar equation has the solution,

$$I_2 = \frac{L_{12} \alpha}{R} \left( 1 - e^{-\frac{tR}{L_2}} \right) \text{ which is the required current}$$

**3.335** Initially, after a steady current is set up, the current is flowing as shown.

In steady condition  $i_{20} = \frac{\xi}{R}$ ,  $i_{10} = \frac{\xi}{R_0}$ .

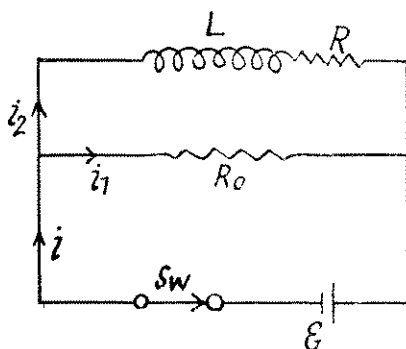
When the switch is disconnected, the current through  $R_0$  changes from  $i_{10}$  to the right, to  $i_{20}$  to the left. (The current in the inductance cannot change suddenly.). We then have the equation,

$$L \frac{di_2}{dt} + (R + R_0) i_2 = 0.$$

This equation has the solution  $i_2 = i_{20} e^{-t(R+R_0)/L}$

The heat dissipated in the coil is,

$$\begin{aligned} Q &= \int_0^\infty i_2^2 R dt = i_{20}^2 R \int_0^\infty e^{-2t(R+R_0)/L} dt \\ &= R i_{20}^2 \times \frac{L}{2(R+R_0)} = \frac{L \xi^2}{2R(R+R_0)} = 3 \mu \text{ J} \end{aligned}$$



- 3.336 To find the magnetic field energy we recall that the flux varies linearly with current. Thus, when the flux is  $\Phi$  for current  $i$ , we can write  $\Phi = A i$ . The total energy inclosed in the field, when the current is  $I$ , is

$$\begin{aligned} W &= \int \xi i \, dt = \int N \frac{d\Phi}{dt} i \, dt \\ &= \int N d\Phi i = \int_0^I N A i \, di = \frac{1}{2} N A I^2 = \frac{1}{2} N \Phi I \end{aligned}$$

The characteristic factor  $\frac{1}{2}$  appears in this way.

- 3.337 We apply circulation theorem,

$$H \cdot 2\pi b = NI, \quad \text{or,} \quad H = NI/2\pi b.$$

Thus the total energy,

$$W = \frac{1}{2} BH \cdot 2\pi b \cdot \pi a^2 = \pi^2 a^2 b BH.$$

Given  $N, I, b$  we know  $H$ , and can find out  $B$  from the  $B-H$  curve. Then  $W$  can be calculated.

- 3.338 From  $\oint \vec{H} \cdot d\vec{r} = NI$ ,

$$H \cdot \pi d + \frac{B}{\mu_0} \cdot b \approx NI, \quad (d \gg b)$$

Also,  $B = \mu \mu_0 H$ . Thus,  $H = \frac{NI}{\pi d + \mu b}$ .

Since  $B$  is continuous across the gap,  $B$  is given by,

$$B = \mu \mu_0 \frac{NI}{\pi d + \mu b}, \quad \text{both in the magnetic and the gap.}$$

$$(a) \quad \frac{W_{\text{gap}}}{W_{\text{magnetic}}} = \frac{\frac{B^2}{2\mu_0} \times S \times b}{\frac{B^2}{2\mu\mu_0} \times S \times \pi d} = \frac{\mu b}{\pi d}.$$

$$(b) \quad \text{The flux is } N \int \vec{B} \cdot d\vec{S} = N \mu \mu_0 \frac{NI}{\pi d + \mu b} \cdot S = \mu_0 \frac{S N^2 I}{b + \frac{\pi d}{\mu}},$$

So, 
$$L = \frac{\mu_0 S N^2}{b + \frac{\pi d}{\mu}}.$$

Energy wise; total energy

$$= \frac{B^2}{2\mu_0} \left( \frac{\pi d}{\mu} + b \right) S = \frac{1}{2} \frac{\mu_0 N^2 S}{b + \frac{\pi d}{\mu}} \cdot I^2 = \frac{1}{2} L I^2$$



The  $L$ , found in the one way, agrees with that, found in the other way. Note that, in calculating the flux, we do not consider the field in the gap, since it is not linked to the winding. But the total energy includes that of the gap.

- 3.339** When the cylinder with a linear charge density  $\lambda$  rotates with a circular frequency  $\omega$ , a surface current density (charge / length  $\times$  time) of  $i = \frac{\lambda\omega}{2\pi}$  is set up.

The direction of the surface current is normal to the plane of paper at  $Q$  and the contribution of this current to the magnetic field at  $P$  is

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{i(\vec{e} \times \vec{r})}{r^3} dS \text{ where } \vec{e} \text{ is the}$$

direction of the current. In magnitude,  $|\vec{e} \times \vec{r}| = r$ , since  $\vec{e}$  is normal to  $\vec{r}$  and the direction of  $d\vec{B}$  is as shown.

Its component,  $d\vec{B}_{\parallel}$  cancels out by cylindrical symmetry. The component that survives is,

$$|\vec{B}_{\perp}| = \frac{\mu_0}{4\pi} \int \frac{idS}{r^2} \cos \theta = \frac{\mu_0 i}{4\pi} \int d\Omega = \mu_0 i,$$

where we have used  $\frac{dS \cos \theta}{r^2} = d\Omega$  and  $\int d\Omega = 4\pi$ , the total solid angle around any point.

The magnetic field vanishes outside the cylinder by similar argument.

The total energy per unit length of the cylinder is,

$$W_1 = \frac{1}{2\mu_0} \mu_0^2 \left( \frac{\lambda\omega}{2\pi} \right)^2 \times \pi a^2 = \frac{\mu_0}{8\pi} a^2 \lambda^2 \omega^2$$

- 3.340**  $w_E = \frac{1}{2} \epsilon_0 E^2$ , for the electric field,

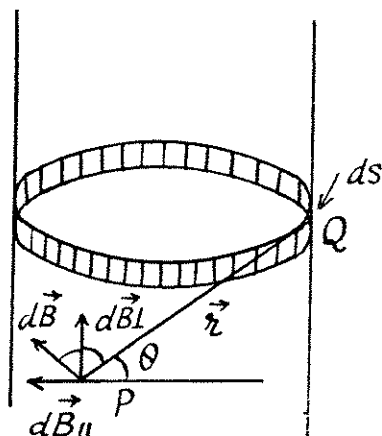
$$w_B = \frac{1}{2\mu_0} B^2 \text{ for the magnetic field.}$$

Thus, 
$$\frac{1}{2\mu_0} B^2 = \frac{1}{2} \epsilon_0 E^2,$$

when 
$$E = \frac{B}{\sqrt{\epsilon_0 \mu_0}} = 3 \times 10^8 \text{ V/m}$$

- 3.341** The electric field at  $P$  is,

$$E_P = \frac{ql}{4\pi \epsilon_0 (a^2 + l^2)^{3/2}}$$

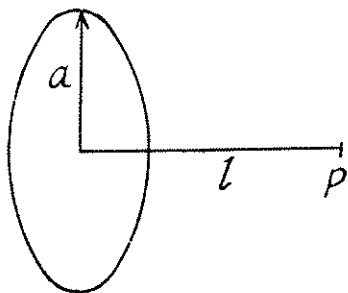


To get the magnetic field, note that the rotating ring constitutes a current  $i = q\omega/2\pi$ , and the corresponding magnetic field at  $P$  is,

$$B_P = \frac{\mu_0 a^2 i}{2(a^2 + l^2)^{3/2}}.$$

$$\begin{aligned}\text{Thus, } \frac{w_E}{w_M} &= \frac{\epsilon_0 \mu_0 E^2}{B^2} = \epsilon_0 \mu_0 \left( \frac{ql \times 2}{4\pi \epsilon_0 \mu_0 a^2 i} \right)^2 \\ &= \frac{1}{\epsilon_0 \mu_0} \left( \frac{l}{a^2 \omega} \right)^2\end{aligned}$$

$$\text{or, } \frac{w_M}{w_E} = \epsilon_0 \mu_0 \omega^2 a^4 / l^2$$



3.342 The total energy of the magnetic field is,

$$\begin{aligned}\frac{1}{2} \int (\vec{B} \cdot \vec{H}) dV &= \frac{1}{2} \int \vec{B} \cdot \left( \frac{\vec{B}}{\mu_0} - \vec{J} \right) dV \\ &= \frac{1}{2\mu_0} \int \vec{B} \cdot \vec{B} dV - \frac{1}{2} \int \vec{J} \cdot \vec{B} dV.\end{aligned}$$

The second term can be interpreted as the energy of magnetization, and has the density

$$-\frac{1}{2} \vec{J} \cdot \vec{B}.$$

3.343 (a) In series, the current  $I$  flows through both coils, and the total e.m.f. induced, when the current changes is,

$$-2L \frac{dI}{dt} = -L' \frac{dI}{dt}$$

or,

$$L' = 2L$$

(b) In parallel, the current flowing through either coil is,  $\frac{I}{2}$  and the e.m.f. induced is

$$-L \left( \frac{1}{2} \frac{dI}{dt} \right).$$

Equating this to  $-L' \frac{dI}{dt}$ , we find  $L' = \frac{1}{2} L$ .

3.344 We use  $L_1 = \mu_0 n_1^2 V$ ,  $L_2 = \mu_0 n_2^2 V$

So,

$$L_{12} = \mu_0 n_1 n_2 V = \sqrt{L_1 L_2}$$

3.345 The interaction energy is

$$\begin{aligned}\frac{1}{2\mu_0} \int |\vec{B}_1 + \vec{B}_2|^2 dV &- \frac{1}{2\mu_0} \int |\vec{B}_1|^2 dV - \frac{1}{2\mu_0} \int |\vec{B}_2|^2 dV \\ &= \frac{1}{\mu_0} \int \vec{B}_1 \cdot \vec{B}_2 dV\end{aligned}$$

Here, if  $\vec{B}_1$  is the magnetic field produced by the first of the current carrying loops, and  $\vec{B}_2$ , that of the second one, then the magnetic field due to both the loops will be  $\vec{B}_1 + \vec{B}_2$ .

3.346 We can think of the smaller coil as constituting a magnet of dipole moment,

$$p_m = \pi a^2 I_1$$

Its direction is normal to the loop and makes an angle  $\theta$  with the direction of the magnetic field, due to the bigger loop. This magnetic field is,

$$B_2 = \frac{\mu_0 I_2}{2b}$$

The interaction energy has the magnitude,

$$|W| = \frac{\mu_0 I_1 I_2}{2b} \pi a^2 \cos \theta$$

Its sign depends on the sense of the currents.

3.347 (a) There is a radial outward conduction current. Let  $Q$  be the instantaneous charge on the inner sphere, then,

$$j \times 4\pi r^2 = -\frac{dQ}{dt} \quad \text{or,} \quad \vec{j} = -\frac{1}{4\pi r^2} \frac{dQ}{dt} \hat{r}.$$

On the other hand  $\vec{j}_d = \frac{\partial \vec{D}}{\partial t} = \frac{d}{dt} \left( \frac{Q}{4\pi r^2} \hat{r} \right) = -\vec{j}$

(b) At the given moment,  $\vec{E} = \frac{q}{4\pi\epsilon_0\epsilon r^2} \hat{r}$

and by Ohm's law  $\vec{j} = \frac{\vec{E}}{\rho} = \frac{q}{4\pi\epsilon_0\epsilon\rho r^2} \hat{r}$

Then,  $\vec{j}_d = -\frac{q}{4\pi\epsilon_0\epsilon\rho r^2} \hat{r}$

and  $\oint \vec{j}_d \cdot d\vec{S} = -\frac{q}{4\pi\epsilon_0\epsilon\rho} \int \frac{dS \cos \theta}{r^2} = -\frac{q}{\epsilon_0\epsilon\rho}.$

The surface integral must be  $-ve$  because  $\vec{j}_d$ , being opposite of  $\vec{j}$ , is inward.

3.348 Here also we see that neglecting edge effects,  $\vec{j}_d = -\vec{j}$ . Thus Maxwell's equations reduce to,  $\text{div } \vec{B} = 0$ ,  $\text{Curl } \vec{H} = 0$ ,  $\vec{B} = \mu \vec{H}$

A general solution of this equation is  $\vec{B} = \text{constant} = \vec{B}_0$ .  $\vec{B}_0$  can be thought of as an extraneous magnetic field. If it is zero,  $\vec{B} = 0$ .

3.349 Given  $I = I_m \sin \omega t$ . We see that

$$j = \frac{I_m}{S} \sin \omega t = -j_d = -\frac{\partial D}{\partial t}$$

or,  $D = \frac{I_m}{\omega S} \cos \omega t$ , so,  $E_m = \frac{I_m}{\epsilon_0 \omega S}$  is the amplitude of the electric field and is

7 V/cm

**3.350** The electric field between the plates can be written as,

$$E = \operatorname{Re} \frac{V_m}{d} e^{i\omega t}, \text{ instead of } \frac{V_m}{d} \cos \omega t.$$

This gives rise to a conduction current,

$$j_c = \sigma E = \operatorname{Re} \frac{\sigma}{d} V_m e^{i\omega t}$$

and a displacement current,

$$j_d = \frac{\partial D}{\partial t} = \operatorname{Re} \epsilon_0 \epsilon i \omega \frac{V_m}{d} e^{i\omega t}$$

The total current is,

$$j_T = \frac{V_m}{d} \sqrt{\sigma^2 + (\epsilon_0 \epsilon \omega)^2} \cos(\omega t + \alpha)$$

where,  $\tan \alpha = \frac{\sigma}{\epsilon_0 \epsilon \omega}$  on taking the real part of the resultant.

The corresponding magnetic field is obtained by using circulation theorem,

$$H \cdot 2\pi r = \pi r^2 j_T$$

or,  $H = H_m \cos(\omega t + \alpha)$ , where,  $H_m = \frac{r V_m}{2d} \sqrt{\sigma^2 + (\epsilon_0 \epsilon \omega)^2}$

**3.351** Inside the solenoid, there is a magnetic field,

$$B = \mu_0 n I_m \sin \omega t.$$

Since this varies in time there is an associated electric field. This is obtained by using,

$$\oint_C \vec{E} \cdot d\vec{r} = -\frac{d}{dt} \int_S \vec{B} \cdot d\vec{S}$$

For  $r < R$ ,  $2\pi r E = -\dot{B} \cdot \pi r^2$ , or,  $E = -\frac{\dot{B} r}{2}$

For  $r > R$ ,  $E = -\frac{\dot{B} R^2}{2r}$

The associated displacement current density is,

$$j_d = \epsilon_0 \frac{\partial E}{\partial t} = \begin{bmatrix} -\epsilon_0 \dot{B} r/2 \\ -\epsilon_0 \dot{B} R^2/2r \end{bmatrix}$$

The answer, given in the book, is dimensionally incorrect without the factor  $\epsilon_0$ .

**3.352** In the non-relativistic limit

$$\vec{E} = \frac{q}{4\pi\epsilon_0 r^3} \vec{r}$$

(a) On a straight line coinciding with the charge path,

$$\vec{j}_d = \epsilon_0 \frac{\partial \vec{E}}{\partial t} = \frac{q}{4\pi} \left[ \frac{-\dot{\vec{V}}}{r^3} - \frac{3\vec{r}\dot{r}}{r^4} \right], \left( \text{using, } \frac{d\vec{r}}{dt} = -\vec{v} \right)$$

But in this case,  $\dot{r} = -v$  and  $v \frac{\vec{r}}{r} = \vec{v}$ , so,  $j_d = \frac{2 q v}{4 \pi r^3}$

(b) In this case,  $\dot{r} = 0$ , as,  $\vec{r} \perp \vec{v}$ . Thus,

$$j_d = -\frac{qv}{4 \pi r^3}$$

3.353 We have,  $E_p = \frac{qx}{4 \pi \epsilon_0 (a^2 + x^2)^{3/2}}$

then  $j_d = \frac{\partial D}{\partial t} = \epsilon_0 \frac{\partial E}{\partial t} = \frac{qv}{4 \pi (a^2 + x^2)^{5/2}} (a^2 - 2x^2)$

This is maximum, when  $x = x_m = 0$ , and minimum at some other value. The maximum displacement current density is

$$(j_d)_{\max} = \frac{qv}{4 \pi a^3}$$

To check this we calculate  $\frac{\partial j_d}{\partial x}$ ;

$$\frac{\partial j_d}{\partial x} = \frac{qv}{4 \pi} [ (-4x(a^2 + x^2) - 5x(a^2 - 2x^2)) ]$$

This vanishes for  $x = 0$  and for  $x = \sqrt{\frac{3}{2}} a$ . The latter is easily shown to be a smaller local minimum (negative maximum).

3.354 We use Maxwell's equations in the form,

$$\oint \vec{B} \cdot d\vec{r} = \epsilon_0 \mu_0 \frac{\partial}{\partial t} \int \vec{E} \cdot d\vec{S},$$

when the conduction current vanishes at the site.

We know that,

$$\begin{aligned} \int \vec{E} \cdot d\vec{S} &= \frac{q}{4 \pi \epsilon_0} \int \frac{d\vec{S} \cdot \hat{r}}{r^2} \\ &= \frac{q}{4 \pi \epsilon_0} \int d\Omega = \frac{q}{4 \pi \epsilon_0} 2 \pi (1 - \cos \theta), \end{aligned}$$

where,  $2\pi(1 - \cos \theta)$  is the solid angle, formed by the disc like surface, at the charge.

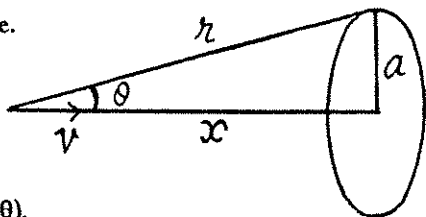
Thus,  $\oint \vec{B} \cdot d\vec{r} = 2 \pi a B = \frac{1}{2} \mu_0 q \cdot \sin \theta \cdot \dot{\theta}$

On the other hand,  $x = a \cot \theta$

differentiating and using  $\frac{dx}{dt} = -v$ ,

$$v = a \operatorname{cosec}^2 \theta \dot{\theta}$$

Thus,  $B = \frac{\mu_0 q v r \sin \theta}{4 \pi r^3}$



This can be written as,  $\vec{B} = \frac{\mu_0 q (\vec{v} \times \vec{r})}{4\pi r^3}$

and  $\vec{H} = \frac{q}{4\pi} \frac{\vec{v} \times \vec{r}}{r^3}$  (The sense has to be checked independently.)

3.355 (a) If  $\vec{B} = \vec{B}(t)$ , then,

$$\text{Curl } \vec{E} = -\frac{\partial \vec{B}}{\partial t} \neq 0.$$

So,  $\vec{E}$  cannot vanish.

(b) Here also,  $\text{curl } \vec{E} \neq 0$ , so  $\vec{E}$  cannot be uniform.

(c) Suppose for instance,  $\vec{E} = \vec{a}f(t)$

where  $\vec{a}$  is spatially and temporally fixed vector. Then  $-\frac{\partial \vec{B}}{\partial t} = \text{curl } \vec{E} = 0$ . Generally

speaking this contradicts the other equation  $\text{curl } \vec{H} = \frac{\partial \vec{D}}{\partial t} \neq 0$  for in this case the left hand side is time independent but RHS. depends on time. The only exception is when  $f(t)$  is linear function. Then a uniform field  $\vec{E}$  can be time dependent.

3.356 From the equation  $\text{Curl } \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{j}$

We get on taking divergence of both sides

$$-\frac{\partial}{\partial t} \text{div } \vec{D} = \text{div } \vec{j}$$

But  $\text{div } \vec{D} = \rho$  and hence  $\text{div } \vec{j} + \frac{\partial \rho}{\partial t} = 0$

3.357 From  $\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$

we get on taking divergence

$$0 = -\frac{\partial}{\partial t} \text{div } \vec{B}$$

This is compatible with  $\text{div } \vec{B} = 0$

3.358 A rotating magnetic field can be represented by,

$$B_x = B_0 \cos \omega t; B_y = B_0 \sin \omega t \text{ and } B_z = B_{z0}$$

Then  $\text{curl } \vec{E} = -\frac{\partial \vec{B}}{\partial t}$ .

$$\text{So, } -(\text{Curl } \vec{E})_x = -\omega B_0 \sin \omega t = -\omega B_y$$

$$-(\text{Curl } \vec{E})_y = \omega B_0 \cos \omega t = \omega B_x \text{ and } -(\text{Curl } \vec{E})_z = 0$$

$$\text{Hence, } \text{Curl } \vec{E} = -\vec{\omega} \times \vec{B},$$

$$\text{where, } \vec{\omega} = \vec{e}_3 \omega.$$

- 3.359** Consider a particle with charge  $e$ , moving with velocity  $\vec{v}$ , in frame  $K$ . It experiences a force  $\vec{F} = e\vec{v} \times \vec{B}$

In the frame  $K'$ , moving with velocity  $\vec{v}$ , relative to  $K$ , the particle is at rest. This means that there must be an electric field  $\vec{E}$  in  $K'$ , so that the particle experiences a force,

$$\vec{F}' = e\vec{E}' = \vec{F} = e\vec{v} \times \vec{B}$$

Thus,

$$\vec{E}' = \vec{v} \times \vec{B}$$

- 3.360** Within the plate, there will appear a  $(\vec{v} \times \vec{B})$  force, which will cause charges inside the plate to drift, until a countervailing electric field is set up. This electric field is related to  $B$ , by  $E = vB$ , since  $v$  &  $B$  are mutually perpendicular, and  $E$  is perpendicular to both. The charge density  $\pm \sigma$ , on the force of the plate, producing this electric field, is given by

$$E = \frac{\sigma}{\epsilon_0} \quad \text{or} \quad \sigma = \epsilon_0 v B = 0.40 \text{ pC/m}^2$$

- 3.361** Choose  $\vec{\omega} \uparrow \uparrow \vec{B}$  along the  $z$ -axis, and choose  $\vec{r}$ , as the cylindrical polar radius vector of a reference point (perpendicular distance from the axis). This point has the velocity,

$$\vec{v} = \vec{\omega} \times \vec{r},$$

and experiences a  $(\vec{v} \times \vec{B})$  force, which must be counterbalanced by an electric field,

$$\vec{E} = -(\vec{\omega} \times \vec{r}) \times \vec{B} = -(\vec{\omega} \cdot \vec{B}) \vec{r}.$$

There must appear a space charge density,

$$\rho = \epsilon_0 \text{div } \vec{E} = -2 \epsilon_0 \vec{\omega} \cdot \vec{B} = -8 \text{ pC/m}^3$$

Since the cylinder, as a whole is electrically neutral, the surface of the cylinder must acquire a positive charge of surface density,

$$\sigma = + \frac{2 \epsilon_0 (\vec{\omega} \cdot \vec{B}) \pi a^2}{2 \pi a} = \epsilon_0 a \vec{\omega} \cdot \vec{B} = +2 \text{ pC/m}^2$$

- 3.362** In the reference frame  $K'$ , moving with the particle,

$$\vec{E}' = \vec{E} + \vec{v}_0 \times \vec{B} = \frac{q \vec{r}}{4 \pi \epsilon_0 r^3}$$

$$\vec{B}' = \vec{B} - \vec{v}_0 \times \vec{E} / c^2 = 0.$$

Here,  $\vec{v}_0$  = velocity of  $K'$ , relative to the  $K$  frame, in which the particle has velocity  $\vec{v}$ .

Clearly,  $\vec{v}_0 = \vec{v}$ . From the second equation,

$$\vec{B} = \frac{\vec{v} \times \vec{E}}{c^2} = \epsilon_0 \mu_0 \times \frac{q}{4 \pi \epsilon_0} \frac{\vec{v} \times \vec{r}}{r^3} = \frac{\mu_0 q (\vec{v} \times \vec{r})}{4 \pi r^3}$$

**3.363** Suppose, there is only electric field  $\vec{E}$ , in  $K$ . Then in  $K'$ , considering nonrelativistic velocity

$$\vec{v}, \vec{E}' = \vec{E}, \vec{B} = -\frac{\vec{v} \times \vec{E}}{c^2},$$

So,

$$\vec{E}' \cdot \vec{B}' = 0$$

In the relativistic case,

$$\left. \begin{aligned} \vec{E}'_{\parallel} &= \vec{E}_{\parallel} \\ E'_{\perp} &= \frac{\vec{E}_{\perp}}{\sqrt{1-v^2/c^2}} \end{aligned} \right\} \begin{aligned} \vec{B}'_{\parallel} &= \vec{B}_{\parallel} = 0 \\ \vec{B}'_{\perp} &= \frac{-\vec{v} \times \vec{E}/c^2}{\sqrt{1-v^2/c^2}} \end{aligned}$$

Now,

$$\vec{E}' \cdot \vec{B}' = \vec{E}'_{\parallel} \cdot \vec{B}'_{\parallel} + \vec{E}'_{\perp} \cdot \vec{B}'_{\perp} = 0, \text{ since}$$

$$E'_{\perp} \cdot B'_{\perp} = -\vec{E}_{\perp} \cdot (\vec{v} \times \vec{E}) / (1 - v^2/c^2) = -\vec{E}_{\perp} \cdot (\vec{v} \times \vec{E}_{\perp}) / \left(1 - \frac{v^2}{c^2}\right) = 0$$

**3.364** In  $K$ ,  $\vec{B} = b \frac{y\hat{i} - x\hat{j}}{x^2 + y^2}$ ,  $b = \text{constant}$ .

$$\text{In } K', \vec{E}' = \vec{v} \times \vec{B} = bv \frac{y\hat{j} - x\hat{i}}{x^2 + y^2} = bv \frac{\vec{r}}{r^2}$$

The electric field is radial ( $\vec{r} = x\hat{i} + y\hat{j}$ ).

**3.365** In  $K$ ,  $\vec{E} = a \frac{\vec{r}}{r^2}$ ,  $\vec{r} = (x\hat{i} + y\hat{j})$

$$\text{In } K', \vec{B}' = -\frac{\vec{v} \times \vec{E}}{c^2} = \frac{a \vec{r} \times \vec{v}}{c^2 r^2}$$

The magnetic lines are circular.

**3.366** In the non relativistic limit, we neglect  $v^2/c^2$  and write,

$$\left. \begin{aligned} \vec{E}'_{\parallel} &= \vec{E}_{\parallel} \\ \vec{E}'_{\perp} &= \vec{E}_{\perp} + \vec{v} \times \vec{B} \end{aligned} \right\} \begin{aligned} \vec{B}'_{\parallel} &= \vec{B}_{\parallel} \\ \vec{B}'_{\perp} &= \vec{B}_{\perp} - \vec{v} \times \vec{E}/c^2 \end{aligned}$$

These two equations can be combined to give,

$$\vec{E}' = \vec{E} + \vec{v} \times \vec{B}, \vec{B}' = \vec{B} - \vec{v} \times \vec{E}/c^2$$

**3.367** Choose  $\vec{E}$  in the direction of the  $z$ -axis,  $\vec{E} = (0, 0, E)$ . The frame  $K'$  is moving with velocity  $\vec{v} = (v \sin \alpha, 0, v \cos \alpha)$ , in the  $x-z$  plane. Then in the frame  $K'$ ,

$$\vec{E}'_{\parallel} = \vec{E}_{\parallel}, \vec{B}'_{\parallel} = 0$$

$$\vec{E}'_{\perp} = \frac{\vec{E}_{\perp}}{\sqrt{1-v^2/c^2}}, \vec{B}'_{\perp} = \frac{-\vec{v} \times \vec{E}/c^2}{\sqrt{1-v^2/c^2}}$$

The vector along  $\vec{v}$  is  $\vec{e} = (\sin \alpha, 0, \cos \alpha)$  and the perpendicular vector in the  $x-z$  plane is,

$$\vec{f} = (-\cos \alpha, 0, \sin \alpha),$$



(a) Thus using  $\vec{E} = E \cos \alpha \vec{e} + E \sin \alpha \vec{f}$ ,

$$E'_{\parallel} = E \cos \alpha \text{ and } E'_{\perp} = \frac{E \sin \alpha}{\sqrt{1 - v^2/c^2}},$$

So  $E' = E \sqrt{\frac{1 - \beta^2 \cos^2 \alpha}{1 - \beta^2}}$  and  $\tan \alpha' = \frac{\tan \alpha}{\sqrt{1 - \beta^2}}$

$$(b) \quad B'_{\parallel} = 0, \quad B'_{\perp} = \frac{\vec{v} \times \vec{E}/c^2}{\sqrt{1 - v^2/c^2}}$$

$$B' = \frac{\beta E \sin \alpha}{c \sqrt{1 - \beta^2}}$$

3.368 Choose  $\vec{B}$  in the  $z$  direction, and the velocity  $\vec{v} = (v \sin \alpha, 0, v \cos \alpha)$  in the  $x - z$  plane, then in the  $K'$  frame,

$$\left. \begin{aligned} \vec{E}'_{\parallel} = \vec{E}_{\parallel} = 0 \\ \vec{E}'_{\perp} = \frac{\vec{v} \times \vec{B}}{\sqrt{1 - v^2/c^2}} \end{aligned} \right| \quad \left. \begin{aligned} \vec{B}'_{\parallel} = \vec{B}_{\parallel} \\ \vec{B}'_{\perp} = \frac{\vec{B}_{\perp}}{\sqrt{1 - v^2/c^2}} \end{aligned} \right.$$

We find similarly,  $E' = \frac{c \beta B \sin \alpha}{\sqrt{1 - \beta^2}}$

$$B' = B \sqrt{\frac{1 - \beta^2 \cos^2 \alpha}{1 - \beta^2}} \quad \tan \alpha' = \frac{\tan \alpha}{\sqrt{1 - \beta^2}}$$

3.369 (a) We see that,  $\vec{E}' \cdot \vec{B}' = \vec{E}'_{\parallel} \cdot \vec{B}'_{\parallel} + \vec{E}'_{\perp} \cdot \vec{B}'_{\perp}$

$$\begin{aligned} &= \vec{E}_{\parallel} \cdot \vec{B}_{\parallel} + \frac{(\vec{E}_{\perp} + \vec{v} \times \vec{B}) \cdot \left( \vec{B}_{\perp} - \frac{\vec{v} \times \vec{E}}{c^2} \right)}{1 - \frac{v^2}{c^2}} \\ &= \vec{E}_{\parallel} \cdot \vec{B}_{\parallel} + \frac{\vec{E}_{\perp} \cdot \vec{B}_{\perp} - (\vec{v} \times \vec{B}) \cdot (\vec{v} \times \vec{E})/c^2}{1 - v^2/c^2} \\ &= \vec{E}_{\parallel} \cdot \vec{B}_{\parallel} + \frac{\vec{E}_{\perp} \cdot \vec{B}_{\perp} - (\vec{v} \times \vec{B}_{\perp}) \cdot (\vec{v} \times \vec{E}_{\perp})/c^2}{1 - \frac{v^2}{c^2}} \end{aligned}$$

But,  $\vec{A} \times \vec{B} \cdot \vec{C} \times \vec{D} = A \cdot C B \cdot D - A \cdot D B \cdot C$ ,

$$\text{so, } \vec{E}' \cdot \vec{B}' = \vec{E}_{\parallel} \cdot \vec{B}_{\parallel} + \vec{E}_{\perp} \cdot \vec{B}_{\perp} \frac{\left(1 - \frac{v^2}{c^2}\right)}{1 - \frac{v^2}{c^2}} = \vec{E} \cdot \vec{B}$$

$$(b) \quad E'^2 - c^2 B'^2 = E_{\parallel}^2 - c^2 B_{\parallel}^2 + E_{\perp}^2 - c^2 B_{\perp}^2$$

$$\begin{aligned}
&= E_{\parallel}^2 - c^2 B_{\parallel}^2 + \frac{1}{1 - \frac{v^2}{c^2}} \left[ (\vec{E}_{\perp} + \vec{v} \times \vec{B})^2 - c^2 \left( \vec{B}_{\perp} - \frac{\vec{v} \times \vec{E}}{c^2} \right)^2 \right] \\
&= E_{\parallel}^2 - c^2 B_{\parallel}^2 + \frac{1}{1 - \frac{v^2}{c^2}} \left[ E_{\perp}^2 - c^2 B_{\perp}^2 + (\vec{v} \times \vec{B}_{\perp})^2 - \frac{1}{c^2} (\vec{v} \times \vec{E}_{\perp})^2 \right] \\
&= E_{\parallel}^2 - c^2 B_{\parallel}^2 + \frac{1}{1 - \frac{v^2}{c^2}} [E_{\perp}^2 - c^2 B_{\perp}^2] \left( 1 - \frac{v^2}{c^2} \right) = E^2 - c^2 B^2,
\end{aligned}$$

since,  $(\vec{v} \times \vec{A}_{\perp})^2 = v^2 A_{\perp}^2$

**3.370** In this case,  $\vec{E} \cdot \vec{B} = 0$ , as the fields are mutually perpendicular. Also,

$$E^2 - c^2 B^2 = -20 \times 10^8 \left( \frac{\text{V}}{\text{m}} \right)^2 \text{ is } -ve.$$

Thus, we can find a frame, in which  $E' = 0$ , and

$$B' = \frac{1}{c} \sqrt{c^2 B^2 - E^2} = B \sqrt{1 - \frac{E^2}{c^2 B^2}} = 0.20 \sqrt{1 - \left( \frac{4 \times 10^4}{3 \times 10^8 \times 2 \times 10^{-4}} \right)^2} = 0.15 \text{ mT}$$

**3.371** Suppose the charge  $q$  moves in the positive direction of the  $x$ -axis of the frame  $K$ . Let us go over to the moving frame  $K'$ , at whose origin the charge is at rest. We take the  $x$  and  $x'$  axes of the two frames to be coincident, and the  $y$  &  $y'$  axes, to be parallel.

In the  $K'$  frame,  $\vec{E} = \frac{1}{4 \pi \epsilon_0} \frac{q \vec{r}'}{r'^3}$ ,

and this has the following components,

$$E'_x = \frac{1}{4 \pi \epsilon_0} \frac{qx'}{r'^3}, \quad E'_y = \frac{1}{4 \pi \epsilon_0} \frac{qy'}{r'^3}.$$

Now let us go back to the frame  $K$ . At the moment, when the origins of the two frames coincide, we take  $t = 0$ . Then,

$$x = r \cos \theta = x' \sqrt{1 - \frac{v^2}{c^2}}, \quad y = r \sin \theta = y'$$

Also,  $E_x = E'_x, \quad E_y = E'_y / \sqrt{1 - v^2/c^2}$

From these equations,  $r'^2 = \frac{r^2 (1 - \beta^2 \sin^2 \theta)}{1 - \beta^2}$

$$\begin{aligned}
\vec{E} &= \frac{q}{4 \pi \epsilon_0} \frac{1}{r^3 (1 - \beta^2 \sin^2 \theta)^{3/2}} \left[ (1 - \beta^2)^{3/2} \left( x' \hat{i} + \frac{y'}{\sqrt{1 - \beta^2}} \hat{j} \right) \right] \\
&= \frac{q \vec{r} (1 - \beta^2)}{4 \pi \epsilon_0 r^3 (1 - \beta^2 \sin^2 \theta)^{3/2}}
\end{aligned}$$

### 3.7 MOTION OF CHARGED PARTICLES IN ELECTRIC AND MAGNETIC FIELDS

**3.372** Let the electron leave the negative plate of the capacitor at time  $t = 0$

As, 
$$E_x = -\frac{d\phi}{dx}, \quad E = \frac{\phi}{l} = \frac{at}{l},$$

and, therefore, the acceleration of the electron,

$$w = \frac{eE}{m} = \frac{eat}{ml} \quad \text{or,} \quad \frac{dv}{dt} = \frac{eat}{ml}$$

or, 
$$\int_0^v dv = \frac{ea}{ml} \int_0^t t dt, \quad \text{or,} \quad v = \frac{1}{2} \frac{ea}{ml} t^2 \quad (1)$$

But, from  $s = \int v dt$ ,

$$l = \frac{1}{2} \frac{ea}{ml} \int_0^t t^2 dt = \frac{eat^3}{6ml} \quad \text{or,} \quad t = \left( \frac{6ml^2}{ea} \right)^{\frac{1}{3}}$$

Putting the value of  $t$  in (1),

$$v = \frac{1}{2} \frac{ea}{ml} \left( \frac{6ml^2}{ea} \right)^{\frac{2}{3}} = \left( \frac{9}{2} \frac{ale}{m} \right)^{\frac{1}{3}} = 16 \text{ km/s.}$$

**3.373** The electric field inside the capacitor varies with time as,

$$E = at.$$

Hence, electric force on the proton,

$$F = eat$$

and subsequently, acceleration of the proton,

$$w = \frac{eat}{m}$$

Now, if  $t$  is the time elapsed during the motion of the proton between the plates, then

$t = \frac{l}{v_{\parallel}}$ , as no acceleration is effective in this direction. (Here  $v_{\parallel}$  is velocity along the length of the plate.)

From kinematics,  $\frac{dv_{\perp}}{dt} = w$

so, 
$$\int_0^{v_{\perp}} dv_{\perp} = \int_0^t w dt,$$

(as initially, the component of velocity in the direction,  $\perp$  to plates, was zero.)

or 
$$v_{\perp} = \int_0^t \frac{ea}{m} \frac{t^2}{2m} = \frac{ea}{2m} \frac{t^2}{v_{\parallel}^2}$$

Now, 
$$\tan \alpha = \frac{v_{\perp}}{v_{\parallel}} = \frac{e a l^2}{2 m v_{\parallel}^3}$$

$$= \frac{e a l^2}{2 m \left( \frac{2 e V}{m} \right)^{\frac{3}{2}}}, \text{ as } v_{\parallel} = \left( \frac{2 e V}{m} \right)^{\frac{1}{2}}, \text{ from energy conservation.}$$

$$= \frac{a l^2}{4} \sqrt{\frac{m}{2 e V^3}}$$

3.374 The equation of motion is,

$$\frac{dv}{dt} = v \frac{dv}{dx} = \frac{q}{m} (E_0 - ax)$$

Integrating

$$\frac{1}{2} v^2 - \frac{q}{m} (E_0 x - \frac{1}{2} ax^2) = \text{constant.}$$

But initially  $v = 0$  when  $x = 0$ , so "constant" = 0

Thus, 
$$v^2 = \frac{2q}{m} \left( E_0 x - \frac{1}{2} ax^2 \right)$$

Thus,  $v = 0$ , again for  $x = x_m = \frac{2 E_0}{a}$

The corresponding acceleration is,

$$\left( \frac{dv}{dt} \right)_{x_m} = \frac{q}{m} (E_0 - 2 E_0) = - \frac{q E_0}{m}$$

3.375 From the law of relativistic conservation of energy

$$\frac{m_0 c^2}{\sqrt{1 - (v^2/c^2)}} - e Ex = m_0 c^2.$$

as the electron is at rest ( $v = 0$  for  $x = 0$ ) initially.

Thus clearly 
$$T = e Ex.$$

On the other hand, 
$$\sqrt{1 - (v^2/c^2)} = \frac{m_0 c^2}{m_0 c^2 + e Ex}$$

or, 
$$\frac{v}{c} = \frac{\sqrt{(m_0 c^2 + e Ex)^2 - m_0^2 c^4}}{m_0 c^2 + e Ex}$$

or, 
$$ct = \int c dt = \int \frac{(m_0 c^2 + e Ex) dx}{\sqrt{(m_0 c^2 + e Ex)^2 - m_0^2 c^4}}$$

$$= \frac{1}{2eE} \int \frac{dy}{\sqrt{y - m_0^2 c^4}} = \frac{1}{eE} \sqrt{(m_0 c^2 + eEx)^2 - m_0^2 c^4} + \text{constant}$$

The "constant" = 0, at  $t = 0$ , for  $x = 0$ ,

$$\text{So,} \quad ct = \frac{1}{eE} \sqrt{(m_0 c^2 + eEx)^2 - m_0^2 c^4}.$$

Finally, using  $T = eEx$ ,

$$ceEt_0 = \sqrt{T(T + 2m_0 c^2)} \quad \text{or,} \quad t_0 = \frac{\sqrt{T(T + 2m_0 c^2)}}{eEc}$$

3.376 As before,  $T = eEx$

Now in linear motion,

$$\begin{aligned} \frac{d}{dt} \frac{m_0 v}{\sqrt{1 - v^2/c^2}} &= \frac{m_0 w}{\sqrt{1 - v^2/c^2}} + \frac{m_0 w}{(1 - v^2/c^2)^{3/2}} \frac{v}{c^2} w \\ &= \frac{m_0}{(1 - v^2/c^2)^{3/2}} w = \frac{(T + m_0 c^2)^3}{m_0^2 c^6} w = eE, \end{aligned}$$

$$\text{So,} \quad w = \frac{eEm_0^2 c^6}{(T + m_0 c^2)^3} = \frac{eE}{m_0} \left( 1 + \frac{T}{m_0 c^2} \right)^{-3}$$

3.377 The equations are,

$$\frac{d}{dt} \left( \frac{m_0 v_x}{\sqrt{1 - (v^2/c^2)}} \right) = 0 \quad \text{and} \quad \frac{d}{dt} \left( \frac{m_0 v_y}{\sqrt{1 - v^2/c^2}} \right) = eE$$

$$\text{Hence,} \quad \frac{v_x}{\sqrt{1 - v^2/c^2}} = \text{constant} = \frac{v_0}{\sqrt{1 - (v_0^2/c^2)}}$$

Also, by energy conservation,

$$\frac{m_0 c^2}{\sqrt{1 - (v^2/c^2)}} = \frac{m_0 c^2}{\sqrt{1 - (v_0^2/c^2)}} + eEy$$

$$\text{Dividing} \quad v_x = \frac{v_0 \epsilon_0}{\epsilon_0 + eEy}, \quad \epsilon_0 = \frac{m_0 c^2}{\sqrt{1 - (v_0^2/c^2)}}$$

$$\text{Also,} \quad \frac{m_0}{\sqrt{1 - (v^2/c^2)}} = \frac{\epsilon_0 + eEy}{c^2}$$

$$\text{Thus,} \quad (\epsilon_0 + eEy) v_y = c^2 eEt + \text{constant.}$$

"constant" = 0 as  $v_y = 0$  at  $t = 0$ .

Integrating again,

$$\epsilon_0 y + \frac{1}{2} eE y^2 = \frac{1}{2} c^2 E t^2 + \text{constant.}$$

"constant" = 0, as  $y = 0$ , at  $t = 0$ .

$$\text{Thus, } (ceEt)^2 = (eyE)^2 + 2\epsilon_0 eEy + \epsilon_0^2 - \epsilon_0^2$$

$$\text{or, } ceEt = \sqrt{(\epsilon_0 + eEy)^2 - \epsilon_0^2}$$

$$\text{or, } \epsilon_0 + eEy = \sqrt{\epsilon_0^2 + c^2 e^2 E^2 t^2}$$

$$\text{Hence, } v_x = \frac{v_0 \epsilon_0}{\sqrt{\epsilon_0^2 + c^2 e^2 E^2 t^2}} \quad \text{also, } v_y = \frac{c^2 e E t}{\sqrt{\epsilon_0^2 + c^2 e^2 E^2 t^2}}$$

$$\text{and } \tan \theta = \frac{v_y}{v_x} = \frac{eEt}{m_0 v_0} \sqrt{1 - (v_0^2/c^2)}.$$

**3.378** From the figure,

$$\sin \alpha = \frac{d}{R} = \frac{dqB}{mv},$$

As radius of the arc  $R = \frac{mv}{qB}$ , where  $v$  is the velocity of the particle, when it enters into the field. From initial condition of the problem,

$$qV = \frac{1}{2}mv^2 \quad \text{or, } v = \sqrt{\frac{2qV}{m}}$$

$$\text{Hence, } \sin \alpha = \frac{dqB}{m \sqrt{\frac{2qV}{m}}} = dB \sqrt{\frac{q}{2mV}}$$

$$\text{and } \alpha = \sin^{-1} \left( dB \sqrt{\frac{q}{2mV}} \right) = 30^\circ, \text{ on putting the values.}$$

**3.379** (a) For motion along a circle, the magnetic force acted on the particle, will provide the centripetal force, necessary for its circular motion.

$$\text{i.e. } \frac{mv^2}{R} = evB \quad \text{or, } v = \frac{eBR}{m}$$

$$\text{and the period of revolution, } T = \frac{2\pi}{\omega} = \frac{2\pi R}{v} = \frac{2\pi m}{eB}$$

$$(b) \text{ Generally, } \frac{d\vec{p}}{dt} = \vec{F}$$

$$\text{But, } \frac{d\vec{p}}{dt} = \frac{d}{dt} \frac{m_0 \vec{v}}{\sqrt{1 - (v^2/c^2)}} = \frac{m_0 \dot{\vec{v}}}{\sqrt{1 - (v^2/c^2)}} + \frac{m_0}{(1 - (v^2/c^2))^{3/2}} \frac{\vec{v}(\vec{v} \cdot \dot{\vec{v}})}{c^2}$$

For transverse motion,  $\vec{v} \cdot \dot{\vec{v}} = 0$  so,

$$\frac{d\vec{p}}{dt} = \frac{m_0 \dot{\vec{v}}}{\sqrt{1 - (v^2/c^2)}} = \frac{m_0}{\sqrt{1 - (v^2/c^2)}} \frac{v^2}{r}, \text{ here.}$$

Thus, 
$$\frac{m_0 v^2}{r \sqrt{1 - (v^2/c^2)}} = B e v \quad \text{or,} \quad \frac{v/c}{\sqrt{1 - (v^2/c^2)}} = \frac{B e r}{m_0 c}$$

or, 
$$\frac{v}{c} = \frac{B e r}{\sqrt{B^2 e^2 r^2 + m_0^2 c^2}}$$

Finally, 
$$T = \frac{2 \pi r}{v} = \frac{2 \pi m_0}{e B \sqrt{1 - v^2/c^2}} = \frac{2 \pi}{c B e} \sqrt{B^2 e^2 r^2 + m_0^2 c^2}$$

3.380 (a) As before,  $p = B q r$ .

(b) 
$$T = \sqrt{c^2 p^2 + m_0^2 c^4} = \sqrt{c^2 B^2 q^2 r^2 + m_0^2 c^4}$$

(c) 
$$w = \frac{v^2}{r} = \frac{c^2}{r \left[ 1 + (m_0 c / B q r)^2 \right]}$$

using the result for  $v$  from the previous problem.

3.381 From (3.279),

$$T = \frac{2 \pi \epsilon}{c^2 e B} \text{ (relativistic),} \quad T_0 = \frac{2 \pi m_0 c^2}{c^2 e B} \text{ (nonrelativistic),}$$

Here, 
$$m_0 c^2 / \sqrt{1 - v^2/c^2} = E$$

Thus, 
$$\delta T = \frac{2 \pi T}{c^2 e B}, \quad (T = K.E.)$$

Now, 
$$\frac{\delta T}{T_0} = \eta = \frac{T}{m_0 c^2}, \quad \text{so,} \quad T = \eta m_0 c^2$$

3.382 
$$T = eV = \frac{1}{2} m v^2$$

(The given potential difference is not large enough to cause significant deviations from the nonrelativistic formula).

Thus, 
$$v = \sqrt{\frac{2eV}{m}}$$

So, 
$$v_{\parallel} = \sqrt{\frac{2eV}{m}} \cos \alpha, \quad v_{\perp} = \sqrt{\frac{2eV}{m}} \sin \alpha$$

Now, 
$$\frac{m v_{\perp}^2}{r} = B e v_{\perp} \quad \text{or,} \quad r = \frac{m v_{\perp}}{B e},$$

and 
$$T = \frac{2 \pi r}{v_{\perp}} = \frac{2 \pi m}{B e}$$

Pitch 
$$p = v_{\parallel} T = \frac{2 \pi m}{B e} \sqrt{\frac{2eV}{m}} \cos \alpha = 2 \pi \sqrt{\frac{2mV}{eB^2}} \cos \alpha$$

3.383 The charged particles will traverse a helical trajectory and will be focussed on the axis after traversing a number of turns. Thus

$$\frac{l}{v_0} = n \cdot \frac{2\pi m}{qB_1} = (n+1) \frac{2\pi m}{qB_2}$$

So, 
$$\frac{n}{B_1} = \frac{n+1}{B_2} = \frac{1}{B_2 - B_1}$$

Hence, 
$$\frac{l}{v_0} = \frac{2\pi m}{q(B_2 - B_1)}$$

or, 
$$\frac{l^2}{2qV/m} = \frac{(2\pi)^2}{(B_2 - B_1)^2} \times \frac{1}{(q/m)^2}$$

or, 
$$\frac{q}{m} = \frac{8\pi^2 V}{l^2 (B_2 - B_1)^2}$$

3.384 Let us take the point  $A$  as the origin  $O$  and the axis of the solenoid as  $z$ -axis. At an arbitrary moment of time let us resolve the velocity of electron into its two rectangular components,  $\vec{v}_{\parallel}$  along the axis and  $\vec{v}_{\perp}$  to the axis of solenoid. We know the magnetic force does no work, so the kinetic energy as well as the speed of the electron  $|\vec{v}_{\perp}|$  will remain constant in the  $x$ - $y$  plane. Thus  $\vec{v}_{\perp}$  can change only its direction as shown in the Fig..  $\vec{v}_{\parallel}$  will remain constant as it is parallel to  $\vec{B}$ .

Thus at  $t = t$

$$v_x = v_{\perp} \cos \omega t = v \sin \alpha \cos \omega t,$$

$$v_y = v_{\perp} \sin \omega t = v \sin \alpha \sin \omega t$$

and 
$$v_z = v \cos \alpha, \quad \text{where } \omega = \frac{eB}{m}$$

As at  $t = 0$ , we have  $x = y = z = 0$ , so the motion law of the electron is.

$$\left. \begin{aligned} z &= v \cos \alpha t \\ x &= \frac{v \sin \alpha}{\omega} \sin \omega t \\ y &= \frac{v \sin \alpha}{\omega} (\cos \omega t - 1) \end{aligned} \right\}$$

(The equation of the helix)

On the screen, 
$$z = l, \text{ so } t = \frac{l}{v \cos \alpha}.$$

Then, 
$$r^2 = x^2 + y^2 = \frac{2v^2 \sin^2 \alpha}{\omega^2} \left( 1 - \cos \frac{\omega l}{v \cos \alpha} \right)$$

$$r = \frac{2v \sin \alpha}{\omega} \left| \sin \frac{\omega l}{2v \cos \alpha} \right| = 2 \frac{mv}{eB} \sin \alpha \left| \sin \frac{leB}{2mv \cos \alpha} \right|$$



- 3.385** Choose the wire along the  $z$ -axis, and the initial direction of the electron, along the  $x$ -axis. Then the magnetic field in the  $x-z$  plane is along the  $y$ -axis and outside the wire it is,

$$B = B_y = \frac{\mu_0 I}{2 \pi x}, \quad (B_x = B_z = 0, \text{ if } y = 0)$$

The motion must be confined to the  $x-z$  plane. Then the equations of motion are,

$$\frac{d}{dt} m v_x = -e v_z B_y$$

$$\frac{d(m v_z)}{dt} = +e v_x B_y$$

Multiplying the first equation by  $v_x$  and the second by  $v_z$  and then adding,

$$v_x \frac{dv_x}{dt} + v_z \frac{dv_z}{dt} = 0$$

or,  $v_x^2 + v_z^2 = v_0^2$ , say, or,  $v_z = \sqrt{v_0^2 - v_x^2}$

Then, 
$$v_x \frac{dv_x}{dx} = -\frac{e}{m} \sqrt{v_0^2 - v_x^2} \frac{\mu_0 I}{2 \pi x}$$

or, 
$$-\frac{v_x dv_x}{\sqrt{v_0^2 - v_x^2}} = \frac{\mu_0 I e}{2 \pi m} \frac{dx}{x}$$

Integrating, 
$$\sqrt{v_0^2 - v_x^2} = \frac{\mu_0 I e}{2 \pi m} \ln \frac{x}{a}$$

on using,  $v_x = v_0$ , if  $x = a$  (i.e. initially).

Now,  $v_x = 0$ , when  $x = x_m$ ,

so, 
$$x_m = a e^{v_0/b}, \text{ where } b = \frac{\mu_0 I e}{2 \pi m}.$$

- 3.386** Inside the capacitor, the electric field follows a  $\frac{1}{r}$  law, and so the potential can be written as

$$\varphi = \frac{V \ln r/a}{\ln b/a}, \quad E = \frac{-V}{\ln b/a} \frac{1}{r}.$$

Here  $r$  is the distance from the axis of the capacitor.

Also, 
$$\frac{m v^2}{r} = \frac{q V}{\ln b/a} \frac{1}{r} \quad \text{or} \quad m v^2 = \frac{q V}{\ln b/a}$$

On the other hand,

$$m v = q B r \text{ in the magnetic field.}$$

Thus, 
$$v = \frac{V}{B r \ln b/a} \quad \text{and} \quad \frac{q}{m} = \frac{v}{B r} = \frac{V}{B^2 r^2 \ln(b/a)}$$

3.387 The equations of motion are,

$$m \frac{dv_x}{dt} = -q B v_z, \quad m \frac{dv_y}{dt} = q E \quad \text{and} \quad m \frac{dv_z}{dt} = q v_x B$$

These equations can be solved easily.

First, 
$$v_y = \frac{qE}{m} t, \quad y = \frac{qE}{2m} t^2$$

Then, 
$$v_x^2 + v_z^2 = \text{constant} = v_0^2 \text{ as before.}$$

In fact,  $v_x = v_0 \cos \omega t$  and  $v_z = v_0 \sin \omega t$  as one can check.

Integrating again and using  $x = z = 0$ , at  $t = 0$

$$x = \frac{v_0}{\omega} \sin \omega t, \quad z = \frac{v_0}{\omega} (1 - \cos \omega t)$$

Thus, 
$$x = z = 0 \text{ for } t = t_n = n \frac{2\pi}{\omega}$$

At that instant, 
$$y_n = \frac{qE}{2m} \times \frac{2\pi}{qB/m} \times n^2 \times \frac{2\pi}{qB/m} = \frac{2\pi^2 m E n^2}{qB^2}$$

Also, 
$$\tan \alpha_n = \frac{v_x}{v_y}, \quad (v_z = 0 \text{ at this moment})$$

$$= \frac{mv_0}{qE t_n} = \frac{mv_0}{qE} \times \frac{qB}{m} \times \frac{1}{2\pi n} = \frac{B v_0}{2\pi E n}$$

3.388 The equation of the trajectory is,

$$x = \frac{v_0}{\omega} \sin \omega t, \quad z = \frac{v_0}{\omega} (1 - \cos \omega t), \quad y = \frac{qE}{2m} t^2 \text{ as before see (3.384).}$$

Now on the screen  $x = l$ , so

$$\sin \omega t = \frac{\omega l}{v_0} \quad \text{or,} \quad \omega t = \sin^{-1} \frac{\omega l}{v_0}$$

At that moment,

$$y = \frac{qE}{2m\omega^2} \left( \sin^{-1} \frac{\omega l}{v_0} \right)^2$$

so, 
$$\frac{\omega l}{v_0} = \sin \sqrt{\frac{2m\omega^2 y}{qE}} = \sin \sqrt{\frac{2qB^2 y}{Em}}$$

and 
$$z = \frac{v_0}{\omega} 2 \sin^2 \frac{\omega t}{2} = l \tan \frac{\omega t}{2}$$

$$= l \tan \frac{1}{2} \left[ \sin^{-1} \frac{\omega l}{v_0} \right] = l \tan \sqrt{\frac{qB^2 y}{2mE}}$$

For small

$$z, \quad \frac{qB^2 y}{2mE} = \left( \tan^{-1} \frac{z}{l} \right)^2 \approx \frac{z^2}{l^2}$$

or, 
$$y = \frac{2mE}{qB^2 l^2} \cdot z^2 \text{ is a parabola.}$$

3.389 In crossed field,

$$eE = evB, \text{ so } v = \frac{E}{B}$$

$$\text{Then, } F = \text{force exerted on the plate} = \frac{I}{e} \times m \frac{E}{B} = \frac{m I E}{e B}$$

3.390 When the electric field is switched off, the path followed by the particle will be helical. and pitch,  $\Delta l = v_{\parallel} T$ , (where  $v_{\parallel}$  is the velocity of the particle, parallel to  $\vec{B}$ , and  $T$ , the time period of revolution.)

$$\begin{aligned} &= v \cos(90 - \varphi) T = v \sin \varphi T \\ &= v \sin \varphi \frac{2\pi m}{qB} \left( \text{as } T = \frac{2\pi}{qB} \right) \end{aligned} \quad (1)$$

Now, when both the fields were present,  $qE = qvB \sin(90 - \varphi)$ , as no net force was effective on the system.

$$\text{or, } v = \frac{E}{B \cos \varphi} \quad (2)$$

$$\text{From (1) and (2), } \Delta l = \frac{E}{B} \frac{2\pi m}{qB} \tan \varphi = 6 \text{ cm.}$$

3.391 When there is no deviation,

$$-q\vec{E} = q(\vec{v} \times \vec{B})$$

$$\text{or, in scalar form, } E = vB \text{ (as } \vec{v} \perp \vec{B} \text{) or, } v = \frac{E}{B} \quad (1)$$

Now, when the magnetic field is switched on, let the deviation in the field be  $x$ . Then,

$$x = \frac{l}{2} \left( \frac{qvB}{m} \right) t^2,$$

where  $t$  is the time required to pass through this region.

$$\text{also, } t = \frac{a}{v}$$

$$\text{Thus } x = \frac{1}{2} \left( \frac{qvB}{m} \right) \left( \frac{a}{v} \right)^2 = \frac{1}{2} \frac{q}{m} \frac{a^2 B^2}{E} \quad (2)$$

For the region where the field is absent, velocity in upward direction

$$= \left( \frac{qvB}{m} \right) t = \frac{q}{m} a B \quad (3)$$

$$\text{Now, } \Delta x - x = \frac{qaB}{m} t'$$

$$= \frac{q}{m} \frac{aB^2 b}{E} \text{ when } t' = \frac{b}{v} = \frac{bB}{E} \quad (4)$$

From (2) and (4),

$$\Delta x - \frac{1}{2} \frac{q}{m} \frac{a^2 B^2}{E} = \frac{q}{m} \frac{a B^2 b}{E}$$

$$\text{or, } \frac{q}{m} = \frac{2E \Delta x}{a B^2 (a + 2b)}$$

3.392 (a) The equation of motion is,

$$m \frac{d^2 \vec{r}}{dt^2} = q (\vec{E} + \vec{v} \times \vec{B})$$

Now, 
$$\vec{v} \times \vec{B} = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ \dot{x} & \dot{y} & \dot{z} \\ 0 & 0 & B \end{vmatrix} = \vec{i} B \dot{y} - \vec{j} B \dot{x}$$

So, the equation becomes,

$$\frac{dv_x}{dt} = \frac{qB}{m} v_y, \quad \frac{dv_y}{dt} = \frac{qE}{m} - \frac{qB}{m} v_x, \quad \text{and} \quad \frac{dv_z}{dt} = 0$$

Here,  $v_x = \dot{x}$ ,  $v_y = \dot{y}$ ,  $v_z = \dot{z}$ . The last equation is easy to integrate;

$$v_z = \text{constant} = 0,$$

since  $v_z$  is zero initially. Thus integrating again,

$$z = \text{constant} = 0,$$

and motion is confined to the  $x-y$  plane. We now multiply the second equation by  $i$  and add to the first equation.

$$\xi = v_x + i v_y$$

we get the equation,

$$\frac{d\xi}{dt} = i\omega \frac{E}{B} - i\omega \xi, \quad \omega = \frac{qB}{m}.$$

This equation after being multiplied by  $e^{i\omega t}$  can be rewritten as,

$$\frac{d}{dt} (\xi e^{i\omega t}) = i\omega e^{i\omega t} \frac{E}{B}$$

and integrated at once to give,

$$\xi = \frac{E}{B} + C e^{-i\omega t - i\alpha},$$

where  $C$  and  $\alpha$  are two real constants. Taking real and imaginary parts.

$$v_x = \frac{E}{B} + C \cos(\omega t + \alpha) \quad \text{and} \quad v_y = -C \sin(\omega t + \alpha)$$

Since  $v_y = 0$ , when  $t = 0$ , we can take  $\alpha = 0$ , then  $v_x = 0$  at  $t = 0$  gives,  $C = -\frac{E}{B}$

and we get,

$$v_x = \frac{E}{B} (1 - \cos \omega t) \quad \text{and} \quad v_y = \frac{E}{B} \sin \omega t.$$

Integrating again and using  $x = y = 0$ , at  $t = 0$ , we get

$$x(t) = \frac{E}{B} \left( t - \frac{\sin \omega t}{\omega} \right), \quad y(t) = \frac{E}{\omega B} (1 - \cos \omega t).$$

This is the equation of a cycloid.

(b) The velocity is zero, when  $\omega t = 2n\pi$ . We see that

$$v^2 = v_x^2 + v_y^2 = \left( \frac{E}{B} \right)^2 (2 - 2 \cos \omega t)$$

or, 
$$v = \frac{ds}{dt} = \frac{2E}{B} \left| \sin \frac{\omega t}{2} \right|$$

The quantity inside the modulus is positive for  $0 < \omega t < 2\pi$ . Thus we can drop the modulus and write for the distance traversed between two successive zeroes of velocity.

$$S = \frac{4E}{\omega B} \left( 1 - \cos \frac{\omega t}{2} \right)$$

Putting  $\omega t = 2\pi$ , we get

$$S = \frac{8E}{\omega B} = \frac{8mE}{qB^2}$$

(c) The drift velocity is in the  $x$ -direction and has the magnitude,

$$\langle v_x \rangle = \left\langle \frac{E}{B} (1 - \cos \omega t) \right\rangle = \frac{E}{B}.$$

3.393 When a current  $I$  flows along the axis, a magnetic field  $B_\phi = \frac{\mu_0 I}{2\pi\rho}$  is set up where  $\rho^2 = x^2 + y^2$ . In terms of components,

$$B_x = -\frac{\mu_0 I y}{2\pi\rho^2}, B_y = \frac{\mu_0 I x}{2\pi\rho^2} \text{ and } B_z = 0$$

Suppose a p.d.  $V$  is set up between the inner cathode and the outer anode. This means a potential function of the form

$$\varphi = V \frac{\ln \rho/b}{\ln a/b}, \quad a > \rho > b,$$

as one can check by solving Laplace equation.

The electric field corresponding to this is,

$$E_x = -\frac{Vx}{\rho^2 \ln a/b}, E_y = -\frac{Vy}{\rho^2 \ln a/b}, E_z = 0.$$

The equations of motion are,

$$\frac{d}{dt} mv_x = +\frac{|e|Vz}{\rho^2 \ln a/b} + \frac{|e|\mu_0 I}{2\pi\rho^2} x \dot{z}$$

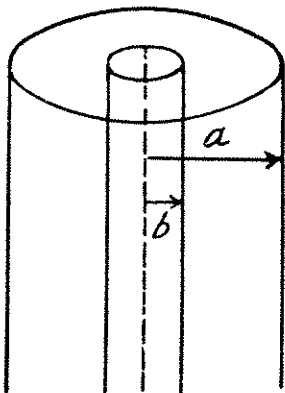
$$\frac{d}{dt} mv_y = +\frac{|e|Vy}{\rho^2 \ln a/b} + \frac{|e|\mu_0 I}{2\pi\rho^2} y \dot{z}$$

and 
$$\frac{d}{dt} mv_z = -|e| \frac{\mu_0 I}{2\pi\rho^2} (x\dot{x} + y\dot{y}) = -|e| \frac{\mu_0 I}{2\pi} \frac{d}{dt} \ln \rho$$

$(-|e|)$  is the charge on the electron.

Integrating the last equation,

$$mv_z = -|e| \frac{\mu_0 I}{2\pi} \ln \rho/a = m\dot{z}.$$



since  $v_z = 0$  where  $\rho = a$ . We now substitute this  $\dot{z}$  in the other two equations to get

$$\begin{aligned} & \frac{d}{dt} \left( \frac{1}{2} m v_x^2 + \frac{1}{2} m v_y^2 \right) \\ &= \left[ \frac{|e|V}{\ln a/b} - \frac{|e|^2}{m} \left( \frac{\mu_0 I}{2\pi} \right)^2 \ln \rho/b \right] \cdot \frac{x\dot{x} + y\dot{y}}{\rho^2} \\ &= \left[ \frac{|e|V}{\ln \frac{a}{b}} - \frac{|e|^2}{m} \left( \frac{\mu_0 I}{2\pi} \right)^2 \ln \frac{\rho}{b} \right] \cdot \frac{1}{2\rho^2} \frac{d}{dt} \rho^2 \\ &= \left[ \frac{|e|V}{\ln \frac{a}{b}} - \frac{|e|^2}{m} \left( \frac{\mu_0 I}{2\pi} \right)^2 \ln \frac{\rho}{b} \right] \frac{d}{dt} \ln \frac{\rho}{b} \end{aligned}$$

Integrating and using  $v^2 = 0$ , at  $\rho = b$ , we get,

$$\frac{1}{2} m v^2 = \left[ \frac{|e|V}{\ln \frac{a}{b}} \ln \frac{\rho}{b} - \frac{1}{2m} |e|^2 \left( \frac{\mu_0 I}{2\pi} \right)^2 \left( \ln \frac{\rho}{b} \right) \right]$$

The RHS must be positive, for all  $a > \rho > b$ . The condition for this is,

$$V \geq \frac{1}{2} \frac{|e|}{m} \left( \frac{\mu_0 I}{2\pi} \right)^2 \ln \frac{a}{b}$$

**3.394** This differs from the previous problem in ( $a \leftrightarrow b$ ) and the magnetic field is along the  $z$ -direction. Thus  $B_x = B_y = 0$ ,  $B_z = B$

Assuming as usual the charge of the electron to be  $-|e|$ , we write the equation of motion

$$\frac{d}{dt} m v_x = \frac{|e|V_x}{\rho^2 \ln \frac{b}{a}} - |e|B\dot{y}, \quad \frac{d}{dt} m v_y = \frac{|e|V_y}{\rho^2 \ln \frac{b}{a}} + |e|B\dot{x}$$

and 
$$\frac{d}{dt} m v_z = 0 \Rightarrow z = 0$$

The motion is confined to the plane  $z = 0$ . Eliminating  $B$  from the first two equations,

$$\frac{d}{dt} \left( \frac{1}{2} m v^2 \right) = \frac{|e|V}{\ln b/a} \frac{x\dot{x} + y\dot{y}}{\rho^2}$$

or, 
$$\frac{1}{2} m v^2 = |e|V \frac{\ln \rho/a}{\ln b/a}$$

so, as expected, since magnetic forces do not work,

$$v = \sqrt{\frac{2|e|V}{m}}, \text{ at } \rho = b.$$

On the other hand, eliminating  $V$ , we also get,

$$\frac{d}{dt} m (xv_y - yv_x) = |e| B (x\dot{x} + y\dot{y})$$

i.e. 
$$(xv_y - yv_x) = \frac{|e|B}{2m} \rho^2 + \text{constant}$$

The constant is easily evaluated, since  $v$  is zero at  $\rho = a$ . Thus,

$$(xv_y - yv_x) = \frac{|e|B}{2m} (\rho^2 - a^2) > 0$$

At  $\rho = b$ ,  $(xv_y - yv_x) \leq vb$

Thus, 
$$vb \geq \frac{|e|B}{2m} (b^2 - a^2)$$

or, 
$$B \leq \frac{2mb}{b^2 - a^2} \sqrt{\frac{2|e|V}{m}} \times \frac{1}{|e|}$$

or, 
$$B \leq \frac{2b}{b^2 - a^2} \sqrt{\frac{2mB}{|e|}}$$

3.395 The equations are as in 3.392.

$$\frac{dv_x}{dt} = \frac{qB}{m} v_y, \quad \frac{dv_y}{dt} = \frac{qE_m}{m} \cos \omega t - \frac{qB}{m} v_x \quad \text{and} \quad \frac{dv_z}{dt} = 0$$

with  $\omega = \frac{qB}{m}$ ,  $\xi = v_x + iv_y$ , we get,

$$\frac{d\xi}{dt} = i \frac{E_m}{B} \omega \cos \omega t - i \omega \xi$$

or multiplying by  $e^{i\omega t}$ ,

$$\frac{d}{dt} (\xi e^{i\omega t}) = i \frac{E_m}{2B} \omega (e^{2i\omega t} + 1)$$

or integrating, 
$$\xi e^{i\omega t} = \frac{E_m}{4B} e^{2i\omega t} + \frac{E_m}{2B} i \omega t$$

or, 
$$\xi = \frac{E_m}{4B} (e^{i\omega t} + 2i\omega t e^{i\omega t}) + C e^{i\omega t}$$

since  $\xi = 0$  at  $t = 0$ ,  $C = -\frac{E_m}{4B}$ .

Thus, 
$$\xi = i \frac{E_m}{2B} \sin \omega t + i \frac{E_m}{2B} \omega t e^{i\omega t}$$

or, 
$$v_x = \frac{E_m}{2B} \omega t \sin \omega t \quad \text{and} \quad v_y = \frac{E_m}{2B} \sin \omega t + \frac{E_m}{2B} \omega t \cos \omega t$$

Integrating again,

$$x = \frac{a}{2\omega^2} (\sin \omega t - \omega t \cos \omega t), \quad y = \frac{a}{2\omega} t \sin \omega t.$$

where  $a = \frac{qE_m}{m}$ , and we have used  $x = y = 0$ , at  $t = 0$ .

The trajectory is an unwinding spiral.

**3.396** We know that for a charged particle (proton) in a magnetic field,

$$\frac{mv^2}{r} = Bev \text{ or } mv = Ber$$

But, 
$$\omega = \frac{eB}{m},$$

Thus 
$$E = \frac{1}{2}mv^2 = \frac{1}{2}m\omega^2 r^2.$$

So, 
$$\Delta E = m\omega^2 r \Delta r = 4\pi^2 v^2 mr \Delta r$$

On the other hand  $\Delta E = 2eV$ , where  $V$  is the effective acceleration voltage, across the Dees, there being two crossings per revolution. So,

$$V \geq 2\pi^2 v^2 mr \Delta r / e$$

**3.397** (a) From  $\frac{mv^2}{r} = Bev$ , or,  $mv = Ber$

and 
$$T = \frac{(Ber)^2}{2m} = \frac{1}{2}mv^2 = 12 \text{ MeV}$$

(b) From  $\frac{2\pi}{\omega} = \frac{2\pi r}{v}$

we get, 
$$f_{\min} = \frac{v}{2\pi r} = \frac{1}{\pi r} \sqrt{\frac{T}{2m}} = 15 \text{ MHz}$$

**3.398** (a) The total time of acceleration is,

$$t = \frac{1}{2v} \cdot n,$$

where  $n$  is the number of passages of the Dees.

But, 
$$T = neV = \frac{B^2 e^2 r^2}{2m}$$

or, 
$$n = \frac{B^2 e r^2}{2mV}$$

So, 
$$t = \frac{\pi}{eB/m} \times \frac{B^2 e r^2}{2mV} = \frac{\pi B r^2}{2V} = \frac{\pi^2 mv r^2}{eV} = 30 \mu\text{s}$$

(b) The distance covered is,  $s = \sum v_n \cdot \frac{1}{2v}$

But, 
$$v_n = \sqrt{\frac{2eV}{m}} \sqrt{n},$$

So, 
$$s = \sqrt{\frac{eV}{2mv^2}} \sum \sqrt{n} = \sqrt{\frac{eV}{2mv^2}} \int \sqrt{n} \, dn = \sqrt{\frac{eV}{2mv^2}} \frac{2}{3} n^{3/2}$$



But,

$$n = \frac{B^2 e^2 r^2}{2 e V m} = \frac{2 \pi^2 m v^2 r^2}{e V}$$

Thus,

$$s = \frac{4 \pi^3 v^2 m r^2}{3 e V} = 1.24 \text{ km}$$

**3.399** In the  $n$ th orbit,  $\frac{2 \pi r_n}{v_n} = n T_0 = \frac{n}{v}$ . We ignore the rest mass of the electron and write  $v_n \approx c$ . Also  $W = cp = c B e r_n$ .

Thus,

$$\frac{2 \pi W}{B e c^2} = \frac{n}{v}$$

or,

$$n = \frac{2 \pi W v}{B e c^2} = 9$$

**3.400** The basic condition is the relativistic equation,

$$\frac{m v^2}{r} = B q v, \quad \text{or,} \quad m v = \frac{m_0 v}{\sqrt{1 - v^2/c^2}} = B q r.$$

Or calling,

$$\omega = \frac{B q}{m},$$

we get,

$$\omega = \frac{\omega_0}{\sqrt{1 + \frac{\omega_0^2 r^2}{c^2}}}, \quad \omega_0 = \frac{B q}{m_0} r$$

is the radius of the instantaneous orbit.

The time of acceleration is,

$$t = \sum_{n=1}^N \frac{1}{2 v_n} = \sum_{n=1}^N \frac{\pi}{\omega_n} = \sum_n \frac{\pi W_n}{q B c^2}.$$

$N$  is the number of crossing of either Dee.

But,  $W_n = m_0 c^2 + \frac{n \Delta W}{2}$ , there being two crossings of the Dees per revolution.

So,

$$\begin{aligned} t &= \sum \frac{\pi m_0 c^2}{q B c^2} + \sum \frac{\pi \Delta W_n}{2 q B c^2} \\ &= N \frac{\pi}{\omega_0} + \frac{N(N+1)}{4} \frac{\pi \Delta W}{q B c^2} \approx N^2 \frac{\pi \Delta W}{4 q B c^2} \quad (N \gg 1) \end{aligned}$$

Also,

$$r = r_N \frac{v_N}{\omega_N} \approx \frac{c}{\pi} \frac{\partial t}{\partial N} = \frac{\Delta W}{2 q B c} N$$

Hence finally,

$$\begin{aligned}\omega &= \frac{\omega_0}{\sqrt{1 + \frac{q^2 B^2}{m_0^2 c^2} \times \frac{\Delta W^2}{4 q^2 B^2 c^2} N^2}} \\ &= \frac{\omega_0}{\sqrt{1 + \frac{(\Delta W)^2}{4 m_0^2 c^4} \times \frac{4 q B c^2}{\pi \Delta W} t}} = \frac{\omega_0}{\sqrt{1 + at}}; \\ a &= \frac{q B \Delta W}{\pi m_0^2 c^2}\end{aligned}$$

- 3.401 When the magnetic field is being set up in the solenoid, and electric field will be induced in it, this will accelerate the charged particle. If  $\dot{B}$  is the rate, at which the magnetic field is increasing, then.

$$\pi r^2 \dot{B} = 2 \pi r E \quad \text{or} \quad E = \frac{1}{2} r \dot{B}$$

Thus,

$$m \frac{dv}{dt} = \frac{1}{2} r \dot{B} q, \quad \text{or} \quad v = \frac{q B r}{2m},$$

After the field is set up, the particle will execute a circular motion of radius  $\rho$ , where

$$mv = B q \rho, \quad \text{or} \quad \rho = \frac{1}{2} r$$

- 3.402 The increment in energy per revolution is  $e \dot{\Phi}$ , so the number of revolutions is,

$$N = \frac{W}{e \dot{\Phi}}$$

The distance traversed is,  $s = 2 \pi r N$

- 3.403 On the one hand,

$$\frac{dp}{dt} = eE = \frac{e}{2\pi r} \frac{d\Phi}{dt} = \frac{e}{2\pi r} \frac{d}{dt} \int_0^r 2\pi r' B(r') dr'$$

On the other ,

$$p = B(r) er, \quad r = \text{constant.}$$

so,

$$\frac{dp}{dt} = er \frac{dB(r)}{dt} = er \dot{B}(r)$$

Hence,

$$er \dot{B}(r) = \frac{e}{2\pi r} \pi r^2 \frac{d}{dt} \langle B \rangle$$

So,

$$\dot{B}(r) = \frac{1}{2} \frac{d}{dt} \langle B \rangle$$

This equations is most easily satisfied by taking  $B(r_0) = \frac{1}{2} \langle B \rangle$ .

- 3.404 The condition,  $B(r_0) = \frac{1}{2} \langle B \rangle = \frac{1}{2} \int_0^{r_0} B \cdot 2\pi r dr / \pi r_0^2$

or,

$$B(r_0) = \frac{1}{r_0^2} \int_0^{r_0} B r dr$$

This gives  $r_0$ .

In the present case,

$$B_0 - ar_0^2 = \frac{1}{r_0^2} \int_0^{r_0} (B - ar^2) r dr = \frac{1}{2} \left( B_0 - \frac{1}{2} ar_0^2 \right)$$

or,

$$\frac{3}{4} ar_0^2 = \frac{1}{2} B_0 \quad \text{or} \quad r_0 = \sqrt{\frac{2B_0}{3a}}.$$

**3.405** The induced electric field (or eddy current field) is given by,

$$E(r) = \frac{1}{2\pi r} \frac{d}{dt} \int_0^r 2\pi r' (r') B(r') dr'$$

Hence,

$$\begin{aligned} \frac{dE}{dr} &= -\frac{1}{2\pi r^2} \frac{d}{dt} \int_0^r 2\pi r' B(r') dr' + \frac{dB(r)}{dt} \\ &= -\frac{1}{2} \frac{d}{dt} \langle B \rangle + \frac{dB(r)}{dt} \end{aligned}$$

This vanishes for  $r = r_0$  by the betatron condition, where  $r_0$  is the radius of the equilibrium orbit.

**3.406** From the betatron condition,

$$\frac{1}{2} \frac{d}{dt} \langle B \rangle = \frac{dB}{dt}(r_0) = \frac{B}{\Delta t}$$

Thus,

$$\frac{d}{dt} \langle B \rangle = \frac{2B}{\Delta t}$$

and

$$\frac{d\Phi}{dt} = \pi r^2 \frac{d\langle B \rangle}{dt} = \frac{2\pi r^2 B}{\Delta t}$$

So, energy increment per revolution is,

$$e \frac{d\Phi}{dt} = \frac{2\pi r^2 eB}{\Delta t}$$

**3.407** (a) Even in the relativistic case, we know that :  $p = Ber$

$$\text{Thus, } W = \sqrt{c^2 p^2 + m_0^2 c^4} - m_0 c^2 = m_0 c^2 \left( \sqrt{1 + (Ber / m_0 c)^2} - 1 \right)$$

(b) The distance traversed is,

$$2\pi r \frac{W}{e\Phi} = 2\pi r \frac{W}{2\pi r^2 eB / \Delta t} = \frac{W \Delta t}{Ber},$$

on using the result of the previous problem.