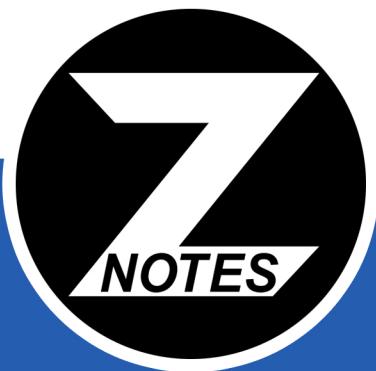


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# CIE A-LEVEL MATHS 9709 (M1)

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FORMULAE AND SOLVED QUESTIONS FOR MECHANICS 1 (M1)

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**NOTES**

# 1. VELOCITY AND ACCELERATION

## 1.1 Kinematics Equations

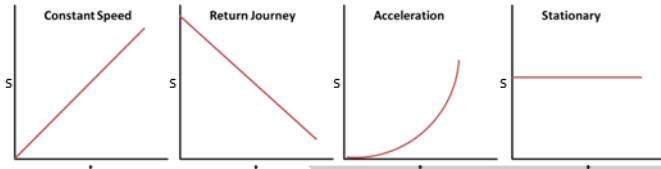
$$v = u + at$$

$$s = ut + \frac{1}{2}at^2 \text{ and } s = vt - \frac{1}{2}at^2$$

$$s = \frac{1}{2}(u + v)t$$

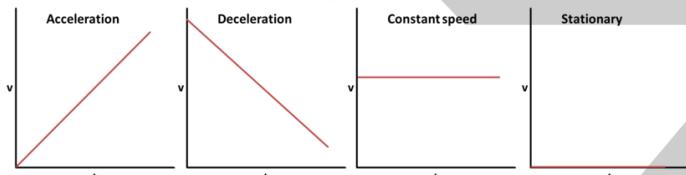
$$v^2 = u^2 + 2as$$

## 1.2 Displacement-Time Graph



- Gradient = speed

## 1.3 Velocity-Time Graph



- Gradient = acceleration
- Area under graph = change in displacement

{S12-P42}



The small block has mass  $0.15\text{kg}$ . The surface is horizontal. The frictional force acting on it is  $0.12\text{N}$ . Block set in motion from  $X$  with speed  $3\text{ms}^{-1}$ . It hits vertical surface at  $Y$   $2\text{s}$  later. Block rebounds from wall directly towards  $X$  and stops at  $Z$ . The instant that block hits wall it loses  $0.072\text{J}$  of its kinetic energy. The velocity of the block from  $X$  to  $Y$  direction is  $v\text{ ms}^{-1}$  at time  $t\text{s}$  after it leaves  $X$ .

- Find values of  $v$  when the block arrives at  $Y$  and when it leaves  $Y$ . Also find  $t$  when block comes to rest at  $Z$ . Then sketch a velocity-time graph of the motion of the small block.
- Displacement of block from  $X$ , in the  $\overrightarrow{XY}$  direction is  $s\text{ m}$  at time  $t\text{s}$ . Sketch a displacement-time graph. On graph show values of  $s$  and  $t$  when block at  $Y$  and when it comes to rest at  $Z$ .

Question 7:

### Part (i)

Calculating deceleration using Newton's second law:

$$0.12 = 0.15a \quad a = \frac{0.12}{0.15} = 0.8\text{ms}^{-2}$$

Calculate  $v$  at  $Y$  using relevant kinematics equation

$$-0.8 = \frac{v-3}{2} \quad v = 1.4\text{ms}^{-1}$$

Calculate kinetic energy at  $Y$

$$E_K = \frac{1}{2}(0.15)(1.4)^2 = 0.147\text{J}$$

Calculate energy lost:

$$\text{Initial} - \text{Change} = \text{Final}$$

$$0.147 - 0.072 = 0.075\text{J}$$

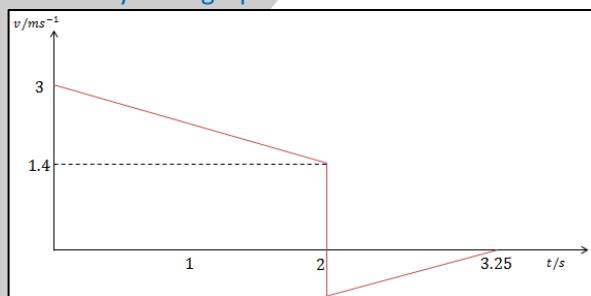
Calculate speed as leaving  $Y$  using  $k.E.$  formula:

$$0.075 = \frac{1}{2}(0.15)v^2 \quad v = 1\text{ms}^{-1}$$

Calculate  $t$  when particle comes to rest:

$$-0.8 = \frac{0-1}{t} \quad t = 1.25\text{s}$$

Draw velocity-time graph with data calculated:



### Part (ii)

Calculate displacement from  $X$  to  $Y$

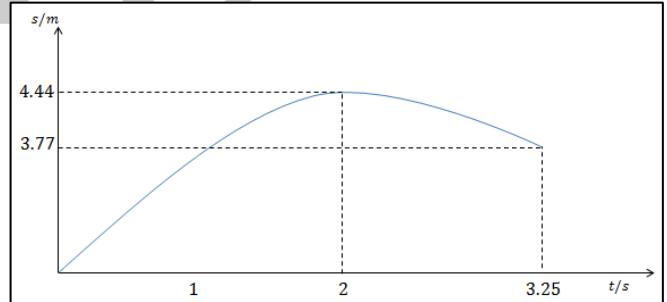
$$s = (3 \times 2) + \frac{1}{2}(-0.8)(2)^2 \quad s = 4.4\text{m}$$

Calculate displacement from  $Y$  to  $Z$

$$s = (1 \times 1.25) + \frac{1}{2}(-0.8)(1.25)^2$$

$s = 0.625\text{m}$  in the opposite direction

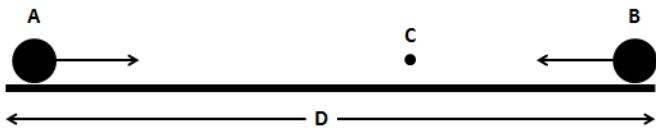
Draw displacement-time graph with data calculated:



## 1.4 Average Velocity

- For an object moving with constant acceleration over a period of time, these quantities are equal:
  - The average velocity
  - The mean of initial & final velocities
  - Velocity when half the time has passed

## 1.5 Relative Velocities



- Let  $s_A$  be the distance travelled by A and  $s_B$  for B  

$$s_A = ut + \frac{1}{2}at^2 \quad s_B = ut - \frac{1}{2}at^2$$
- If a collision occurs at point C  

$$s_A + s_B = D$$
- This gives you the time of when the collision occurred
- Same analysis if motion is vertical

## 2. FORCE AND MOTION

### Newton's 1<sup>st</sup> Law of Motion:

*Object remains at rest or moves with constant velocity unless an external force is applied*

### Newton's 2<sup>nd</sup> Law of Motion:

$$F = ma$$

## 3. VERTICAL MOTION

- Weight:** directly downwards
- Normal contact force:** perpendicular to place of contact

### 3.1 Common Results of Vertical Motion

Finding time taken to reach maximum height by a projectile travelling in vertical motion:

$$v = u + at$$

- Let  $v = 0$  and find  $t$
- The time taken to go up and come back to original position would be double of this  $t$

Finding maximum height above a launch point use:

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

- Let  $v = 0$  and find  $s$

Finding time interval for which a particle is above a given height:

- Let the height be  $H$  and use

$$s = ut + \frac{1}{2}at^2$$

- Let  $s = H$

There will be a quadratic equation in  $t$

- Solve and find the difference between the 2  $t$ 's to find the time interval

**{S04-P04}**

Particle  $P_1$  projected vertically upwards, from horizontal ground, with speed  $30\text{ms}^{-1}$ . At same instant  $P_2$  projected vertically upwards from tower height  $25\text{m}$ , with speed  $10\text{ms}^{-1}$

**Question 7:**

- Find the time for which  $P_1$  is higher than the top of the tower
- Find velocities of the particles at instant when they are same height
- Find the time for which  $P_1$  is higher than  $P_2$  and moving upwards

**Solution:**

### Part (i)

Substitute given values into displacement equation:

$$25 = (30)t + \frac{1}{2}(10)t^2$$

$$5t^2 + 30t - 25 = 0$$

Solve quadratic for  $t$

$$t = 1\text{s or } 5\text{s}$$

$P_1$  reaches tower at  $t = 1$  then passes it again when coming down at  $t = 5\text{s}$

Therefore time above tower =  $5 - 1 = 4$  seconds

### Part (ii)

Displacement of  $P_1$  is  $S_1$ , and of  $P_2$  is  $S_2$  & relationship:

$$S_1 = 25 + S_2$$

Create equations for  $S_1$  and  $S_2$

$$S_1 = 30t + \frac{1}{2}(-10)t^2 \quad S_2 = 10t + \frac{1}{2}(-10)t^2$$

Substitute back into initial equation

$$30t + \frac{1}{2}(-10)t^2 = 25 + 10t + \frac{1}{2}(-10)t^2$$

Simple cancelling

$$t = 1.25\text{s}$$

Find velocities

$$v = u + at$$

$$V_1 = 30 - 10(1.25) = 17.5\text{ms}^{-1}$$

$$V_2 = 10 - 10(1.25) = -2.5\text{ms}^{-1}$$

### Part (iii)

We know when  $P_1$  and  $P_2$  at same height  $t = 1.25\text{s}$ .

Find time taken to reach max height for  $P_1$

$$v = u + at$$

$V$  is 0 at max height

$$0 = 30 - 10t \quad t = 3\text{s}$$

Time for  $P_1$  above  $P_2 = 3 - 1.25 = 1.75$  seconds

## 4. RESOLVING FORCES

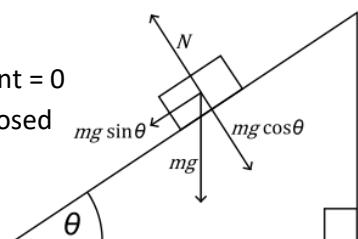
- If force  $F$  makes an angle  $\theta$  with a given direction, the effect of the force in that direction is  $F \cos \theta$

$$F \cos(90 - \theta) = F \sin \theta$$

$$F \sin(90 - \theta) = F \cos \theta$$

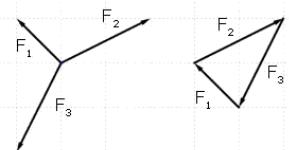
- Forces in equilibrium: resultant = 0

- If drawn, forces will form a closed polygon



- Methods of working out forces in equilibrium:

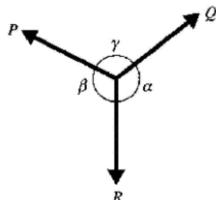
- Construct a triangle and work out forces
- Resolve forces in  $x$  and  $y$  directions; sum of each = 0



**Lami's Theorem:**

- For any set of three forces P, Q and R in equilibrium

$$\frac{P}{\sin \theta} = \frac{Q}{\sin \beta} = \frac{R}{\sin \gamma}$$



## 5. FRICTION

Friction = Coefficient of Friction  $\times$  Normal Contact Force

$$F = \mu r$$

- Friction always acts in the opposite direction of motion
- Limiting equilibrium: on the point of moving, friction at max (limiting friction)
- Smooth contact: friction negligible

**Contact force:**

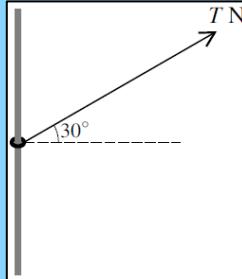
- Refers to both  $F$  and  $N$
- Horizontal component of Contact force =  $F$
- Vertical component of Contact force =  $N$
- Magnitude of Contact force given by the formula:

$$C = \sqrt{F^2 + N^2}$$

**{W11-P43}**

The ring has a mass of 2kg. The horizontal rod is rough and the coefficient of friction between ring and rod is 0.24. Find the two values of  $T$  for which the ring is in limiting equilibrium

**Question 6:**



**Solution:**

The ring is in limiting equilibrium in two different scenarios; we have to find  $T$  in both:

**Scenario 1: ring is about to move upwards**

Resultant =  $T \sin 30 - \text{friction} - \text{Weight of Ring}$   
Since the system is in equilibrium, resultant = 0:

$$\text{Contact Force} = T \cos 30$$

$$\therefore \text{Friction} = 0.24 \times T \cos 30$$

Substitute relevant information in to initial equation

$$0 = T \sin 30 - 0.24T \cos 30 - 20$$

$$T = 68.5N$$

**Scenario 2: ring is about to move downwards**

This time friction acts in the opposite direction since friction opposes the direction of motion, thus:

$$\text{Resultant} = T \sin 30 + \text{Friction} - \text{Weight of Ring}$$

Using information from before:

$$0 = T \sin 30 + 0.24T \cos 30 - 20$$

$$T = 28.3N$$

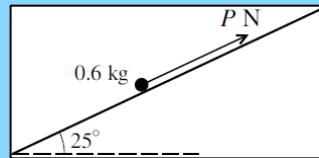
## 5.1 Equilibrium

**Force required to keep a particle in equilibrium on a rough plane**

Max Value	Min Value
 MAX	 MIN
<ul style="list-style-type: none"> <li>• The particle is about to move up</li> <li>• Thus friction force acts down the slope</li> </ul> $P = F + mg \sin \theta$	<ul style="list-style-type: none"> <li>• The particle is about to slip down</li> <li>• Thus frictional force acts up the slope</li> </ul> $F + P = mg \sin \theta$

**{W12-P43}**

**Question 6:**



Coefficient of friction is 0.36 and the particle is in equilibrium. Find the possible values of  $P$

**Solution:**

The magnitude of friction on particle in both scenarios is the same but acting in opposite directions  
Calculate the magnitude of friction first:

$$\text{Contact Force} = 6 \cos 25$$

$$\therefore \text{Friction} = 0.36 \times 6 \cos 25$$

**Scenario 1: particle is about to move upwards**

$$P = 6 \sin 25 + \text{Friction}$$

$$P = 4.49N$$

**Scenario 2: particle is about to move downwards**

$$P = 6 \sin 25 - \text{friction}$$

$$P = 0.578N$$

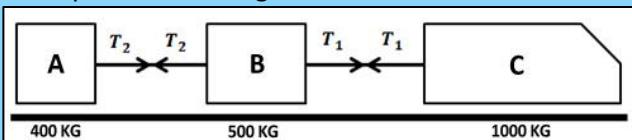
## 6. CONNECTED PARTICLES

**Newton's 3<sup>rd</sup> Law of Motion:**

For every action, there is an equal and opposite reaction

**{Exemplar Question}**

A train pulls two carriages:



The forward force of the engine is  $F = 2500\text{N}$ . Find the acceleration and tension in each coupling. The resistance to motion of A, B and C are 200, 150 and 90N respectively.

**Solution:**

To find acceleration, regard the system as a single object. The internal  $T$ s cancel out and give:

$$2500 - (200 + 150 + 90) = 1900a \\ \therefore a = 1.08\text{ms}^{-2}$$

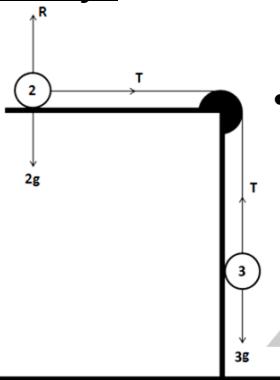
To find  $T_1$ , look at C

$$F - T_1 - 200 = 1000a \\ 2500 - T_1 - 200 = 1000 \times 1.08 \\ T_1 = 1220\text{N}$$

To find  $T_2$ , look at A

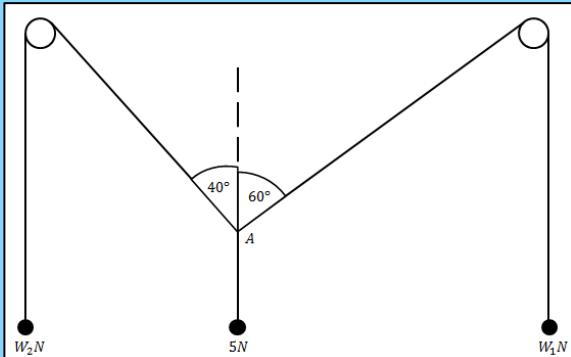
$$T_2 - 90 = 400a \\ T_2 - 90 = 400 \times 1.08 \\ T_2 = 522\text{N}$$

## 6.1 Pulleys



- Equation 1:  
No backward force  $\therefore T = 2a$
- Equation 2:  
 $3g - T = 3a$

**{W05-P04}**

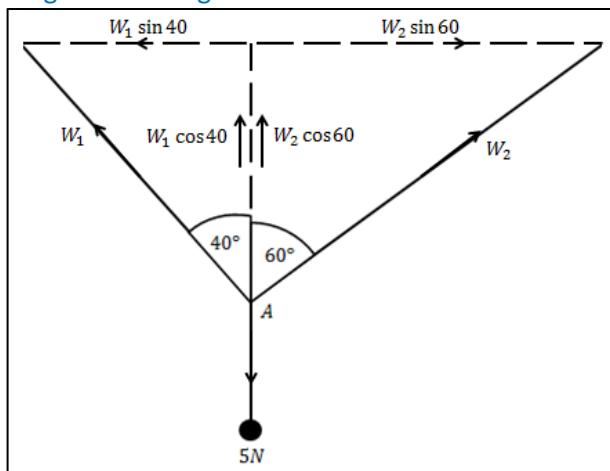


**Question 3:**

The strings are in equilibrium. The pegs are smooth. All the weights are vertical. Find  $W_1$  and  $W_2$

**Solution:**

Diagram showing how to resolve forces:



Resolving forces at A vertically:

$$W_1 \cos 40 + W_2 \cos 60 = 5$$

Resolving forces at A horizontally:

$$W_1 \sin 40 = W_2 \sin 60$$

Substitute second equation into first:

$$\left(\frac{W_2 \sin 60}{\sin 40}\right) \cos 40 + W_2 \cos 60 = 5$$

Solve to find  $W_2$ :

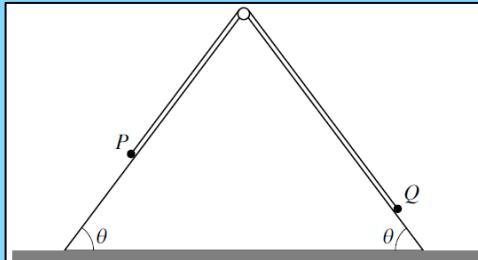
$$W_2 = 3.26\text{N}$$

Put this value back into first equation to find  $W_1$

$$W_1 = 4.40\text{N}$$

**{S12-P41}**

**Question 6:**



P has a mass of  $0.6\text{kg}$  and Q has a mass of  $0.4\text{kg}$ . The pulley and surface of both sides are smooth. The base of triangle is horizontal. It is given that  $\sin \theta = 0.8$ . Initially particles are held at rest on slopes with string taut. Particles are released and move along the slope

- Find tension in string. Find acceleration of particles while both are moving.
- Speed of P when it reaches the ground is  $2\text{ms}^{-1}$ . When P reaches the ground it stops moving. Q continues moving up slope but does not reach the pulley. Given this, find the time when Q reaches its maximum height above ground since the instant it was released

Solution:

**Part (i)**

Effect of weight caused by  $P$  in direction of slope:

$$\text{Effect of weight} = mg \sin \theta \text{ where } \sin \theta = 0.8$$

$$\text{Effect of weight} = 4.8N$$

Effect of weight caused by  $Q$  in direction of slope:

$$\text{Effect of weight} = 0.4 \times 10 \times 0.8 = 3.2N$$

Body  $P$  has greater mass than body  $Q$  so when released  $P$  moves down  $Q$  moves up on their slopes  $\therefore$

$$4.8 - T = 0.6a$$

$$T - 3.2 = 0.4a$$

Solve simultaneous equations:

$$\frac{4.8-T}{0.6} = \frac{T-3.2}{0.4} \quad T = 3.84N$$

Substitute back into initial equations to find  $a$ :

$$4.8 - 3.84 = 0.6a \quad a = 1.6ms^{-2}$$

**Part (ii)**

Use kinematics equations to find the time which it takes  $P$  to reach the ground:

$$a = \frac{v-u}{t} \text{ and } t = \frac{2-0}{1.6}$$

$$t_1 = 1.25s$$

When  $P$  reaches the ground, only force acting on  $Q$  is its own weight in the direction of slope  $= 3.2N$

$$F = ma \quad -3.2 = 0.4a$$

$$a = -8ms^{-2}$$

Now calculate the time taken for  $Q$  to reach max height

This occurs when its final velocity is 0.

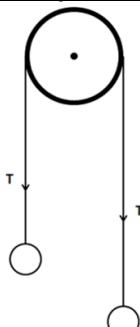
$$-8 = \frac{0-2}{t} \quad t_2 = 0.25s$$

Now do simple addition to find total time:

$$\text{Total Time} = 1.25 + 0.25 = 1.5s$$

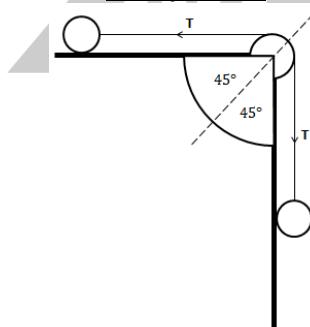
## 6.2 Force Exerted by String on Pulley

**Pulley Case 1**



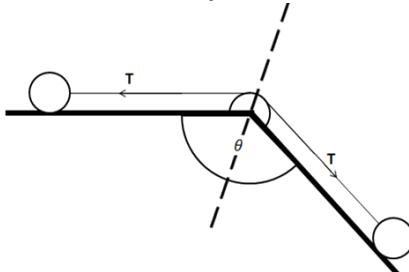
Force on pulley  $= 2T$   
Acts: downwards

**Pulley Case 2**



Force on pulley  $= T\sqrt{2}$   
Acts: along dotted line

**Pulley Case 3**



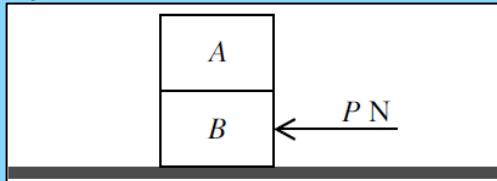
$$\text{Force on pulley} = 2T \cos\left(\frac{1}{2}\theta\right)$$

Acts: inwards along dotted line which bisects  $\theta$

## 6.3 Two Particles

{S10-P43}

**Question 7:**



$A$  and  $B$  are rectangular boxes of identical sizes and are at rest on rough horizontal plane.  $A$  mass =  $200kg$  and  $B$  mass =  $250kg$ . If  $P \leq 3150$  boxes remain at rest. If  $P > 3150$  boxes move

- Find coefficient of friction between  $B$  and floor
- Coefficient of friction between boxes is 0.2. Given that  $P > 3150$  and no sliding occurs between boxes. Show that the acceleration of boxes is not greater than  $2ms^{-2}$
- Find the maximum possible value of  $P$  in the above scenario

Solution:

**Part (i)**

$$F = \mu N$$

$F =$  to max  $P$  that does not move the boxes

$N =$  to contact force of both boxes acting on floor

$$\therefore 3150 = \mu \times (2000 + 2500)$$

$$\mu = 0.7$$

**Part (ii)**

Find frictional force between  $A$  and  $B$ :

$$F = 0.2 \times 2000 \quad F = 400N$$

Use Newton's Second Law of Motion to find max acceleration for which boxes do not slide (below  $F$ )

$$400 = 200a \quad a = 2ms^{-2}$$

**Part (iii)**

$P$  has to cause an acceleration of  $2ms^{-2}$  on  $B$  which will pass on to  $A$  as they are connected bodies

Simply implement Newton's Second Law of Motion

$$\therefore P = (200 + 250)(2) + 3150$$

The 3150 comes from the force required to overcome the friction

$$P = 900 + 3150 \quad P = 4050N$$

## 7. WORK, ENERGY AND POWER

### Principle of Conservation of Energy:

*Energy cannot be created or destroyed, it can only be changed into other forms*

**Work Done:**  $W = Fs$

**Kinetic Energy:**  $E_k = \frac{1}{2}mv^2$

**Gravitational Potential Energy:**  $E_p = mgh$

**Power:**  $P = \frac{W.d}{T}$  and  $P = Fv$

### 7.1 Changes in Energy

$$\epsilon_f - \epsilon_i = (\text{Work})_{\text{engine}} - (\text{Work})_{\text{friction}}$$

- $\epsilon_f$  is the final energy of the object
- $\epsilon_i$  is the initial energy of the object
- $(\text{Work})_{\text{engine}}$  is the energy caused by driving force acting on the object
- $(\text{Work})_{\text{friction}}$  is the energy used up by frictional force or any resistive force

**{S05-P04}**

**Question 7:**

Car travelling on horizontal straight road, mass 1200kg. Power of car engine is 20kW and constant. Resistance to motion of car is 500N and constant. Car passes point A with speed  $10ms^{-1}$ . Car passes point B with speed  $25ms^{-1}$ . Car takes 30.5s to move from A to B.

- Find acceleration of the car at A
- Find distance AB by considering work & energy

[Solution:](#)

**Part (i)**

Use formula for power to find the force at A

$$P = Fv$$

$$20000 = 10F \quad \text{Driving force} = 2000N$$

We must take into account the resistance to motion

$$\therefore F = \text{Driving Force} - \text{Resistance} = 2000 - 500$$

$$F = 1500$$

Use Newton's Second Law to find acceleration:

$$1500 = 1200a \quad a = \frac{1500}{1200} = 1.25ms^{-2}$$

**Part (ii)**

Use power formula to find work done by engine:

$$P = \frac{w.d.}{t}$$

$$20000 = \frac{w.d.}{30.5} \quad w.d. = 610000J$$

There is change in kinetic energy of the car so that means some work done by the engine was due to this:

$$k.E. \text{ at } A = \frac{1}{2}1200(10)^2 \quad k.E. \text{ at } B = \frac{1}{2}1200(25)^2$$

$$\text{Change in k.E.} = k.E. \text{ at } B - k.E. \text{ at } A$$

$$\text{Change in k.E.} = 375000 - 60000 = 315000$$

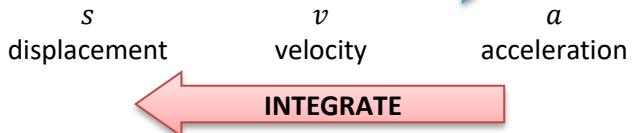
There is also some work done against resistive force of 500N; due to law of conservation of energy, this leads us to the main equation:

$$\begin{aligned} \text{w.d. by engine} &= \text{change in k.E.} \\ &\quad + \text{w.d. against resistance} \end{aligned}$$

$$\begin{aligned} 610000 &= 315000 + 500s \\ s &= \frac{610000 - 315000}{500} = \frac{295000}{500} = 590m \end{aligned}$$

## 8. GENERAL MOTION IN A STRAIGHT LINE

DIFFERENTIATE



INTEGRATE

- Particle at instantaneous rest,  $v = 0$
- Maximum displacement from origin,  $v = 0$
- Maximum velocity,  $a = 0$

**{W10-P42}**

**Question 7:**

Particle P travels in straight line. It passes point O with velocity  $5ms^{-1}$  at time  $t = 0s$ .

$P$ 's velocity after leaving O given by:

$$v = 0.002t^3 - 0.12t^2 + 1.8t + 5$$

$v$  of  $P$  is increasing when:  $0 < t < T_1$  and  $t > T_2$

$v$  of  $P$  is decreasing when:  $T_1 < t < T_2$

- Find the values of  $T_1$  and  $T_2$  and distance  $OP$  when  $t = T_2$
- Find  $v$  of  $P$  when  $t = T_2$  and sketch velocity-time graph for the motion of  $P$

[Solution:](#)

**Part (i)**

Find stationary points of  $v$ ; maximum is where  $t = T_1$  and minimum is where  $t = T_2$

$$\frac{dv}{dt} = 0.006t^2 - 0.24t + 1.8$$

Stationary points occur where  $\frac{dv}{dt} = 0$

$$\therefore 0.006t^2 - 0.24t + 1.8 = 0$$

Solve for  $t$  in simple quadratic fashion:

$$t = 30 \quad \text{and} \quad 10$$

Naturally  $T_1$  comes before  $T_2$

$$\therefore T_1 = 10s \quad \text{and} \quad T_2 = 30$$

Finding distance  $OP$  by integrating

$$\therefore s = \int_0^{30} v dt$$

$$s = \int_0^{30} (0.002t^3 - 0.12t^2 + 1.8t + 5) dt$$

$$s = \int_0^{30} [0.0005t^4 - 0.04t^3 + 0.9t^2 + 5t] dt$$

$$s = 285m$$

**Part (ii)**

Do basic substitution to find  $v$

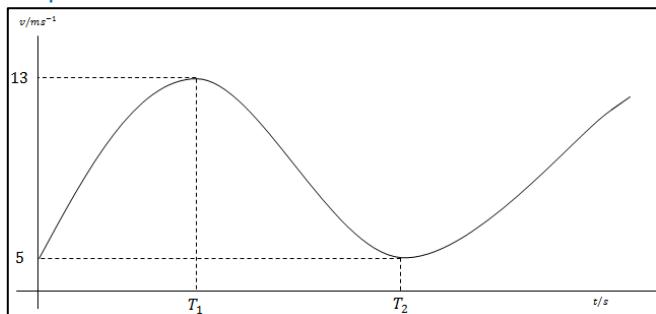
$$v = 0.002t^3 - 0.12t^2 + 1.8t + 5$$

$$t = 30 \quad v = 5$$

To draw graph find  $v$  of  $P$  at  $T_1$  using substitution and plot roughly

$$v \text{ at } T_1 = 13$$

Graph:



Since the distance before 20 seconds has already been taken into consideration:

$$t = t - 20$$

$$a = \frac{6.5 - 2}{6}$$

$$a = 0.75$$

$$\therefore s_2 = 2(t - 20) + \frac{1}{2}(0.75)(t - 20)^2$$

$$s_2 = 2t - 40 + 150 + 0.375t^2 - 15t$$

$$s_2 = 0.375t^2 - 13t + 110$$

Finally add both to give you  $s$

$$s = s_1 + s_2$$

$$s = 0.375t^2 - 13t + 110 + 92$$

$$s = 0.375t^2 - 13t + 202$$

**{S13-P42}**

**Question 6:**

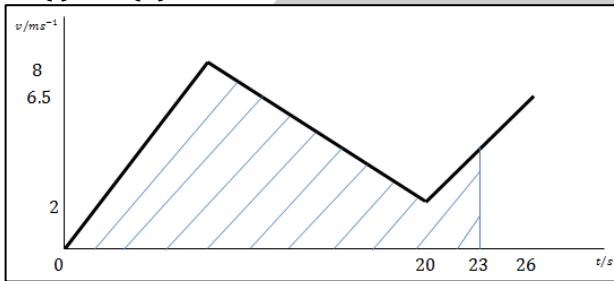
Particle  $P$  moves in a straight line. Starts at rest at point  $O$  and moves towards a point  $A$  on the line. During first 8 seconds,  $P$ 's speed increases to  $8\text{ms}^{-1}$  with constant acceleration. During next 12 seconds  $P$ 's speed decreases to  $2\text{ms}^{-1}$  with constant deceleration.  $P$  then moves with constant acceleration for 6 seconds reaching point  $A$  with speed  $6.5\text{ms}^{-1}$

- Sketch velocity-time graph for  $P$ 's motion
- The displacement of  $P$  from  $O$ , at time  $t$  seconds after  $P$  leaves  $O$ , is  $s$  metres. Shade region of the velocity-time graph representing  $s$  for a value of  $t$  where  $20 \leq t \leq 26$
- Show that for  $20 \leq t \leq 26$ ,

$$s = 0.375t^2 - 13t + 202$$

**Solution:**

**Part (i) and (ii)**



**Part (iii)**

First find  $s$  when  $t = 20$ , this will produce a constant since  $20 \leq t \leq 26$

$$s_1 = \frac{1}{2}(8)(8) + \frac{1}{2}(8+2)(12) = 92\text{m}$$

Finding  $s$  when  $20 \leq t \leq 26$ :

$$s = ut + \frac{1}{2}at^2$$

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