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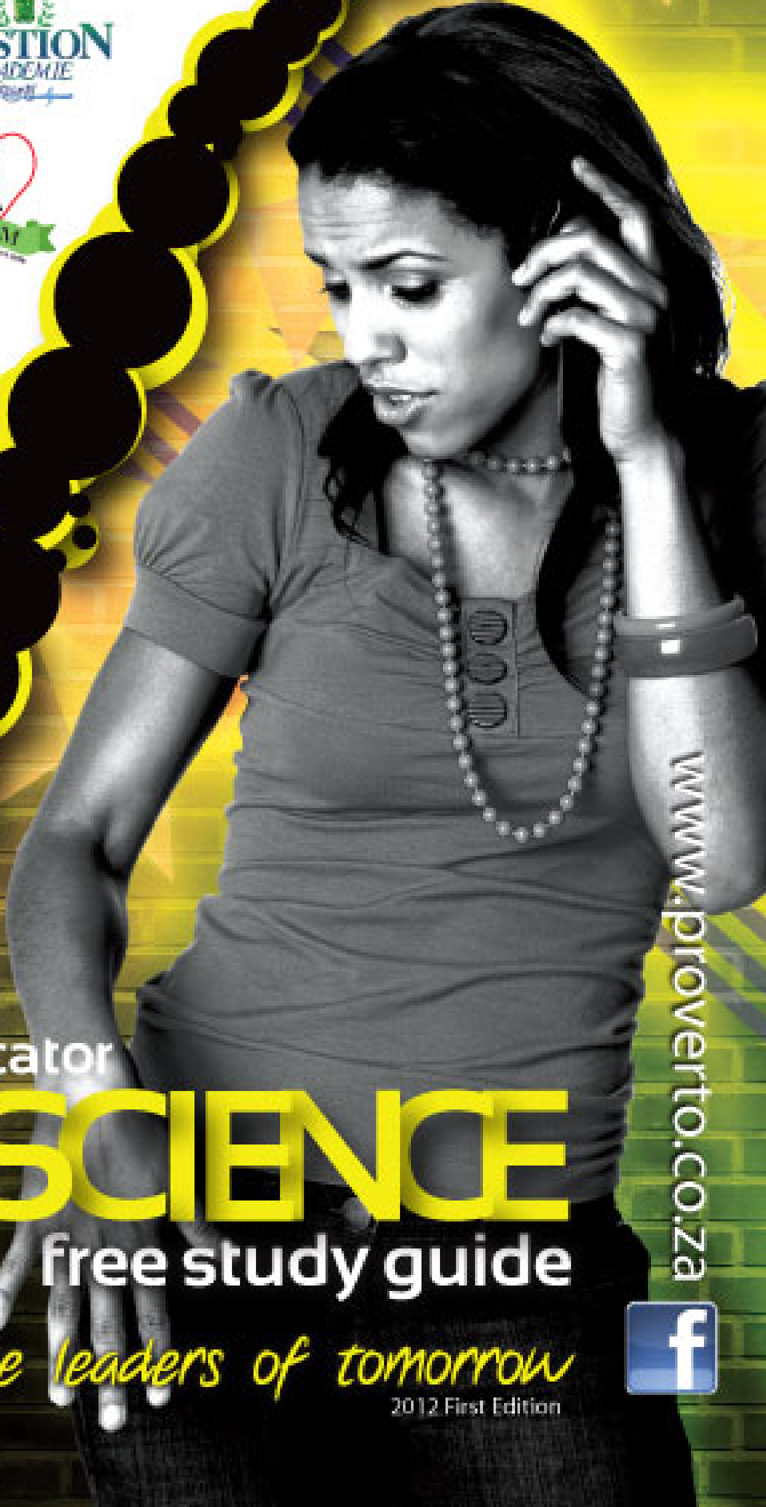

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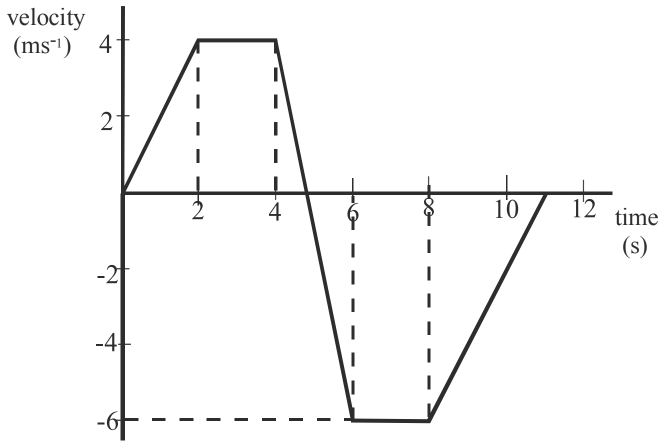
MECHANICS

GENERAL NOTES:

- In this study guide the value for gravitational acceleration will be taken as 9,8 ms^{-2}.
- We use the subscript i for initial values of a certain interval and f for the final values of the interval. For example, v_i will be the initial velocity of a certain interval (instead of u as used in some textbooks) and v_f will be the final velocity of the interval (instead of just v as used in some textbooks.)

PROBLEM 1: GRAPHS OF MOTION

The path of a moving particle is limited to a straight line running north-south. Use a coordinate system where north is positive. The accompanying graph gives the velocity as a function of time. The graph intersects the horizontal axis at 4,8 s and 11 s.



1.1 Complete a table in which you indicate the directions of the velocity in one column and the acceleration in another column for the following instants: 1,0s, 3,0s, 4,2s, 5,0s, 7,0s, 10,0s. In a third column indicate whether the object is moving slower, faster, or maintaining a constant speed.

Time	Velocity	Acceleration	faster/slower
1,0s	North (+)	North (+)	faster
3,0s	North (+)	zero	constant speed
4,2s	North (+)	South (-)	slower
5,0s	South (-)	South (-)	faster
7,0s	South (-)	zero	constant speed
10s	South (-)	North (+)	slower

It is important to note that a negative acceleration does not necessarily mean *deceleration*. As seen from the table above, the directions (signs) of both the velocity and the acceleration indicate whether an object moves faster or slower.

1.2 What is the total displacement of the object during the journey?

Find the area under the graph. The areas below the x-axis are negative.

$$\text{Area} = \tfrac{1}{2}(2)(4) + (2)(4) + \tfrac{1}{2}(0{,}8)(4) - \tfrac{1}{2}(1{,}2)(6) - (2)(6) - \tfrac{1}{2}(3)(6)$$
$$= -11\,\text{m}$$

1.3 What is the average velocity for the entire journey?

Definition of velocity: velocity = displacement ÷ time

$$\vec{v} = \frac{\Delta x}{\Delta t} = \frac{-11\text{m}}{11\text{s}} = -1{,}0\ \text{ms}^{-1}$$

1.4 What is the acceleration

1.4.1. during the first two seconds?

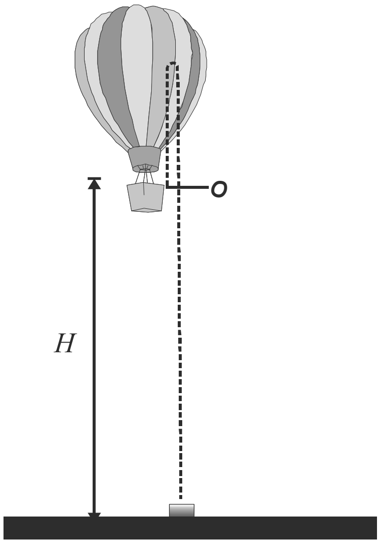
1.4.2 between $t = 4\text{s}$ and $t = 6\text{s}$?

Calculate the gradient of the velocity -time graph.

$$1.4.1 \quad a = \frac{\Delta v}{\Delta t} = \frac{4-0}{2-0} = 2\,ms^{-2} \quad \therefore\ 2\,ms^{-2},\ north$$

$$1.4.2 \quad a = \frac{\Delta v}{\Delta t} = \frac{-6-4}{6-4} = -5\,ms^{-2} \quad \therefore\ 5\,ms^{-2},\ south$$

PROBLEM 2: VERTICAL PROJECTILE MOTION



A Hot air balloon is ascending with a speed of 5,00 ms^{-1}. A person in the basket releases a bag of flour at a height H. The bag strikes the earth with a speed of 18,0 ms^{-1}.

2.1 How long will the bag be in the air?

Choose a coordinate system with the origin (O) at the point where the bag is released and the positive Y-axis pointing upwards. With this choice of coordinate system, gravitational acceleration will always be negative (whether the bag of flour is moving upward or not), because gravity is always pulling downwards. Remember that all the quantities in the equations of motion are vectors (except time). We therefore need to substitute the signs of these quantities together with their magnitudes. There are two ways to solve this problem:

Method 1

Divide the motion in three parts: ① upward to maximum height, ② from the maximum height downward to the origin, and ③ from the origin downward to the ground.

①For the upward motion:

$$g = -9{,}8\ ms^{-2}$$
$$v_i = +5{,}0\ ms^{-1}$$
$$v_f = 0$$

$$v_f = v_i + gt$$
$$\therefore 0 = 5 - 9{,}8t$$
$$\therefore t_1 = 0{,}51\,\text{s}$$

②For downward motion (from maximum height to the origin):

$$v_i = 0$$
$$v_f = -5{,}0\,\text{ms}^{-1}$$
$$\therefore t_2 = 0{,}51\,\text{s} \text{ (same as for 1)}$$

③From the origin to the ground: $a = g = -9{,}8\,\text{ms}^{-2}$ $v_f = v_i + at$

$v_i = -5{,}0\,\text{ms}^{-1}$ $\therefore -18 = -5 - 9{,}8t$

$v_f = -18\,\text{ms}^{-1}$ $\therefore t_3 = 1{,}33\,\text{s}$

$$\text{Total time} = t_1 + t_2 + t_3 = 0{,}51 + 0{,}51 + 1{,}33 = 2{,}35\text{s}$$

Method 2

Do not divide the motion into sections, but consider the complete motion at once.

$a = g = -9{,}8\,\text{ms}^{-2}$ $v_f = v_i + at$

$v_i = 5\text{ms}^{-1}$ $\therefore -18 = 5 - 9{,}8t$

$v_f = -18\,\text{ms}^{-1}$ $\therefore t = 2{,}35\text{s}$

2.2 Find H, the height from which the bag was released.

Again consider the complete motion.

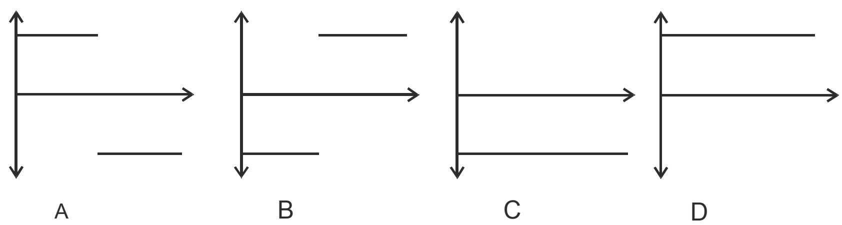
$v_i = 5\,\text{ms}^{-1}$ $s = v_i t + \frac{1}{2}at^2$

$a = -9{,}8\,\text{ms}^{-2}$ $= (5)(2{,}35) + \frac{1}{2}(-9{,}8)(2{,}35)^2$

$t = 2{,}35\text{s}$ $= -15{,}3\text{m}$

$\therefore H = 15{,}3\,\text{m}$

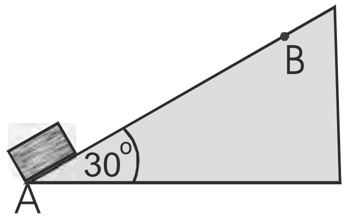
2.3 Which one of the graphs below represents the acceleration-time graph for this motion?



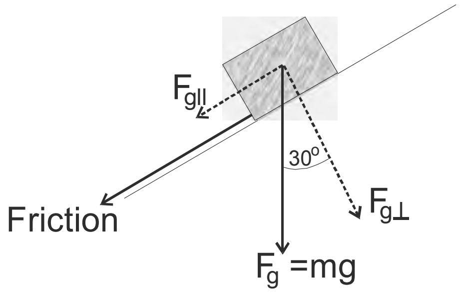
Answer: **C**. A and B are wrong, because they imply that the direction of the acceleration changes after the bag has reached its maximum height, which is of course not true. Gravitational acceleration is always downward. For our choice of coordinate system with the negative y-axis downward, the correct acceleration-time graph is C.

PROBLEM 3: WORK AND ENERGY

A block is kicked at the bottom of an inclined plane (at point A) so that it starts sliding upwards with an initial speed of 2,9 ms^{-1}. The mass of the block is 3,1 kg. A frictional force of 6,5 N is acting on the block. The block comes to rest at point B.



3.1 Draw a force diagram showing the forces acting on the block while it is moving upward.



3.2 Calculate the total work done on the block.

Remember: $W_{tot} = \Delta E_k$ (this is always true)

$$\begin{aligned} W_{tot} &= E_{kf} - E_{ki} \\ &= 0 - \tfrac{1}{2} m v_i^2 \\ &= -\tfrac{1}{2}(3{,}1)(2.9)^2 \\ &= -13\ \mathrm{J} \end{aligned}$$

3.3 Calculate the component of the resultant force on the block, parallel to the plane.

$$\begin{aligned} F_{res} &= F_{friction} + F_{gll} \\ &= 6{,}5 + mg\sin 30^\circ \\ &= 21{,}7\ \mathrm{N} \end{aligned}$$

3.4 Calculate how far the block will travel up the plane.

Definition of work: $W = F.\ \Delta x$

Both F and Δx are vectors, therefore we should include signs to indicate their directions. Choose a coordinate system with the x - axis parallel to the inclined plane with positive upwards along the plane.

$\therefore F = -21{,}7\ \mathrm{N}$ (down the incline) and Δx is positive

$$\begin{aligned} W &= F.\Delta x \\ -13 &= (-21{,}7)\Delta x \\ \therefore \Delta x &= 0{,}60\ \mathrm{m} = \text{the distance AB} \end{aligned}$$

PROBLEM 4: CONSERVATION OF ENERGY

A brick of mass 1,2 kg is thrown off a building, 25 m high, with a speed of 1,1 ms^{-1} directly downwards. As it falls onto the earth, it penetrates 15 cm into the ground. Ignore air friction.

4.1 Calculate the speed with which the brick hits the ground. (Note: This can be solved either by equations of motion or by energy principles. Let's use energy conservation in this case.)

Total mechanical energy at the top = Total mechanical energy at the bottom
(This is true, because we ignore air friction)

$$\text{Tot}\,E_{\substack{\text{mech}\\\text{at top}}} = \text{Tot}\,E_{\substack{\text{mech}\\\text{at bottom}}}$$

$$\therefore (E_k + E_p)_{top} = (E_k + E_p)_{bottom}$$

$$\therefore \tfrac{1}{2}mv_{top}^2 + mgh = \tfrac{1}{2}mv_{bottom}^2 + 0$$

$$\therefore \tfrac{1}{2}v_{top}^2 + gh = \tfrac{1}{2}v_{bottom}^2$$

$$\tfrac{1}{2}(1{,}1)^2 + (9{,}8)(25) = \tfrac{1}{2}v_{bottom}^2$$

$$\therefore v_{bottom} = 22{,}2\ \text{ms}^{-1}$$

Note that in the fourth step, the mass cancels from the equation. It means that if the brick had a different mass its final speed would still be the same.

4.2 Calculate the total work done on the brick as it enters the ground.

$$W_{tot} = \Delta E_k = E_{kf} - E_{ki}$$

Since it comes to rest in the ground $E_{kf} = 0$.

$$W_{tot} = -\tfrac{1}{2}mv_i^2 = -(1{,}2)(22{,}2)^2 = -296\,\text{J}$$

4.3 Calculate the frictional force exerted by the ground on the brick to bring it to rest. (Let's take downwards as negative.)

$$W_{tot} = F_{res}.\Delta x$$

$$-296 = F_{res}(-0{,}15)$$

$$\therefore F_{res} = 1973\ \text{N}$$

This is not the frictional force yet. F_{res} comprises of the contribution by gravity F_{g} (downward) and friction F_{f} (upward).

$$-F_g + F_f = F_{res}$$

$$-mg + F_f = 1973$$

$$F_f = 1973 + (1{,}2)(9{,}8) = 1985\ \text{N}$$

4.4 Calculate the change in momentum the brick experiences from the moment it hits the ground until it comes to rest. (Take downwards as negative)

$$\Delta p = mv_f - mv_i$$
$$= 0 - (1{,}2)(-22{,}2)$$
$$= 26{,}6\ \text{kgms}^{-1}$$

4.5 Calculate the time it takes the brick to come to rest from the moment it hits the ground.

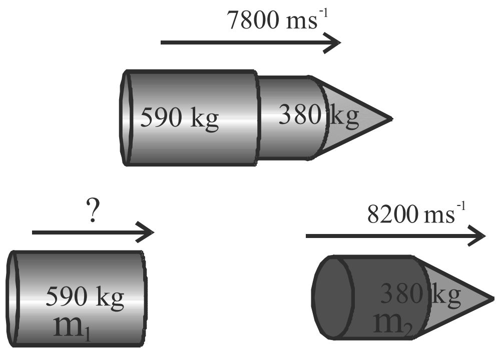
$$\text{Impuls} = \text{change in momentum}$$

$$F_{res}.\Delta t = \Delta p$$
$$\therefore\ (1973)\Delta t = -26{,}6$$
$$\therefore\ \Delta t = 0{,}013\,\text{s}$$

This is only a fraction of a second, but it is in accordance with our experience. We know that when a brick falls onto the ground it comes to rest almost immediately.

PROBLEM 5: CONSERVATION OF MOMENTUM

A space vehicle consists of a rocket motor with a mass of 590 kg and a capsule with a mass of 380 kg. While the space vehicle is travelling with a speed of 7800 ms^{-1} (as measured from the earth) the rocket motor is disengaged and when a compressed spring is released, the rocket motor is sent away from the capsule. As a result the capsule speeds forward at 8200 ms^{-1} (as measured form the earth).



5.1 What is the speed of the rocket motor after the two sections have been separated?

Total momentum before separation = total momentum after separation

$$(m_1 + m_2)u_{(before)} = m_1v_1 + m_2v_2$$
$$(590 + 380)(7800) = (380)(8200) + (590)v_2$$
$$v_2 = 7542\ \text{ms}^{-1}$$

5.2 An observer in the capsule looks backward at the rocket motor. How fast and in which direction is the rocket motor moving according to him?

The rocket motor is still moving in the original direction (as seen by someone on the earth), but just slower than before the separation. An observer in the capsule will see the motor receding (moving backward) at a speed of (8200-7542) = 658 ms^{-1}. Thus, in the earths reference frame the motor is moving forward at 7542 ms^{-1} and in the reference frame of the capsule, the motor is moving backward at 658 ms^{-1}.

PROBLEM 6: CONSERVATION OF MOMENTUM (2D)

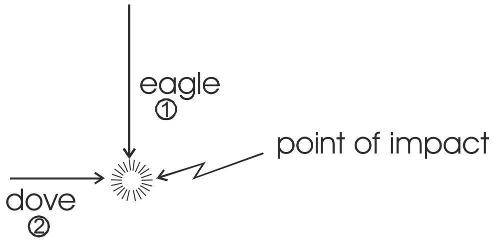
An eagle soaring high in the sky, spots a dove 30 m below, flying horizontally with a speed of 12 ms^{-1}. The eagle goes into a vertical dive and grabs the dove when it is directly below the point where the eagle went into its dive. The mass of the dove is 0,80 kg and the mass of the eagle is 2,1 kg. Assume that the initial vertical speed of the eagle is zero.

6.1 What is the speed of the eagle when it grabs the dove. Choose upwards as positive.

$$y = v_i t + \tfrac{1}{2} g t^2$$
$$-30 = 0 + \tfrac{1}{2}(-9{,}8)t^2$$
$$t = 2{,}5\,\text{s}$$
$$v = gt = -24{,}2\ \text{ms}^{-1}$$

6.2 Calculate the speed of the eagle just after it has grabbed the dove in its claws.

Choose a coordinate system: Positive x is to the right and positive y is upwards.



Momentum is conserved in the X- and the Y -direction:

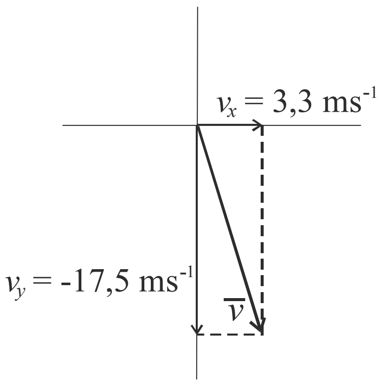
X-direction:

$$m_1 u_{x1} + m_2 u_{x2} = (m_1 + m_2) v_x$$
$$0 + (0{,}8)(12) = (0{,}8 + 2{,}1) v_x$$
$$\therefore\ v_x = 3{,}3\ \text{ms}^{-1}$$

Y-direction:

$$m_1 u_{y1} + m_2 u_{y2} = (m_1 + m_2) v_y$$
$$(2{,}1)(-24{,}2) + 0 = (2{,}9) v_y$$
$$\therefore\ v_y = -17{,}5\ \text{ms}^{-1}$$

Now that we have the two components of the velocity, we can find the magnitude of the instantaneous velocity just after the eagle has grabbed the dove, which is the speed required in the question.



$$|\overline{v}| = \sqrt{(3{,}3)^2 + (-17{,}5)^2} = 17{,}8\ \text{ms}^{-1}$$

6.3 Is the collision between the dove and the eagle elastic or inelastic?

For an elastic collision the change in kinetic energy for the whole system is equal to zero.

Kinetic energy of dove + eagle before collision = $(\frac{1}{2}mv^2)_{eagle} + (\frac{1}{2}mv^2)_{dove}$

$= \frac{1}{2}(2{,}1)(24{,}2)^2 + \frac{1}{2}(0{,}8)(12)^2$

$= 673\ \text{J}$

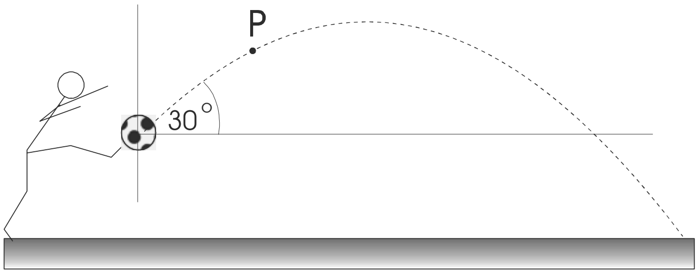
Kinetic energy of dove + eagle after collision = $\frac{1}{2}(2{,}1 + 0{,}8)(17{,}8)^2$

$= 459\ \text{J}$

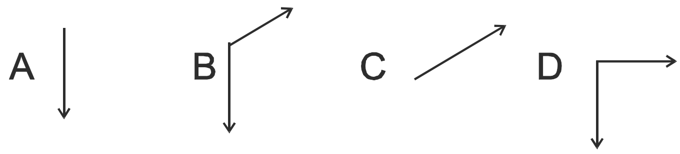
The total kinetic energy decreased significantly. This collision is therefore inelastic.

PROBLEM 7: PROJECTILE MOTION (2D)

A boy kicks a soccer ball and the ball leaves the boy's boot at a height of 0,80 m above the ground with a speed of 8,8 ms^{-1} at an angle of 30° with the horizontal. Ignore air friction.



7.1 Which diagram shows the direction(s) of the force(s) acting on the ball, when the ball is at point P along its trajectory?



Answer: **A** Gravity is the only force acting on the ball during its journey through the air. There are no horizontal forces acting on the ball. As soon as the ball leaves the boy's boot, the force between the ball and the boot ceases to exist. The boot cannot exert a force on the ball without touching it. Someone choosing B as answer, is probably confusing force and momentum. It is true that the ball has momentum in the direction of motion, but one cannot indicated force and momentum on the same vector diagram.

Let us analyse the problem:

X-components	**Y-components**
$a_x = 0$ $v_x = v_{xi}$ (stays constant) At max. height $v_x = v_{xi}$ displacement $x = v_{xi} \times t$	$a_y = -9{,}8\ ms^{-2}$ v_y not constant At max. height $v_y = 0$ displacement: $y = v_{yi}\,t + ½\,gt^2$

7.2 Write the x- and y-components of the initial velocity.

$$v_{xi} = 8{,}8\cos 60°\ \mathrm{ms^{-1}} = 4{,}4\ \mathrm{ms^{-1}}$$
$$v_{yi} = 8{,}8\sin 60°\ \mathrm{ms^{-1}} = 7{,}6\ \mathrm{ms^{-1}}$$

7.3 Calculate the maximum height the ball reaches above the ground.

This question requires us to look at the vertical motion (y-components). When the ball reaches its maximum height v_y = 0.

$$v_y = v_{yi} + gt$$
$$\therefore 0 = 7{,}6 - 9{,}8t$$
$$\therefore t = 0{,}775 = 0{,}78\ \mathrm{s}$$

$$y = v_{yi}t + \tfrac{1}{2}gt^2$$
$$\therefore y = (7{,}6)(0{,}78) + \tfrac{1}{2}(-9{,}8)(0{,}78)^2$$
$$\therefore y = 2{,}9\ \mathrm{m}$$

The height above the ground = 2,9 m + 0,8 m = 3,7 m

7.4 Calculate how far the boy kicks the ball, that is, what distance from the boy's boot does the ball fall to the ground.

When the ball reaches the ground y = -0,80 m. (That is 0,8 m below the point where the ball was kicked). This question asks us to find x when y = -0,8 m. First find the time it takes the ball to reach the ground.

$$y = v_{yi}t + \tfrac{1}{2}a_y t^2$$
$$-0{,}8 = 7{,}6t - \tfrac{1}{2}(9{,}8)t^2$$

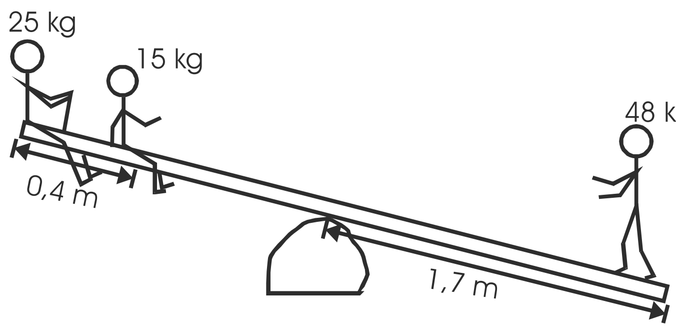
Solve for t: $t = 1{,}65\ \mathrm{s}$

Substitute in x:

$$x = v_x t$$
$$\therefore\ x = (4{,}4)(1{,}65) = 7{,}3\ \mathrm{m}$$

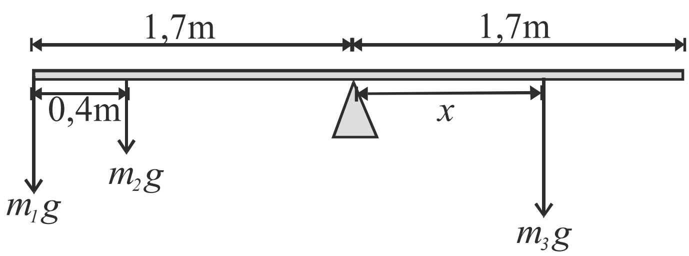
PROBLEM 8: MOMENT OF FORCE

Three children are playing on a see-saw they made by balancing a 3,4 m long plank on a rock in the middle of the plank. The plank is homogeneous. The two smallest children (with masses m_1 = 25 kg and m_2 = 15 kg) sit on the left side (0,40 m apart) as shown in the diagram. When the oldest child (mass m_3 = 48 kg) stand on the right end, that end touches the ground. How far must the oldest child walk along the plank towards the rock, so that the see-saw will balance horizontally again?



Remember: Moment of force: $\tau = F \times l$, where F is an applied force and l the distance from the point where the force is applied to the pivot point.

First draw a force diagram:



We will apply the following principle: the sum of clockwise moments = the sum of counter clockwise moments.

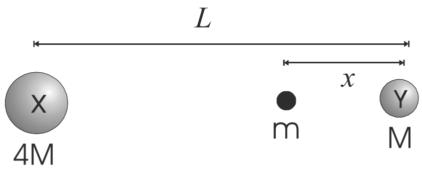
(We do not take the mass of the plank and the effect gravitation has on the plank into account, because the plank is homogeneous and balanced in the middle. (Homogeneous means that the plank has the same density right through and that it will balance in the middle when it has nothing on it) Gravitation has therefore no moment (rotating effect) on the plank itself.)

$$m_3 g x = m_1(1{,}7) + m_2 g(1{,}3)$$
$$(\div g)$$
$$(48)x = (25)(1{,}7) + (15)(1{,}3)$$
$$\therefore \quad x = 1{,}3\,\text{m}$$

$\therefore$ distance that the oldest child will walk $= 0{,}4$ m

PROBLEM 9: GRAVITY

The distance between the centres of two spheres, X and Y, is L. The mass of X is 4 times that of Y. Where, measured from Y, is the gravitational force on an object between the spheres, equal to zero?



A. ½L B. ⅓L C. ¼L D. ⅛L

Answer: **B**

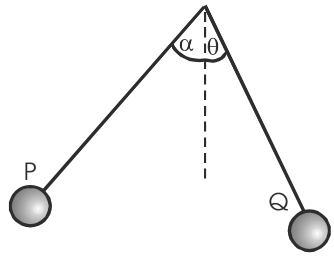
Consider the diagram: Let the mass of Y be M, then the mass of X is 4M. The mass of the other object is m. We require the force of X on m (F_{Xm}) to be equal the force of Y on m (F_{Ym}).

$$F_{\text{Xm}} = F_{\text{Ym}}$$
$$\frac{G(4M)m}{(L-x)^2} = \frac{GMm}{x^2}$$
$$4x^2 = (L-x)^2$$
$$x = \tfrac{1}{3}L$$

ELECTRICITY AND MAGNETISM

MULTIPLE CHOICE QUESTIONS

1. The diagram shows a setup where two spheres (P and Q), attached to thin strings, have been charged positively. The two angles that the strings make with the vertical are not equal. A possible reason for this is



A. The force Q exerts on P is greater than the force P exerts on Q
B. The charge on Q must be more than charge on P
C. Q must be heavier than P
D. none of the above

Answer: **C**
According to Newton's third law, the force Q exerts on P is equal in magnitude to the force P exerts on Q. Therefore A and B is wrong, because they both violate Newton's third law. The only reason why the electrostatic repulsion between the two spheres (as calculated by Coulomb's law) cannot lift Q as high as it does P, is because Q has a greater weight than P.

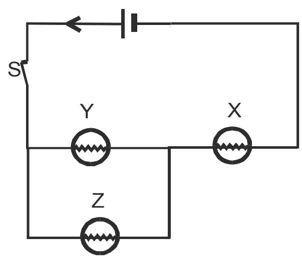
2. In which unit is the work done on a unit charge, as it moves from one point in a circuit to another, measured?
A. Ampere
B. Volt
C. Ohm
D. Watt

Answer: **B,** $V = \frac{W}{q}$ (volt = joule/coulomb)

3. Which energy transfer is mainly taking place when charged particles move through a cell with low internal resistance?
A. chemical energy to electric potential energy
B. chemical energy to kinetic energy
C. kinetic energy to electric potential energy
D. heat to kinetic energy?

Answer: **A**

4. If all the bulbs in the circuit are identical and the resistance of the conductors and the cell is negligible, how does the brightness of bulb X compare with that of bulb Y?



A. X is brighter than Y
B. the same
C. X is dimmer than Y

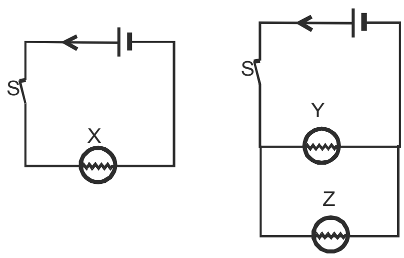
Answer: **A** Y and Z will glow much dimmer than X.

Let us assume that at the instant we compare the brightness of the bulbs, the resistances of the three bulbs are equal (see note below). Say $R = 2\ \Omega$ for all the bulbs. If the current through X is1 A, the current through Y is 0,5 A. The power in each bulb is the rate at which electrical potential energy is converted to light and heat and can be an indication of the brightness of the bulb:

$$P_X = I^2 R = (1)^2(2) = 2\ \mathrm{W}$$
$$P_Y = (0{,}5)^2(2) = 0{,}5\mathrm{W}$$

(Note: Because X glow brighter than Y and Z, the temperature of X is higher than that of Y and Z. Since the temperature influences the resistance of a wire, the resistance of the three bulbs are probably not exactly the same as we would expect of identical bulbs)

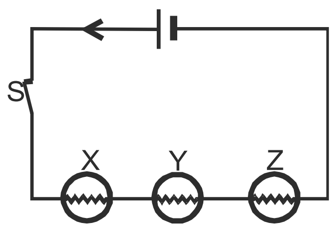
5. If all the components in these circuits are identical and the resistance of the conductors and the cell is negligible, how does the brightness of bulb X compare with that of bulb Y?



A. X is brighter than Y
B. the same
C. X is dimmer than Y

Answer: **B,** the voltage across the two bulbs is the same and they have the same resistance. The power $P = \frac{V^2}{R}$ is the same for both.
Note: Remember that the resistance of filament light bulbs are influenced by the temperature of the filament. It might happen that if you close the circuit on the left long before the other one, that particular bulb will reach a higher temperature and won't have the same resistance as the others any more. For the situation above, we assumed that the bulbs have the same resistance at the instant the comparison of brightness was done.

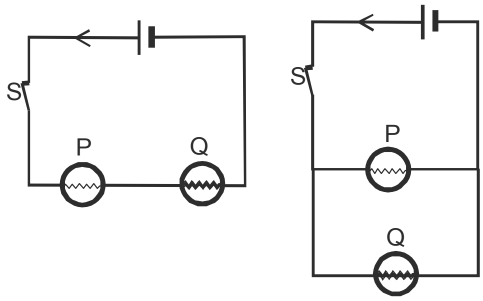
6. The diagram shows an electric circuit with three different light bulbs X, Y and Z. When switch S is closed, we find that bulbs X and Y are glowing, but not bulb Z. The reason for this is that .....



A. Z has fused
B. the resistance of Z is too low
C. the resistance for Z is too high
D. the current is to weak by the time it reaches Z

Answer: **B**, If Z has fused, the circuit will be broken and none of the bulbs will glow - so A is wrong. A bulb glows because the filament gets hot and that happens because the resistance of the filament is high. If the resistance is low the filament won't get hot and the bulb will not glow.

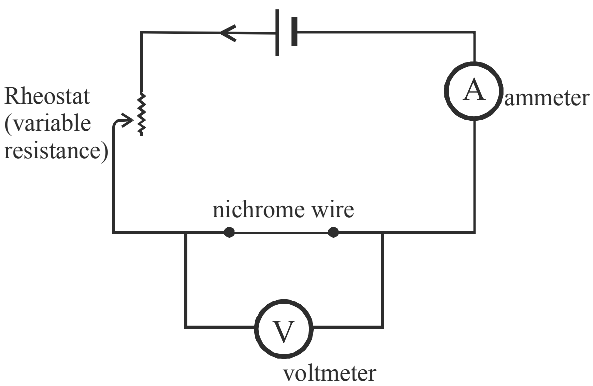
7. Two light bulbs, one with a thin filament (P) and the other with a thicker filament (Q) but of the same length and material as P, are connected in circuits consecutively, as shown. The cells are identical with negligible internal resistance. Compare the brightness of P with that of Q in each circuit. Choose from the table below the correct combination.



	Series circuit	Parallel circuit
A	P is dimmer than Q	P is dimmer than Q
B	P is dimmer than Q	P is brighter than Q
C	P is brighter than Q	P is dimmer than Q
D	P is brighter than Q	P is brighter than Q

Answer: **C.** P has a higher resistance than Q. In the series circuit the current is the same through both bulbs. Looking at $P = I^2R$ we see that the power in the bulb with the highest resistance is the highest and therefore will glow the brightest. In the parallel circuit the potential difference across the bulbs is the same and from $P = \frac{V^2}{R}$ we see that the bulb with the highest resistance has the lowest power and will therefore glow dimmer.

8. Susan reads in her science textbook that for a certain type of resistor, the ratio of the potential difference (V) across the resistor to the current through the resistor (I) stays constant as long as the temperature of the resistor does not change. She wants to check if this is true for a piece of nichrome wire by connecting it in a circuit similar to the one in the diagram. If Susan did the investigation correctly, which one of the tables below can be a representation of her data?



A

V (volt)	I (ampere)
1,0	0,2
1,0	0,2
1,0	0,2
1,0	0,2
1,0	0,2

B

V (volt)	I (ampere)
0,50	0,10
0,95	0,19
1,45	0,28
1,70	0,35
1,90	0,38

C

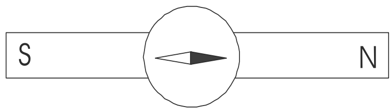
V (volt)	I (ampere)
1,1	0,20
1,0	0,19
0,9	0,21
0,9	0.20
1,0	0,21

D

V (volt)	I (ampere)
1,0	0,2
1,0	0,3
1,0	0,4
1,0	0,5
1,0	0,6

Answer: **B**

9. We place a compass right on top of a bar magnet and see that the orientation of the compass needle is as shown in the diagram.

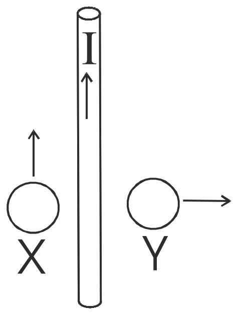


We remove the compass from the bar magnet and let the needle orientate itself in the magnetic field of the earth. In which direction will the black end of the compass needle point?

A. to the North
B. to the South
C. It depends on whether we are in the northern or southern hemisphere.

Answer: **B**. The magnetic pole in the Earth's Southern Hemisphere (near the south geographic pole) is actually the north pole of the Earth's magnetic dipole.

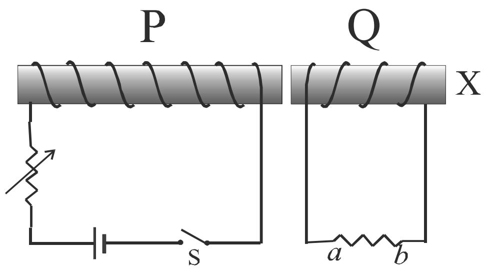
10. The diagram shows a section of a long straight conductor carrying a constant current to the top of the page. Two metal rings (X and Y) on opposite sides of the conductor are being moved in the directions shown in the diagram. The current(s) induced in the two metal rings (X and Y) can be described by



A. X: No current induced, Y: clockwise
B. X: clockwise, Y: counter clockwise
C. X: counter clockwise, Y: clockwise
D. X: No current induced, Y: counter clockwise
E. X: counter clockwise, Y: no current induced

Answer: **A**, at a constant distance from the wire, the magnetic field is constant, so there is no change in magnetic flux through loop X as it moves parallel to the wire and therefore no induced current. As loop Y moves away from the wire the field lines going into the page through loop Y decreases, and according to Lenz's law a clockwise current will be induced in Y.

11. Two sets of coils of insulated wire are wound around two cardboard tubes and connected in circuits as shown in the diagram. A student is experimenting with this by changing something in the setup to create different situations. She also uses a compass to see what the induced magnetic pole at X will be.



Situation (i): Coil P is being moved towards the left, while S is closed.
Situation (ii): By means of the rheostat, the resistance in circuit P is gradually increased

Decide in each situation what the induced magnetic pole at X will be.

	Situation (i)	Situation (ii)
A	North	North
B	South	South
C	North	South
D	South	North

Answer: **A**

12. Magnets attract
A. only iron, nickel and cobalt
B. all metals except aluminum
C. all metals
D. only steel

Answer: **A**

PROBLEM 1: COULOMB'S LAW

Two small conducting spheres (A and B) are charged with +2,0 μC and -3,0 μC respectively and placed at a distance of 5,0 cm from each other and experience an attractive force F. A third uncharged, conducting sphere with an insulating handle is brought into contact with the first sphere (A) and then, without touching anything else, brought into contact with B. By which distance should A and B be separated now, to experience the same force of attraction, F, between them as before?

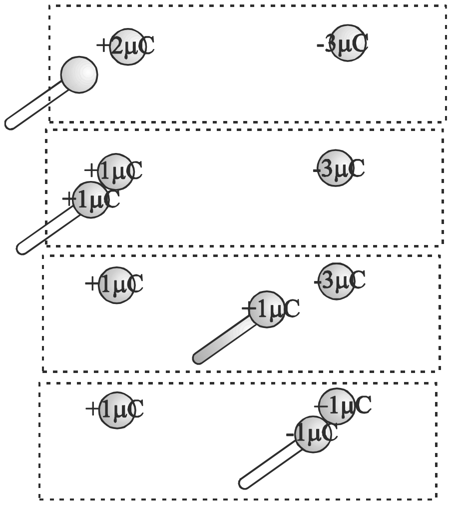
First find the initial force of attraction between the spheres.

$$F = \frac{kq_1q_2}{r^2}$$

$$F = \frac{(9\times10^9)(2\times10^{-6})(3\times10^{-6})}{(0{,}05)^2}$$

$$F = 21{,}6\,\text{N}$$

Find out what the final charges on the spheres will be after contact with the third sphere. See the diagram.



We see that the final charges on the two spheres are +1,0 μC and -1,0 μC. The attractive force between them must be 21,6 N as required by the question.

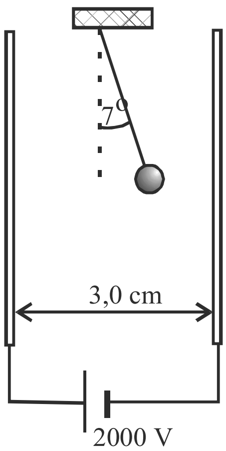
$$21{,}6 = \frac{(9\times10^9)(10^{-6})(10^{-6})}{r^2}$$

$$\therefore\ r = 0{,}0204\ \text{m}$$

$$\therefore\ r = 2{,}0\ \text{cm}$$

PROBLEM 2: A CHARGED PARTICLE IN A UNIFORM FIELD

A small, charged sphere is suspended on a very light string between two oppositely charged parallel plates, as shown in the diagram. The plate separation is 3,0 cm and the potential difference between the plates is 2000 V. The mass of the sphere is 8,0 g and the angle between the string and the vertical is 7,0°.



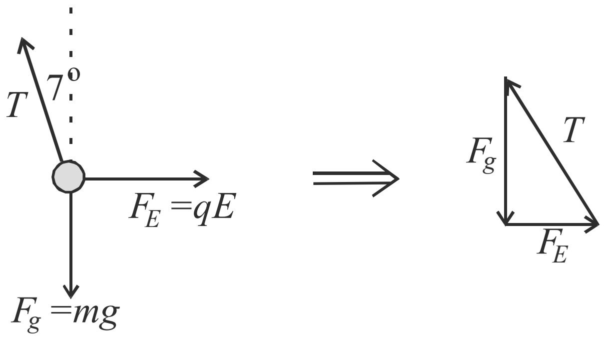
2.1 Calculate the electric field between the plates.

$$E = \frac{V}{d}$$

$$\therefore\ E = \frac{2000}{0{,}03} = 6{,}67\times10^4\ \text{Vm}^{-1}$$

2.2 Calculate the charge on the sphere. Give the answer in nC.

The forces acting on the sphere are in equilibrium.

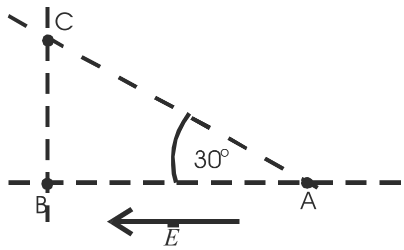


$$\begin{aligned} F_E &= F_g \tan 7° \\ &= (0{,}008)(9{,}8)\tan 7° \\ &= 9{,}63 \times 10^{-3}\,\text{N} \end{aligned}$$

$$\therefore qE = 9{,}63 \times 10^{-3}\,\text{N}$$
$$\therefore q = 1{,}44 \times 10^{-7}\,\text{C} = 144\,\text{nC}$$

PROBLEM 3: WORK AND ENERGY IN AN ELECTRIC FIELD

A particle with mass $3{,}00 \times 10^{-23}$ kg and charge + 1,50 nC moves in a uniform field from rest from point A to point B where its speed is found to be $2{,}00 \times 10^{6}$ ms^{-1}. Point A and point B are separated by 5,00 cm.



3.1 How much work is done on the particle by the field?

$$\begin{aligned} W = \Delta E_k &= E_{kB} - E_{kA} \\ &= \tfrac{1}{2} m v_B^2 - 0 \\ &= \tfrac{1}{2}(3 \times 10^{-23})(2 \times 10^{6})^2 \\ &= 6{,}0 \times 10^{-11}\,\text{J} \end{aligned}$$

3.2 Find the potential difference between points A and B and explain what the answer means in terms of the definition of potential difference.

$$V_{AB} = \frac{W_{A \to B}}{q} = \frac{6 \times 10^{-11}}{1{,}5 \times 10^{-9}} = 0{,}04\,\text{V}$$

This means that 0,04 joules of work is done (by the field) per unit charge to move the charged particle from point A to point B.

3.3 Find the magnitude of the electric field.

$$E = \frac{V}{d} = \frac{0{,}04}{0{,}05} = 0{,}8\ \text{Vm}^{-1}$$

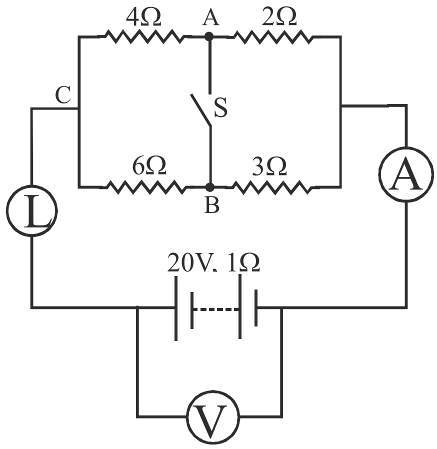
3.4 An identical particle is moved by an external force from point C to point A. How much work is done by this force? Explain your answer.

$$W = 6{,}0 \times 10^{-11}\ \text{J}$$

Since the field is uniform, point B and point C are at the same electric potential. It means that a given charged particle will have the same electrical potential energy at C than is has at B and therefore the same amount of work will be done to take a particle from C to A as will be done by the field to take the particle from A to B.

PROBLEM 4: ELECTRIC CIRCUIT

A circuit is connected as shown in the diagram. The lightbulb L has a resistance of 0,4Ω. The effect the temperature has on the resistance of the lightbulb can be ignored.



4.1 With switch S open, determine the effective resistance, R_{eff}, of the circuit, battery included.

For the parallel combination: $\frac{1}{R} = \frac{1}{4+2} + \frac{1}{6+3} = \frac{5}{18}$

$$\therefore R_{parallel} = 3{,}6\,\Omega$$

$$R_{eff} = 3{,}6 + 0{,}4 + 1 = 5\,\Omega$$

4.2 Calculate the reading on the ammeter with S still open.

$$I = \frac{V}{R} = \frac{20}{5} = 4\ \text{A}$$

4.3 Calculate the reading on the voltmeter with S still open.

The reading on the voltmeter gives the amount of energy that is available to the circuit per unit charge that leaves the battery. If the battery had no internal resistance all 20 joules of energy (per unit charge) would be available to the rest of the circuit. But now, because of the internal resistance, some of the energy is converted to heat right inside the battery and is not available to the circuit. This amount is often called the "lost volts".

So, the voltmeter reading is equal to the total amount of energy that the battery can provide (per unit charge), that is the emf (ε), minus the energy converted to heat before the charge left the battery, that is Ir.

$$V = \varepsilon - Ir$$

$$\therefore\ V = 20 - (5)(1) = 15\,\text{V}$$

4.4 With S still open, determine the potential difference (voltage) between A and B.

Voltage across the parallel combination: $V = IR = (4)(3{,}6) = 14{,}4$ V
Now we can calculate the currents through the top and bottom branches of the parallel section.

$$\therefore I_{top} = \frac{14{,}4}{(4+2)} = 2{,}4\ \text{A} \quad \text{and} \quad I_{bottom} = \frac{14{,}4}{(6+3)} = 1{,}6\ \text{A}$$

$$\therefore V_{CA} = I_{CA}R = (2{,}4)(4) = 9{,}6\ \text{V} \quad \text{and} \quad V_{CB} = I_{CB}R = (1{,}6)(6) = 9{,}6\,\text{V}$$

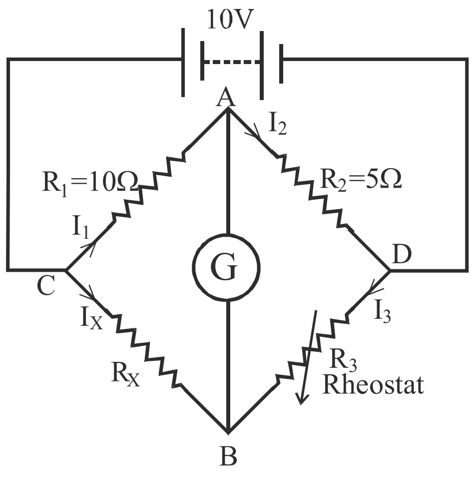
Thus, the potential at A is equal to the potential at B and there is no potential difference between A and B. $V_{AB} = 0$ V.

4.5 Switch S is now closed. What will be the effect on the brightness of the lightbulb?

No effect, since there was no potential difference between A and B, no current will flow from A to B when the switch is closed and the current in the circuit will not be affected.

PROBLEM 5: THE WHEATSTONE BRIDGE

The Wheatstone bridge is a device used to measure resistance very accurately. With the setup below we want to measure the resistance of R_X. At first we see that the galvanometer registers a current between A and B when the rheostat is set at 6Ω.



5.1 What should be done to be able to measure the resistance of R_X?

We should vary the resistance of the rheostat until no current registers on the galvanometer. When that is the case, we know that $V_{AB} = 0$ or $V_A = V_B$, and therefore $V_{CA} = V_{CB}$ and $V_{AD} = V_{BD}$. Thus

$$I_1R_1 = I_XR_X$$

$$\text{and}\quad I_2R_2 = I_3R_3$$

$$\therefore\quad \frac{I_1R_1}{I_2R_2} = \frac{I_XR_X}{I_3R_3}$$

But if there is no current between A and B, then $I_1 = I_2$ and $I_X = I_3$

$$\therefore \quad \frac{R_1}{R_2} = \frac{R_X}{R_3}$$

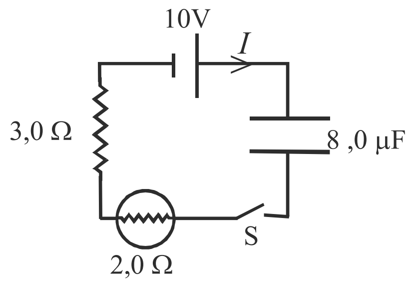
$$\therefore \quad R_X = \frac{R_1 R_3}{R_2}$$

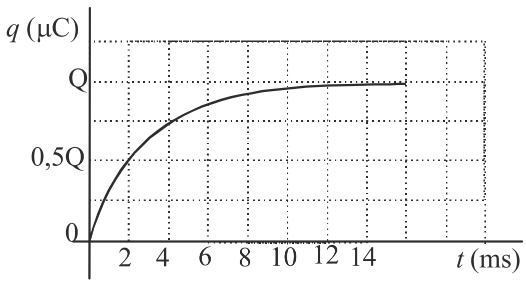
5.2 If we set the rheostat to 8Ω, we see that the reading on the galvanometer is zero. Find the resistance of R_X.

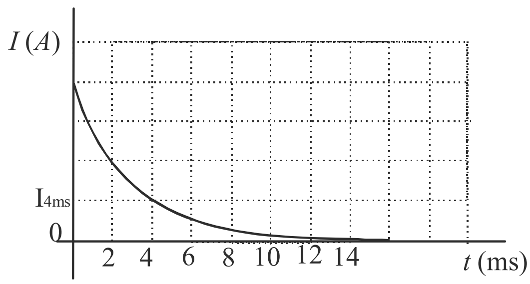
$$R_X = \frac{(10)(8)}{5} = 16\Omega$$

PROBLEM 6: THE RC-CIRCUIT

The capacitor in the circuit, with a capacitance of 8,0 μF, will be fully charged after 12,0 ms from the instant the switch is closed. Included in the circuit is a resistor of 3,0 Ω and a lightbulb with a resistance of 2,0 Ω. The internal resistance of the cell can be ignored. Study the graphs and answer the questions below.







6.1 Calculate the value of Q indicated on graph on the left.

Q is the charge on the capacitor when it is fully charged. When the capacitor is fully charge, the current in the circuit is zero and so, the potential differences across the resistance and the lightbulb are also zero. The potential difference across the capacitor is therefore 10 V.

$$\therefore \quad Q = CV = (8\mu F)(10V) = 80\mu C$$

6.2 Calculate the value of I at 4 ms, indicated on the graph on the right.

First find the initial (maximum) value of the current. At $t = 0$ s the charge on and the voltage across the capacitor is zero. Thus, the voltage across the resistors is 10 V.

$$I = \frac{V}{R} = \frac{10}{5} = 2\ \text{A}$$

The value of I at 4 ms is one quarter of the initial, maximum value, $\therefore I_{4\text{ms}} = 0{,}5\ \text{A}$.

6.3 Calculate the power in the bulb at 4 ms.

$$P = I^2 R = (0{,}5)^2 2 = 0{,}5\,\text{W}$$

6.4 What would be the area of the plates if the plate separation is 5 mm.

$$C = \frac{\varepsilon_0 A}{d}$$

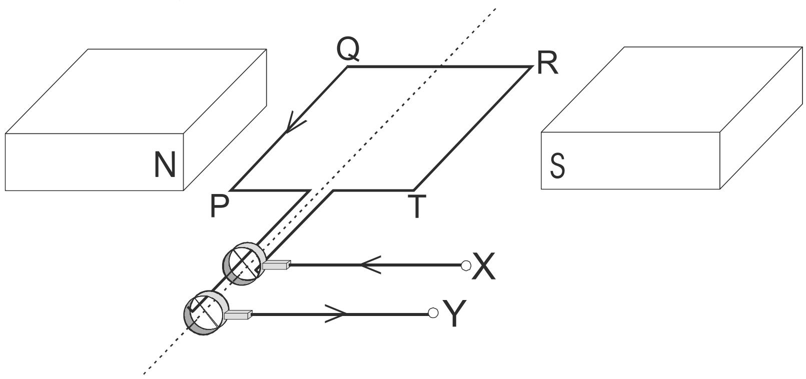
$$8 \times 10^{-6} = \frac{(8{,}85 \times 10^{-12})(A)}{0{,}005}$$

$$\therefore \quad A = 4{,}5 \times 10^3\ \text{m}^2$$

We see that this is an immense area for a circuit component. In reality, "flat" parallel plates are not used in circuits, but rather capacitors which are basically two parallel plates separated by a insulating material, such as plastic, wax or paper, wound up tightly in a cylinder.

PROBLEM 7: AC-GENERATOR

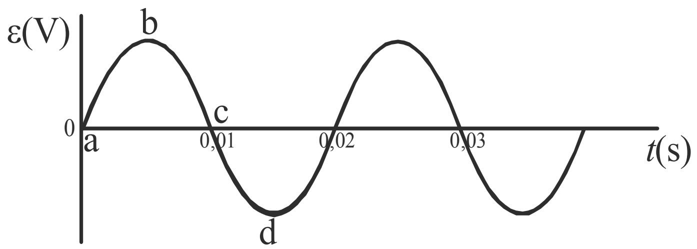
The simplified sketch below shows in principle the operation of the alternating current (AC) generator. When the current goes from X to Y through the generator, the induced emf is taken to be positive.



7.1 In which direction does segment PQ of the coil have to be rotated in order to cause the current direction as shown? Write down clockwise or anticlockwise.

Counter clockwise
Initially there is no current in the loop. As the loop starts to rotate, a current will be induced in the circuit. If PQ moves downward, as a result of a counter clockwise rotation, the magnetic flux from left to right through the loop, will increase. According to Lenz's law, a current will be induced such that the change will be opposed. Determine with the right hand rule: grab PQ with the fingers pointing through the loop from south to north ⇒ thumb points downward from Q to P.

7.2 Draw the induced emf versus time- graph. Show which point on the graph corresponds to the situation in the diagram above (the loop is horizontal with P to the left of T)

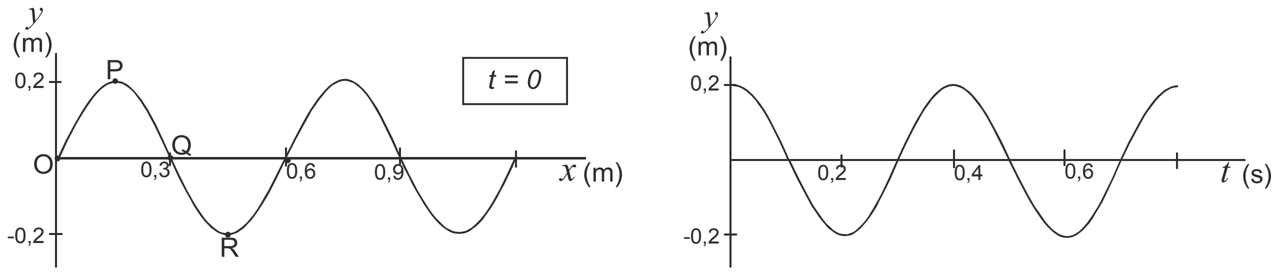


As indicated in the question, the current is positive when it goes from X to Y through the generator. That coincides with the situation in the diagram above and thus with point b on the graph. Points a and c coincides with the situation when the loop is vertical between the magnetic poles - the induced emf is zero when the loop is vertical (minimum change in magnetic flux). At d the loop is horizontal again with T to the left of P and the current flows in the opposite direction.

WAVES, SOUND AND LIGHT

PROBLEM 1: TRANSVERSE WAVES

The figure shows two graphs for one and the same wave motion in a given string. The wave is moving towards the right. The first graph shows the vertical displacement of the string as a function of the position of the particles in the string at time t = 0. The second graph shows the vertical displacement of only one of the particles in the string as a function of time .



1.1 What are the amplitude, wavelength, the period, the frequency and the speed of the wave?
Amplitude: $A = 0{,}2$ m
Wavelength: $\lambda = 0{,}6$ m (read from the graph on the left)
Period: $T = 0{,}4$ s (read from the graph on the right)
Frequency: $f = 1/T = 2{,}5$ Hz
Wave speed: $v = f\lambda = 1{,}5$ ms^{-1}

1.2 For each of the points O, P, Q and R on the graph on the left, choose from the possibilities below, a direction in which that particular point will be moving immediately after t = 0.

(a)	(b)	(c)	(d)	(e)	(f)
↘	↗	↓	↑	→	←

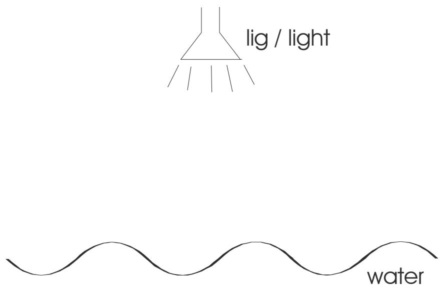
Answer: point O (c); point P (c); point Q (d); point R (d)
This graph can be seen as a snapshot of the string at a certain instant. Every particle in the string is oscillating vertically up and down as the wave travels towards the right in the string. The wave does not transfer particles from one point to another in the direction of motion of the wave.

1.3 Of which point (O, P, Q or R) is the other diagram a position - time graph? Explain your choice.

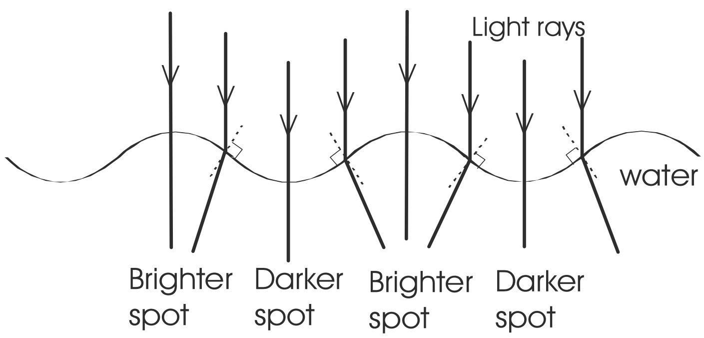
Answer: P. On the instant for which the first graph is drawn, point P has already reached its maximum displacement and will start moving downwards (see question 1.2). This corresponds to the position-time graph showing a particle starting at its maximum displacement and moving downwards.

PROBLEM 2: WAVES IN A RIPPLE TANK

In a ripple tank light is shone from above on shallow water in which little wavelets are made. The diagram shows a side view of the wavelets. The pattern of light and shadowy lines (or circles) that is formed on a white surface below the ripple tank, is a result of the wave pattern. Does a shadowy line correspond to a crest or a trough in the water wave? Explain.



The best way to explain this is to draw a ray diagram indicating the direction of the light rays after refraction at the surface of the water. When light rays travel from an optical less dense medium to a denser medium the rays refract towards the normal. (Remember: the normal is an imaginary line perpendicular to the interface between the two mediums). When a light ray enters the medium along a line perpendicular to the surface it goes through undeflected.

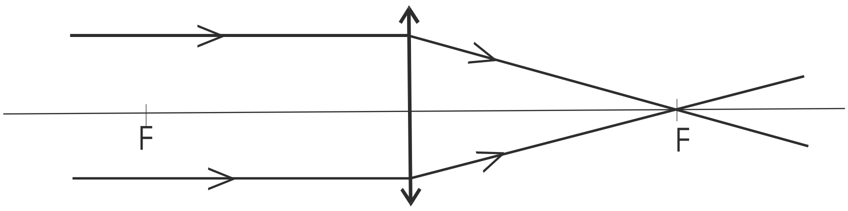


Darker (or shadowy) spots will form if most light rays are directed away from that spot. So we see that the brighter lines form underneath the crests and the shadowy (or darker lines) form underneath the troughs.

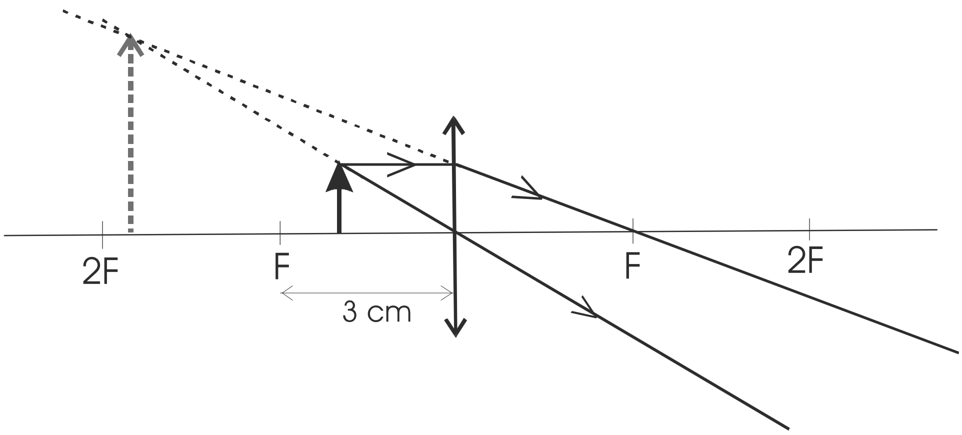
PROBLEM 3: LENSES

Use ray diagrams to indicate image formation in the following cases: Use the symbol ↕ to indicate a convex lens.

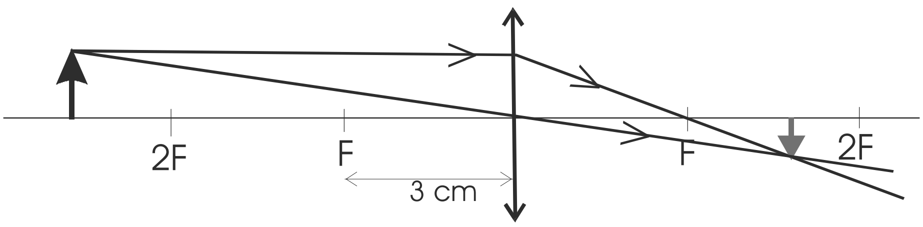
3.1 A convex lens with focal length 5 cm, with light rays coming from a very distant source.
Light rays coming from a very distance source can be considered as being parallel to the main axis and rays parallel to the main axis always converge in the focal point.



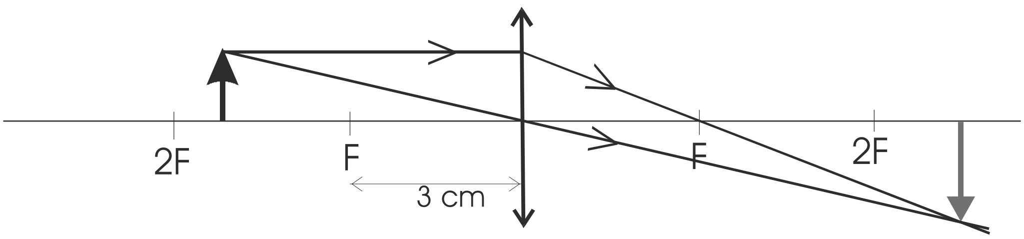
3.2 A convex lens with focal length 3 cm with an object 2 cm to the left of the lens.



3.3 A convex lens with focal length 3 cm with an object 8 cm to the left of the lens.

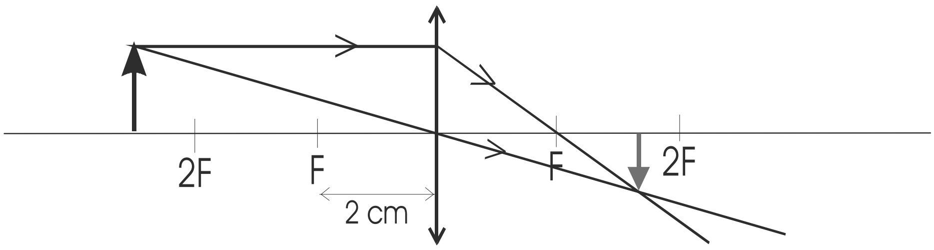


3.4 A convex lens with focal length 3 cm with an object 5 cm to the left of the lens.



3.5 A convex lens with focal length 2 cm with an object 5 cm to the left of the lens. Also say how a lens with shorter focal length differ from a lens with longer focal length.

When a lens has a shorter focal length it is more curved than a lens with a longer focal length.



3.6 Which case above corresponds to:
(i) using a magnifying glass to examine a small object
(ii) burning a hole in a dry leaf using a magnifying glass ,
(iii) image formation in the eye.
Explain your answers.

(i) **3.2** In this case we see a magnified, upright image as is required when we examine small objects with a magnifying glass. We see that if we want to use a lens as a magnifying glass, the object must be between the lens and the focal point.

(ii) **3.1** The sun is a very distant object and the rays from the sun can be considered as falling in parallel to the main axis. The sun's rays will converge in the focal point and the intensity will be high enough to burn something like a dry leaf.

(iii) **3.3 to 3.5** The cornea and the lens of the eye converges light coming from objects further away from the eye than its focal point. The image that forms on the retina is real, inverted and much smaller than the object. (The retina is the light sensitive "film" at the back of the eye on which the images form.)

3.7 Use diagrams 3.3 to 3.5 to explain the function of the lens and eye muscles in the eye.

One should note that we can only see something clearly focussed if the image forms exactly on the retina. If the image forms behind or in front of the retina we will perceive an out of focus or blurred image. The distance between the eye lens and the retina is constant. Thus, if the lens could not adapt in some way to the distance the object is in front of the eye, most of the images will not from exactly on the retina.

When comparing diagrams 3.3 and 3.4 we see that the closer an object is to the lens (provided it is still further away from the lens than the focal point) the further away the image is from the lens. Suppose that 3.3 represents an object distance that is exactly right for a specific eye lens and that the image forms on the retina. If the object now comes closer (as in diagram 3.4) the image will move further away from the lens and form behind the retina.

Now compare diagrams 3.4 and 3.5. Here we see that for a lens with a shorter focal distance the image will form closer to the lens for the same object distance. So, if the lens could become more curved (and have a shorter focal length) when the object is closer to the eye, the image could form exactly on the retina again. This is what the lens muscles do; when an object is close to the eye, the lens muscles contract and in doing so increase the curvature of the lens so that the image still forms on the retina.

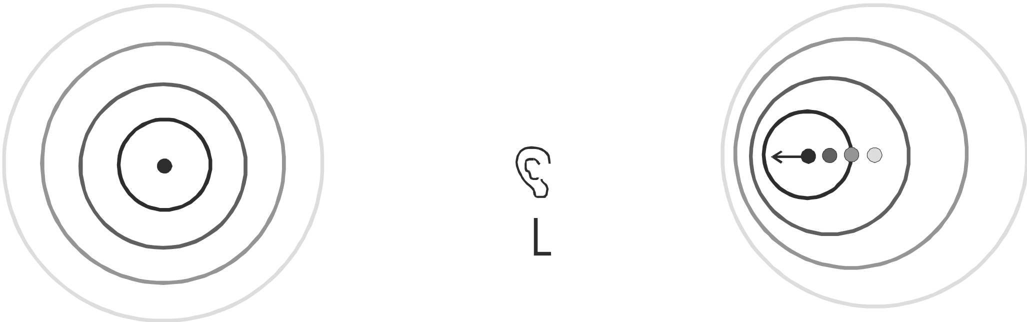
When a person gets older, it often happens that the lens muscles lose their ability to contract and therefore the lens cannot become curved enough for the person to be able to focus on nearby objects and they often need to wear glasses with convex lenses to compensate for the lack of curvature of their own eye lenses.

PROBLEM 4: THE DOPPLER EFFECT

What should I know?

- Frequency - determines the pitch of a sound
  determined by the source of the sound
- Wavefront - "neighbouring" particles in the medium in phase with each other
- Speed of a wave - depends on the medium through which the sound propagates (the density and the elasticity of the medium)

The Doppler-effect can be observed whenever a sound source and a listener or observer are in motion relative to each other. Because of the relative motion, the listener perceives a frequency different from the frequency created by the source. When a source, generating some sound, is moving towards a listener, the listener will perceive a higher sound than when the source is not moving.



Doppler equation

$$f_L = \frac{v - v_L}{v - v_s} f_s$$

A boy on a bicycle, riding with a speed of 6,5 ms^{-1}, is approaching an oncoming train moving with a speed of 26 ms^{-1}. The siren of the train is wailing at a frequency of 415 Hz. Determine the frequency of the sound the boy will perceive. Speed of sound in air = 340 ms^{-1}.

Remark: The speed of sound through air does not have a fixed value. The value depends on the density and the temperature of the air at a particular location.

To solve the problem we need to choose a reference frame. It makes it easier to work with the signs if we choose positive as the direction in which the sound is travelling (that is: from the source towards the listener).

$f_s = 415\,Hz$

$v_s = 26 \text{ ms}^{-1}$

$v_L = -6{,}5 \text{ ms}^{-1}$

$f_L = ?$

$$f_L = \frac{340-(-6{,}5)}{340-26}(415)$$

$$\therefore \; = 458 \text{ Hz}$$

PROBLEM 5: THE DOPPLER EFFECT WITH REFLECTION

The sound source of a ship's sonar device operates at a frequency of 30 kHz. A submarine is travelling directly away from the ship with a speed of 24 ms^{-1}. The ship is at rest in the water and sends out a signal which reflects at the moving submarine. After the signal has reflected at the submarine it is detected by the sonar device on the ship. The speed of sound in water is 1480m/s.

5.1 Calculate the frequency of the soundwave as it will be detected by a device on the submarine.

Treat the submarine in this part of the problem as the "listener" L and the ship as the source S. We need to calculate f_L. (Also remember that v_L and v_S is positive when L and/or S move in the same direction as the sound and negative when they move in the opposite direction as the sound.)

$f_S = 30\,\text{kHz}$

$v_L = +24\,\text{ms}^{-1}$

$v_S = 0$

$f_L = ?$

$$f_L = \left(\frac{1480-24}{1480}\right)30 = 29{,}5\,\text{kHz}$$

5.2 Calculate the frequency that is detected by ship's sonar device after the reflected signal has arrived at the ship.

In this part of the problem, we treat the submarine as the source, because the sound signal now comes from the submarine. The frequency of the reflected signal is f_S. Here v_S is negative, because the sound is travelling towards the ship, but the submarine is travelling away from the ship.

$f_L = ?$ (the signal detected by the ship)

$f_S = 29{,}5\,kHz$ (the frequency reflected at the submarine $= f_L$ of 4.1)

$v_L = 0$

$v_S = -24\,ms^{-1}$

$$f_L = \frac{1480}{1480+24}29{,}5 = 29{,}0\text{ kHz}$$

By comparing the outgoing signal with the reflected signal the crew on a ship can determine the speed of another vessel moving in its vicinity.

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Introduction

To the Learner:

In chemistry there are many things that you must simply learn. Understanding comes after you have learnt the definitions, names, symbols and descriptions of the concepts.

In this study guide, things that should be learnt will be mentioned as the answer to a question is given.

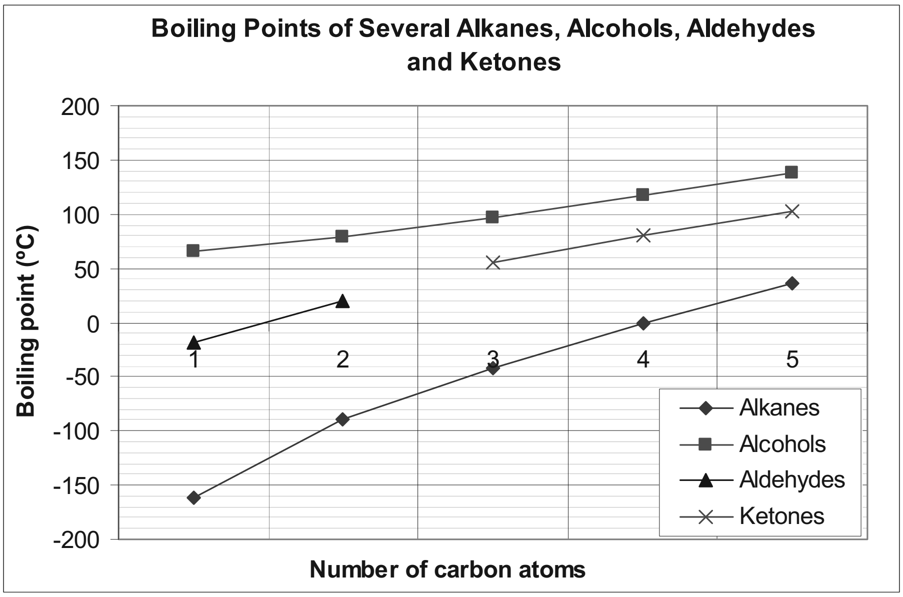
The space in the study guide is too short to cover everything in chemistry, (but perhaps by reading this study guide and working through the questions, you will learn how to approach problems in chemistry, and how to reason to reach a correct answer, so that when you are faced with an unfamiliar question, you will be able to apply the same methods of problem-solving to sections of chemistry not covered in this guide, and find enjoyment in answering the questions.)

The method that will be followed is to present some questions, and then to give you a model answer so that you can see how to solve the questions. When you have learnt how to think and reason in chemistry, you will be able to apply the techniques of reasoning to many different problems.

Organic Chemistry

Question 1

The graph shows the boiling points of some alkanes, alcohols, aldehydes and ketones.



Different questions could be asked, such as:

(a) Explain why the boiling point increases with an increase in the number of carbon atoms for (i) the alkanes (ii) for the aldehydes, and ketones and (iii) for the alcohols.

(b) Explain the difference in boiling points for the different homologous series. In your answer refer to the number of carbon atoms and the effect of the intermolecular forces.

When you have to answer questions where a graph is shown, quickly but thoroughly, analyze the graph (that means make sure you understand what the graph is showing):

- The *x* axis shows the **number of carbon atoms**. The numbers one to five are found just above the -50 ºC line on the graph and not at the bottom of the graph on the *x* axis.
- The *y* axis shows the **boiling points**, for instance for one carbon atom on the alkane line (-♦-) the boiling point is approximately -160 ºC, and the boiling point for the ketone with three carbon atoms (-x-) is just more than 50 ºC.

Notice that all the line-graphs show a positive slope; which can be seen by the gentle rising of the line. The meaning of a positive slope is that the values on the *y* axis are increasing together with an increase in the values on the x-axis.

Now analyze the question - that means make sure you understand what is actually being asked.

Let us analyze the first question ((a)). (Make sure you know what is meant by all the words).

> Explain why the boiling point increases with an increase in the number of carbon atoms for the alkanes. (The question would be totally different yet the reasoning would be similar when "alkanes" is replaced by "aldehydes" or "ketones" or "alcohols").

You must know (because you learnt it before!) that the alkanes have the general formula of C_nH_{2n+2}. So you should be able to find the formula of the different alkanes.

(See Table 1 at the end of this answer).

An "*increase in the number of carbon atoms*" means that you have an alkane with one carbon atom (CH_4), then an alkane with two carbon atoms (CH_3CH_3 or C_2H_6), followed by an alkane with three carbon atoms ($CH_3CH_2CH_3$ or C_3H_8) and so on. (You should also have learnt how to name these compounds!).

An "*increase in boiling point"* means that the boiling point is getting higher, or that the boiling point of the first one is lower than the boiling point of the second one which is lower than the boiling point of the third one, and so on.

So what is actually being asked?

The question asks you to explain why the boiling point of the alkane with one carbon atom is less than the boiling point of the alkane with two carbon atoms, which is less than the alkane with three carbon atoms and so on.

The graph shows this:

- *The boiling points (on the y-axis) of the alkane series* (-♦-) *increase with increasing number of carbon atoms (on the x-axis). Similarly the boiling points of the aldehyde series (-■-), the ketone series (-x-) and the alcohol series (-●-) become higher as the number of carbon atoms increase.*

Let us analyze the second question ((b)). (Make sure you know what is meant by all the words).

Explain the difference in boiling points for the different homologous series. In your answer refer to the number of carbon atoms and the effect of the intermolecular forces.

Homologous series refers to the family, namely alkanes or alcohols or aldehydes or ketones (You should learn about this).

Intermolecular forces refer to the force between different molecules (Do not confuse intermolecular and intramolecular. For inter- think of the 'the internet' a 'world wide web' linking you all over the world in the same way intermolecular refer to the links (or bonds) between molecules. Intramolecular forces, on the other hand, refer to the forces inside a single molecule between the atoms of that molecule (think of 'intravenous' that refer to 'inside the body'.

So what is actually being asked is:

Why is the boiling point of the alcohol with one carbon atom different from the boiling point of the alkane with one carbon atom, and why are both boiling points different from the boiling point of the aldehyde with one carbon atom? (What is the reason for these differences?) Why is the boiling point of the alcohol with two carbon atoms different from the boiling point of the alkane with two carbon atoms, and both boiling points are different from the boiling point of the aldehyde with two carbon atoms? And so on.

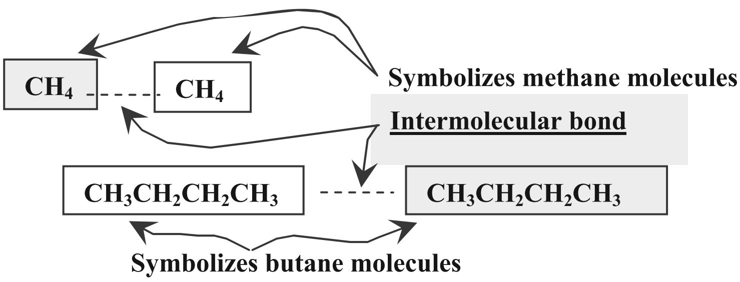
From the graph one notices that

- *The boiling points of the alkanes are lower than the boiling points for the aldehydes and ketones with a similar number of carbon atoms and the boiling points of the alcohols with a* *similar number of carbon atoms are higher than the boiling points of both the alkanes and the aldehyde / ketones. (You can see this because the lowest (or bottom) line on the graph is that of the alkanes and the top line is that of the alcohols).*

The graph is simply a way of showing this trend in the boiling points of the different homologous series. **The answer to these questions lies elsewhere, but where?**

In the second question you are provided with a 'tip' or a 'clue' to finding the answer, when the question refers to "*the effect of the intermolecular forces*". In your answer you will have to say something about the intermolecular forces of these substances. Start with that!
What do you know about the intermolecular forces of these molecules?

The alkanes are non-polar. Between two similar alkane molecules **induced dipole – induced dipole bonds** form. The force that holds these similar molecules together are **Van der Waals forces.**



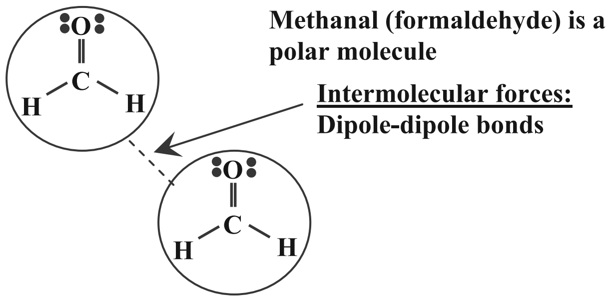
How can you tell what the strength of these forces are?
The boiling point of a substance is an indication of how strong the intermolecular bonds are that hold the molecules of the species together; that is, the easier it is to break the bonds, the lower the boiling point will be.
The more carbon atoms an alkane molecule has the more places are available for induced dipole – induced dipole "bonds" to form, so that more energy is needed to break the "bonds". "More energy" means that the substance must reach a higher boiling point before the molecules can separate into the gas phase or in ordinary language, before the substance 'boils'.

Answer to Question 1 (a):
Weak Van der Waals forces are responsible for the intermolecular bonds that form between alkane molecules.
The intermolecular bonds between alkane molecules with only one carbon atom are weaker than the bonds between alkane molecules with more carbon atoms; this is known because the boiling point of alkanes increases with an increase in the number of carbon atoms.

When answering Question 1 (ii) and (iii), for the situation where the "alkane" is replaced with "aldehyde" / "ketone" or "alcohol" one is also answering Question 1 (b).
In the answer one must look at the type of bond and the intermolecular forces that hold aldehydes (or ketones or alcohols) together.

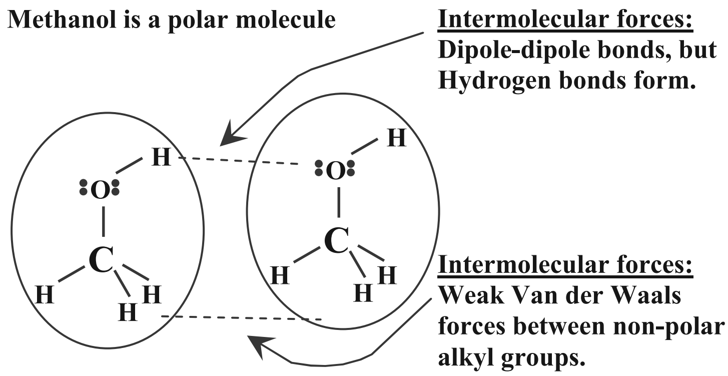
<u>Answer to Question 1(ii):</u>

For aldehydes and ketones dipole-dipole bonds form in the carbonyl groups (C=O), they are stronger bonds and need more energy to break. Therefore the boiling points of aldehydes (with a similar number of carbon atoms as the alkanes) are higher.



<u>Answer when alkane is replaced by alcohol (Question 1(iii)):</u>

Similarly for alcohols we find that the intermolecular forces binding two alcohols together are strong hydrogen bonds which are generally stronger bonds than ordinary dipole-dipole bonds.



Therefore the boiling points of alcohols (with a similar number of carbon atoms as the alkanes or aldehydes) are higher.

<u>Answer to Question 1 (b):</u>

Induced dipole-induced dipole bonds (in alkanes) are weaker than dipole-dipole bonds (in aldehydes and ketones) which are usually weaker than hydrogen bonds (in alcohols) therefore the boiling points of alkanes are lower than the boiling points of aldehydes and ketones which are lower than the boiling points of alcohols with the same number of carbon atoms. The longer a chain becomes (more carbon atoms) the stronger the bonds become that bind similar molecules together. Therfore more energy is needed to break the bonds and the boiling point increases.

Point to consider:

In stating the question the graph could be replaced with a table such as Table 1.

Then you could have been asked to draw such a graph and answer the questions.

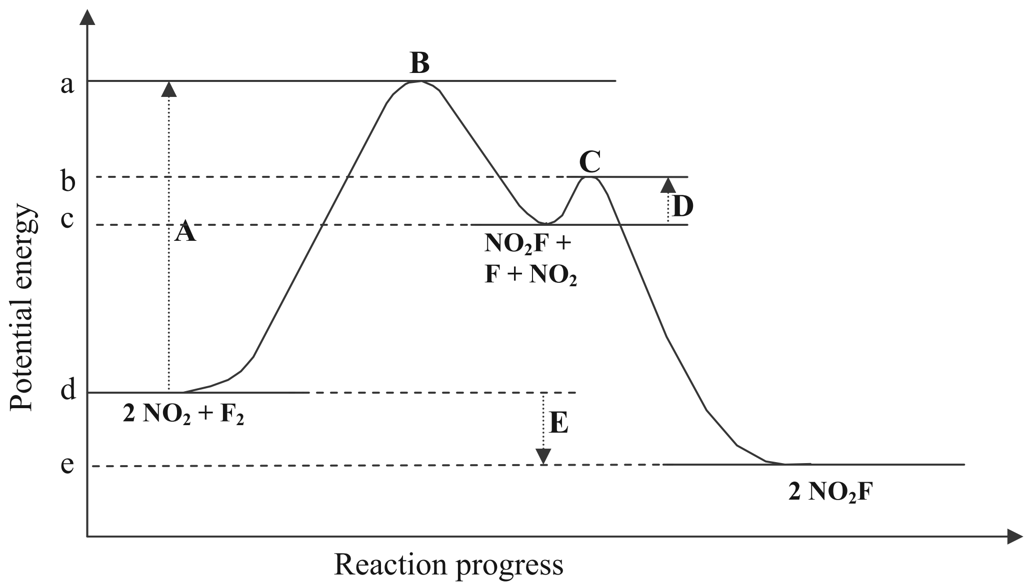
In whatever way the question is stated, the same things need to be known to answer the question and many of those things in Organic chemistry must simply be learnt!

Table 1.		Boiling points (°C) of some alkanes, alcohols, aldehydes and ketones							
		Alkanes		Alcohols		Aldehydes		Ketones	
Number of carbon atoms	1	CH_4	-162	CH_3OH	65	HCHO	-19		
	2	C_2H_6	-89	CH_3CH_2OH	79	CH_3CHO	20		
	3	C_3H_8	-42	$CH_3CH_2CH_2OH$	97			CH_3COCH_3	56
	4	C_4H_{10}	-0.5	$CH_3CH_2CH_2CH_2OH$	117			$CH_3CH_2COCH_3$	80
	5	C_5H_{12}	36	$CH_3CH_2CH_2CH_2CH_2OH$	138			$CH_3CH_2COCH_2CH_3$	102

Energy and Chemical Change

Question 2

For the given graph answer the following questions:



2.1 Give the meaning of A, B, C, D, and E.

2.2 Give the overall reaction.

2.3 How many steps does the reaction have?

2.4 What type of enthalpy change is experienced by the forward reaction? Explain.

<u>You must first of all analyze and interpret the diagram</u>:

- This diagram is a 'Reaction Energy Diagram', that means it shows what energy changes occur during a reaction.
- On the *y* axis the potential energy is shown.
- On the *x* axis the progress of the reaction is shown, but where is the reaction?
- The graph starts on energy 'd', and there you also find the 'Reactants', namely $2\ NO_2 + F_2$.
- The graph ends on energy 'e', and there you also find the 'Products', namely $2\ NO_2F$.
- So the overall (forward) reaction is $2\ NO_2 + F_2 \rightarrow 2\ NO_2F$
- The energy on which the reaction ends 'e' can also be expressed as $E_{Products}$, and is for this example lower in value than the energy on which the reaction started 'd' also expressed as $E_{Reactants}$.
- When $E_{Products} < E_{Reactantsl}$ then energy is given off during the reaction (energy flows out of the system to the surroundings), the arrow (E) indicating the energy flow points downward meaning energy flowed out.
- For the forward reaction, $\Delta H = E_{Products} - E_{Reactants}$ = (value at 'e') – (value at 'd') < 0 so that the enthalpy change $\Delta H < 0$ and we say an exothermic reaction occurred. Such a reaction can be expressed (written as):

$$\left.\begin{array}{lll} & 2\ NO_2 + F_2 \rightarrow 2\ NO_2F + \text{energy} & \\ \text{- Or} & 2\ NO_2 + F_2 \rightarrow 2\ NO_2F & \Delta H < 0 \\ \text{- Or} & 2\ NO_2 + F_2 \rightarrow 2\ NO_2F & \Delta H = - \end{array}\right\} \text{All indicate 'Exothermic reaction'}$$

- The graph has two peaks, one at B and one at C. This means that
  - there are two transition states
  - two intermediates were formed during the reaction
  - the reaction is a two step reaction. We find the proposed intermediates (or products for the first step) at energy 'c' and also (at energy 'c') the proposed reactants for he second step is shown, namely:

$$\underbrace{NO_2 + F_2}_{\text{Reactants at the start at energy 'd'}} \longrightarrow \underbrace{NO_2F + F}_{\text{Substances found at energy 'c' (after a 'reaction' has occurred).}} \quad \text{(Proposed reaction for first step)}$$

$$\underbrace{NO_2 + F}_{\text{Reactants shown at energy 'c'}} \longrightarrow \underbrace{NO_2F}_{\text{Products shown At energy 'e'}} \quad \text{(Proposed reaction for second step)}$$

Notice that both proposed reactions are balanced.

When these two reactions are added together the F atoms on both sides cancel and we find: $NO_2 + NO_2 + F_2 \rightarrow NO_2F + NO_2F$ (Overall reaction) or add similar compounds together:

$2\ NO_2 + F_2 \rightarrow 2\ NO_2F$

- The energy values at ‘a’ and at ‘b’ indicate to what level (value) the energy had to rise to get the first step to take place (going from ‘d’ to ‘a’) and then to what level (value) the energy had to rise to get the second step to take place (going from ‘c’ to ‘b’).
- The energy to get the reaction going is shown by A and has the value of (‘a’ – ‘d’) and is called $E_{activation}$(step 1). The arrow indicating ‘A’ is pointing upward, because energy was needed (energy flowed from the surroundings into the system, meaning the energy of the system increased).
- The energy to get the second step going is shown by ‘D’ and has the value of (‘b’ – ‘c’) and is called $E_{activation}$(step 2). The arrow indicating ‘D’ points upward; because energy was needed (energy was added from the surroundings to the system).

Now you are ready to give the answers.

Answers:

2.1 Give the meaning of A, B, C, D, and E.

A – Activation energy for the first step and has value ‘a’ – ‘d’, (a positive value).
B – First reaction intermediate.
C – Second reaction intermediate.
D – Activation energy for the second step and has value ‘b’ – ‘c’, (a positive value).
E – Overall energy change or the change in enthalpy and has value ‘e’ –‘d’, (a negative value), therefore $\Delta H < 0$, indicating an exothermic reaction.

2.2 Give the overall reaction.

$$2\ NO_2 + F_2 \rightarrow 2\ NO_2F \qquad \Delta H < 0$$

2.3 How many steps does the reaction have?

The two peaks at B and C indicate that this is a two step reaction.

Step one is shown on the graph as starting at energy 'd' (and reactants: 2 $NO_2 + F_2$), by adding the activation energy (A) the intermediate at B is formed, and then the reaction proceeds to the point with energy 'c' showing the products for that step as: **$NO_2F + F$**

Step two is shown as starting at energy 'c' (showing the reactants as: **$F + NO_2$** where the F has just previously been shown as one of the products of step one), raising the energy by input D to the reaction intermediate at C and then the reaction proceeds to the products of step 2 (and the overall products of the reaction: 2 NO_2F) at energy with value 'e'.

2.4 What type of enthalpy change is experienced by the forward reaction? Explain.

$\Delta H = E_{Products} - E_{Reactants}$ = 'e' – 'd' < 0
The forward reaction is an exothermic reaction, because the final energy (at 'e') is lower than the energy at the start (at 'd'); energy flowed out of the system to the surroundings.

For interest: the enthalpy change experienced by the step one reaction is endothermic starting at energy 'd' and ending at energy 'c'.
In using the formula: $\Delta H_{step\ one} = (E_{Products} - E_{Reactants})_{step\ one}$ = 'd' – 'c' > 0.
The enthalpy change for the second step is exothermic, so that the overall energy change for the reaction is exothermic.

Question 3

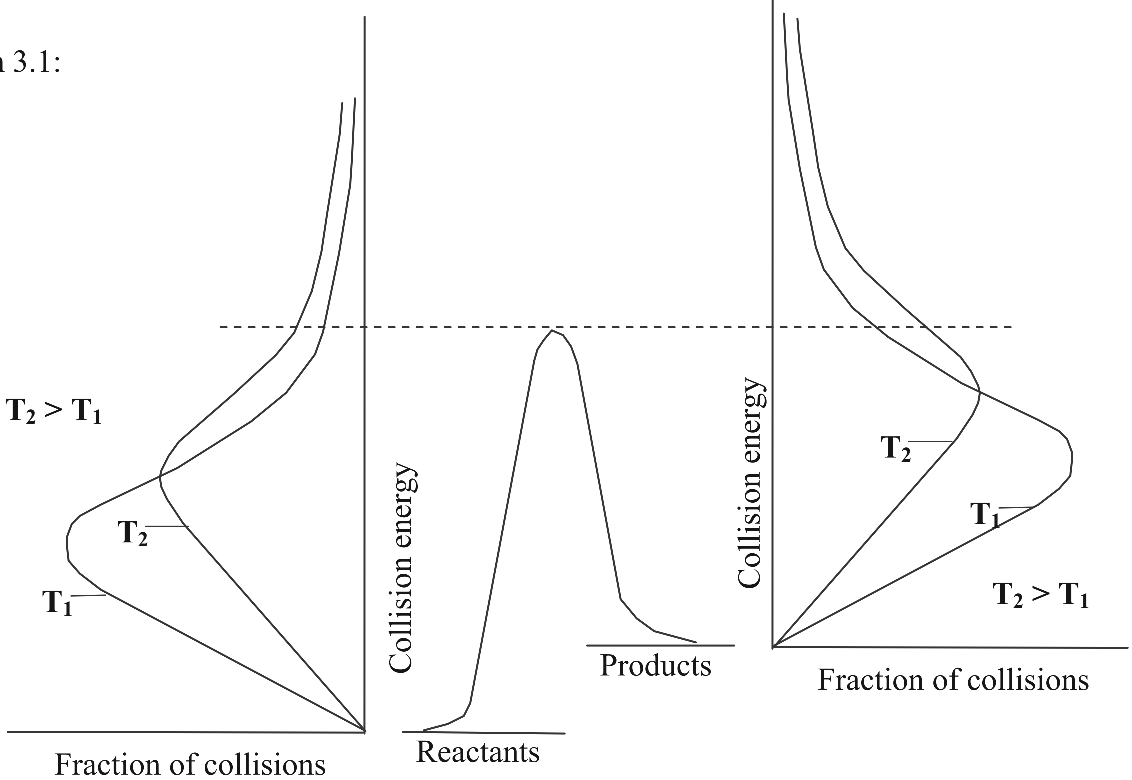
In referring to Diagram 3.1, answer the following questions:

(a) What type of enthalpy change is experienced by the forward reaction? Explain.
(b) What type of enthalpy change is experienced by the reverse reaction? Explain.
(c) What is the meaning of the dotted line?
(d) By referring to the collision theory, discuss the effect that an increase in the temperature has on the reaction rate of the forward and reverse reaction.

Note the "Explain" in questions (a) and (b) – remember to "explain" when giving your answer!
Note the "and" in question (d) – remember to give the answer for both the forward and reverse reaction!
Retention of the question (meaning: remembering what is asked) is part of the assessment!

Note that questions (a), (b) and (c) deal with energy and energy change, while question (d) deals with rate of reaction!

Diagram 3.1:

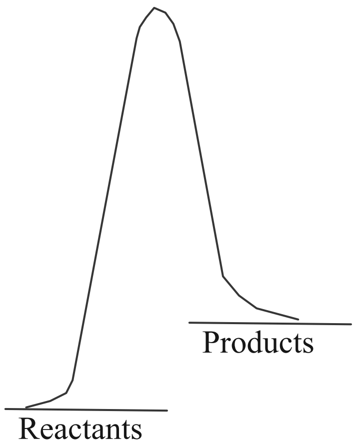


Notice that Diagram 3.1 is a combination of the **Reaction Energy Diagram (Diagram 3.2)** and the **Maxwell-Boltzmann distribution curve** for the same reaction.

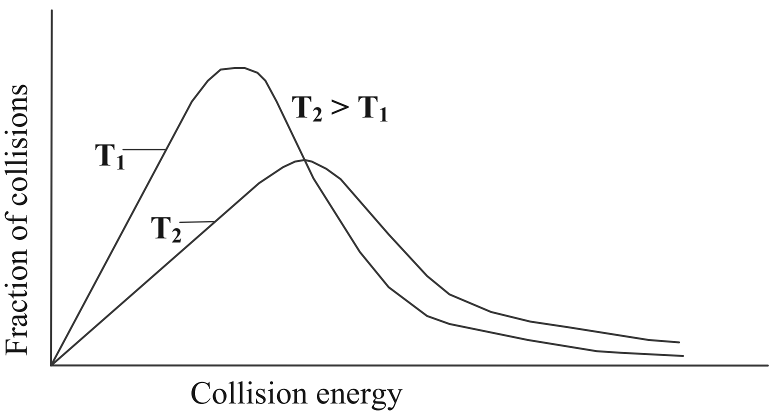
Diagram 3.2 is an energy level diagram for a reversible reaction:

Reactants → Products (forward reaction)
Products → Reactants (reversible reaction)

Diagram 3.2:



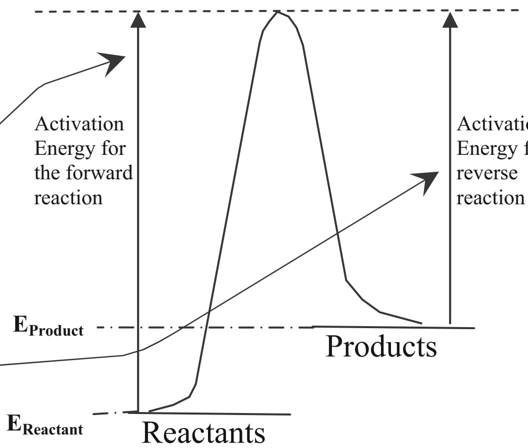
The **Maxwell-Boltzmann distribution curve** for the same reaction at different temperatures is shown below:



<u>You must first of all analyze and interpret the different diagrams</u>:

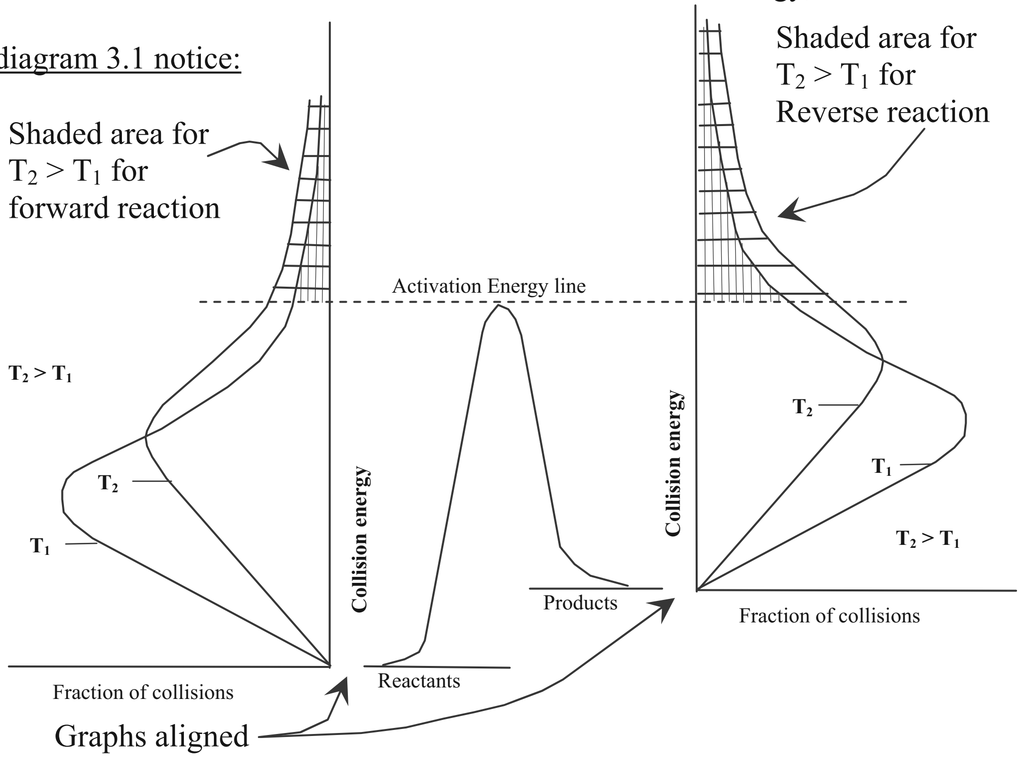
- <u>Diagram 3.2</u> is a simple 'Reaction Energy Diagram', that means it shows what energy changes occur during a reaction. What are not shown are the axes, but you should know that for such a curve the *y* axis shows the potential energy and the *x* axis shows the progress of the forward reaction.
- For the forward reaction $E_{Reactants} < E_{Products}$, that means that $\Delta H = E_{Products} - E_{Reactants} > 0$.
- $\Delta H > 0$ or $\Delta H = +$ is an indication of an endothermic reaction. (The forward reaction is endothermic, but the reverse reaction (Products → Reactants) is an exothermic reaction.

- The activation energy for the forward reaction is given by the energy needed to get from the reactants to the top of the curve (the dotted line).
- The activation energy for the reverse reaction is given by the energy needed to get from the products to the top of the curve (the dotted line).



So in both cases the dotted line is an indication of the activation energy, E_a.

<u>For diagram 3.1 notice:</u>



- Notice that there is a Maxwell-Boltzmann distribution curve that has been turned 90º in an anti-clockwise direction on the left of the 'Reaction Energy Diagram' (diagram 3.2) and on the right is a Maxwell-Boltzmann distribution curve that was rotated and flipped horizontally.
- Furthermore notice (for diagram 3.1) that the *y* axis of this Maxwell-Boltzmann diagram (or the starting point of the *x* axis) has been aligned with the Reactant Energy line of the 'Reaction Energy Diagram' – which is also the starting point of the forward reaction.

  Notice that the dotted line (activation energy line) dissects a part of the Maxwell-Boltzmann curve.
- Notice that on the right of the 'Reaction Energy Diagram' is a Maxwell-Boltzmann distribution curve that has been rotated and flipped horizontally. Furthermore notice that the *y* axis of this Maxwell-Boltzmann diagram (or the starting point of the *x* axis) has been aligned with the Product Energy line of the 'Reaction Energy Diagram' – which is also the starting point of the reverse reaction.

  Notice that the dotted line (activation energy line) dissects a part of this Maxwell-Boltzmann curve.
- A Maxwell-Boltzmann distribution curve is a special type of curve. Not only does it show the 'fraction of collisions' on the one axis and the 'collision energy' (or kinetic energy of the particles) on the other axis, but the total area under the curve represents the total number of particles taking part in the reaction. None of these particles were removed and no extra particles were added during the reaction. The given Maxwell-Boltzmann curve shows that the temperature was increased from T_1 to T_2. Notice what happened: the peak of the T_2 curve is flatter (on the *y* axis), but because the same number of particles remain under the curve, the curve is more spread out on the *x* axis and at the end, thicker (or fatter). The meaning of this is that there are more particles with higher collision energy (at the end of the curve). This is known, because the T_2 curve is above the T_1 curve toward the end of the curve.
- Very important is that the activation energy line (dotted line) remains the activation energy line even when it dissects the Maxwell-Boltzmann curve. The meaning is that only the top section of the Maxwell-Boltzmann curve (the section that lies to the top of the dotted line and has been shaded) has the correct collision orientation and enough energy to collide successfully and form products.
- Notice what has changed when the temperature was increased: There is a larger area of the T_2 – curve above the dotted line (for both Maxwell-Boltzmann curves) than for the T_1 curve. This is seen because the area shaded like ≡ is larger than the area shaded like ‖ ‖. The

importance of having a larger area above the dotted line is that there are more particles with the correct activation energy, so that more particles can take part in the reaction when the temperature increased to T_2 because at the higher temperature there are more successful or effective collisions.

Now answer the questions:

(a) What type of enthalpy change is experienced by the forward reaction? Explain.

The forward reaction is an endothermic reaction, because $\Delta H = E_{Products} - E_{Reactants} > 0$.

(b) What type of enthalpy change is experienced by the reverse reaction? Explain.

The reverse reaction is an exothermic reaction.
For the reverse reaction the products of the forward reaction becomes the reactants of the reverse reaction (the reaction is going back!) and the reactants of the forward reaction becomes the products of the reverse reaction.
So that the general formula: $\Delta H = E_{Products} - E_{Reactants}$ becomes

$$= E_{\text{Products now become Reactants}} - E_{\text{Reactants now become Products}}$$

< 0. (Indicating an exothermic reaction).

(c) What is the meaning of the dotted line?

The dotted line indicates the energy needed for the reaction to proceed (whether in the forward or the reverse direction). This energy is known as the 'activation energy'

(d) By referring to the collision theory, discuss the effect increasing the temperature has on the reaction rate for the forward and reverse reaction. (Notice that this question actually deals with chemical kinetics and not so much with the energy of the reaction)

Only when effective collisions occur does a reaction take place. For an effective collision to occur the particles involved must have energy higher than the activation energy needed for that reaction. At a higher temperature the average kinetic energy of the particles involved in the reaction increases resulting in more particles with energy higher than the activation energy. (*The shaded area of the graphs gives an indication of particles with energy higher than the activation energy*). There are more particles with an energy higher than the activation energy at a higher temperature (*this is seen by the shaded area (═) for both the T_2 graphs (for the forward and reverse reactions) being greater than the shaded area (‖ ‖) for the T_1 graphs)*. The rate of a reaction is determined by the number of effective collisions that occur. By increasing the number of effective collisions the rate of the reaction increases. When there are more particles with energy higher than the activation energy (curve T_2) the result is that more effective collisions occur consequently the rate of the reaction increases.

CHEMICAL KINETICS

Question 4

In the engine of a car a combustion reaction occurs when petrol (C_8H_{18}) reacts with the oxygen in air. However, at such high temperatures the nitrogen in the air also reacts with the oxygen in air and forms nitric oxide (NO). When the 'timing' of the engine is not right the temperature at which such a combustion reaction occurs is not high enough and the combustion is not complete and unburned hydrocarbons and carbon monoxide form. Most modern cars are equipped with a two-stage catalytic converter. An efficient catalytic converter serves two purposes: it oxidizes CO and the unburned hydrocarbons to CO_2 and H_2O, and it reduces NO and NO_2 to N_2 and O_2.

Answer the following questions:

(a) Give balanced chemical reaction equations for the combustion of petrol and air at a high temperature (complete combustion) and at a lower temperature (incomplete combustion).

(b) Give a balanced chemical equation for the reaction of oxygen and nitrogen to form nitrogen monoxide at high temperatures.

(c) What are hydrocarbons?

(d) What is so bad about the exhaust gases of a car that the exhaust of a car should be equipped with a catalytic converter?

(e) Give a short description of the way in which a two-stage catalytic converter works.

(f) Is the catalytic converter regarded as a homogeneous or a heterogeneous catalyst?

(g) Explain what is meant by

(i) "it oxidizes CO and the unburned hydrocarbons to CO_2 and H_2O" and

(ii) "it reduces NO and NO_2 to N_2 and O_2".

Note this question is a combination question: it has a little organic chemistry, rates of chemical reactions, and electro chemistry all thrown together. Do not let that disturb you. Continue to start by analyzing the question and then proceed to answer the question.

Analyze the question:

Combustion means "to burn" so a combustion reaction is when something is burned.

In the question three reactions are mentioned:

(1) the combustion reaction of petrol and air at high temperature (complete combustion),

(2) the combustion reaction of petrol and air at a lower temperature (incomplete combustion), and

(3) the reaction between the nitrogen (in air) and the oxygen (in air) at high temperatures.

In all three reactions the reactants are mentioned, but what about the products?

Tackle the equations one by one:

(1) When you studied organic chemistry you should actually have learned about the combustion of alkanes and oxygen! Is petrol an alkane? Remember the general formula for an alkane is C_nH_{2n+2}. So check: $C_8H_{2(8)+2} = C_8H_{18}$ showing that petrol is an alkane.

You should have learned that the complete combustion reaction of an alkane produces carbon dioxide and water as products, so the equation for the reaction is: $C_8H_{18} + O_2 \rightarrow CO_2 + H_2O$.

Now proceed to balance the equation. On the reactant side Petrol has 8 carbon atoms.

	Reactants (left hand side)	Products (right hand side)	
For carbon	8 From C_8H_{18}	1 From CO_2	therefore multiply CO_2 by 8, then there will also by 8 carbon atoms on the product side
Now you have: $C_8H_{18} + O_2 \rightarrow \mathbf{8}\ CO_2 + H_2O$			
How do you know which element to balance next? Note that hydrogen is bonded to other elements on both the reactant and product side (to C on the reactants side and to O on the product side), whereas oxygen stands alone on the reactant side. Therefore it would be less complicated to balance the oxygen, so leave oxygen till last.			
For hydrogen	18 From C_8H_{18}	2 From H_2O	Multiply H_2O by 9, then there will also by 18 hydrogen atoms on the product side
Now you have: $C_8H_{18} + O_2 \rightarrow \mathbf{8}\ CO_2 + \mathbf{9}\ H_2O$			
For oxygen	1 x 2 = 2 From O_2	(**8** x 2) + (**9**) = 25 From 8 CO_2 + 9 H_2O	The 2 oxygen atoms on the reactant side are stuck together, you cannot separate them. For 25 oxygen atoms you will have

			to multiply the oxygen by $\frac{25}{2}$, that is by 12½
Now you have: C_8H_{18} + **12½** $O_2 \rightarrow$ **8** CO_2 + **9** H_2O			
May you have "½" a molecule? Yes, as long as you refer to the stoichiometric coefficient as moles, since you could have ½ a mole, but it would be better to get rid of the ½. You do that by multiplying every stoichiometric coefficient by 2.			
then you have: **2** C_8H_{18} + **25** $O_2 \rightarrow$ **16** CO_2 + **18** H_2O			
Now check the number of each element on both sides again! (Are you wasting time? – not if this will earn you marks!)			

	Left hand side (reactants)	Right hand side (products)
For carbon:	2 x 8 = 16	16 x 1 = 16
For hydrogen:	2 x 18 = 36	18 x 2 = 36
For oxygen:	25 x 2 = 50	(16 x 2) + (18 x 1) = 32 + 18 = 50

So equation (1) *the combustion of petrol and air at a high temperature (complete combustion),* is

2 C_8H_{18} + **25** $O_2 \rightarrow$ **16** CO_2 + **18** H_2O

(2) The combustion reaction of petrol and air at a lower temperature (incomplete combustion): when you studied the alkane reactions you should also have learnt about this type of reaction! Incomplete combustion occurs when there is not enough oxygen available.
Consider the above reaction: **2** C_8H_{18} + **25** $O_2 \rightarrow$ **16** CO_2 + **18** H_2O, if there is not enough oxygen (on the reactant side) what would happen? You should have fewer oxygen atoms on the products side. How would that be possible? Well instead of CO_2 (where 2 oxygen atoms are present) CO form (where only one oxygen atom is present!). So the basic outline for reaction (2) is:

C_8H_{18} + $O_2 \rightarrow$ **CO** + H_2O

Balance this reaction (Follow the same procedure as above): First balance the carbon atoms, and then hydrogen and lastly oxygen and you should get as answer:

C_8H_{18} + **8½** $O_2 \rightarrow$ **8** CO + **9** H_2O

Again multiply all the stoichiometric coefficients by 2 and you find:

2 C_8H_{18} + **17** $O_2 \rightarrow$ **16** CO + **18** H_2O

Notice that you only used 17 moles of oxygen molecules (or 17 O_2 molecules) for this reaction (reaction (2)) compared to 25 moles (or 25 molecules) in reaction (1)!
(When you read the coefficients as moles you do so for the whole reaction or if you read the coefficients as molecules/atoms you do so for the whole reaction – don't mix the two!)

(3) The reaction between the nitrogen (in air) and the oxygen (in air) at high temperatures: Again you are given the reactants: nitrogen (in air) and oxygen (in air), N_2 and O_2. What about the products? Go read the question! …*at such high temperatures the nitrogen in the air also reacts with the oxygen in air and forms nitric oxide (NO)*.

$N_2 + O_2 \rightarrow NO$

The balancing should not be a problem: $N_2 + O_2 \rightarrow 2\ NO$

Next question:

(c) *What are hydrocarbons?* You should have learnt this in organic chemistry! What does the name tell you? "Hydro" is short for hydrogen and "carbons" means just that! So hydrocarbons are compounds of hydrogen and carbon. Do you know any such compounds? The alkanes and alkenes are such compounds!

Next question:

(d) *What is so bad about the exhaust gases of a car that the exhaust of a car should be equipped with a catalytic converter?*

(If you had not learned about this don't despair! Use your common sense!)

There are (according to the question) two exhaust chemicals that are formed, CO and NO. Say something about each chemical:

- Carbon monoxide combines with hemoglobin in the blood, thereby preventing the blood from transporting oxygen (with which the hemoglobin should have combined) around the body. Since carbon monoxide is an odorless, colourless and tasteless gas it is not easily detected.
- Nitrogen monoxide is a colourless reactive gas that is only slightly soluble in water. NO is a good reducing agent and reacts readily with quite a few other gases found in the atmosphere:

 * Nitrogen monoxide is slowly oxidized by oxygen to form nitrogen dioxide. The balanced reaction is: $2\ NO(g) + O_2(g) \rightarrow 2\ NO_2(g)$
 - NO_2 is a health hazard, primarily because it attacks the lungs, but usually the concentration is not high enough.
 * Nitrogen monoxide reduces ozone to oxygen and is oxidized to NO_2. The balanced reaction is: $NO(g) + O_3(g) \rightarrow O_2(g) + NO_2(g)$

- Ozone is an important chemical in the stratosphere (at altitudes (height above sea level) of 15 to 25 km). The reason why we need ozone is that an equilibrium situation is set up between two reactions:

  In one reaction the ozone absorbs dangerous ultraviolet radiation, with wavelengths between 240 and 310 nm (from the sun) and break up into oxygen atoms and oxygen molecules.

  O_3 + UV radiation $\rightarrow O + O_2$

  In the other reaction, at lower altitudes, the oxygen atoms immediately react with the oxygen molecules to form ozone

  $O + O_2 \rightarrow O_3$

  Equilibrium is set up:

  O_3 + UV radiation $\leftrightarrows O + O_2$

  The result of the equilibrium is that most of the ultraviolet radiation from the sun is absorbed before it reaches the earth's surface (where it could destroy living cells).

* Nitrogen monoxide also reacts with carbon dioxide to form carbon monoxide and nitrogen dioxide, increasing the concentrations of two dangerous gases in the atmosphere!

  $NO(g) + CO_2(g) \rightarrow CO(g) + NO_2(g)$

Do you have to give all of this as your answer? It (mainly) depends on the marks allocated to the question and on how much time you have to answer the question. Rather say too much than too little.

Next question:

(e) *Give a short description of the way in which a two-stage catalytic converter works*.

Never heard of a catalytic converter? You have no idea what one does not to mention a two stage one! Don't despair! Read the question again – the answer is given in the question!

> … Most modern cars are equipped with a two-stage catalytic converter. An efficient catalytic converter serves two purposes: it oxidizes CO and the unburned hydrocarbons to CO_2 and H_2O, and it reduces NO and NO_2 to N_2 and O_2.

You found that sentence? Now turn the sentence into the answer.

An efficient catalytic converter serves two purposes – **the two stages:**

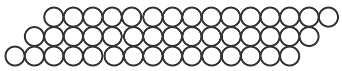
(1) *it oxidizes CO and the unburned hydrocarbons to CO_2 and H_2O* – first stage and

(2) *it reduces NO and NO_2 to N_2 and O_2* – second stage.

If you inspect the exhaust of a modern car you should see, starting from the exhaust outlet and looking back underneath the car, the exhaust pipe going into a rectangular shaped "box". On the other side of the "box" the exhaust pipe comes out just to go into a second, similarly shaped rectangular "box". Again the exhaust pipe comes out on the other side of the box and eventually the exhaust pipe connects up to the car engine. The rectangular shaped "boxes" contain the converters.

Usually the converter closest to the part of the engine (when the gases coming from the engine are still very hot), is the one converting the carbon monoxide, CO, and the unburned hydrocarbons (containing carbon and hydrogen compounds, C_xH_y) to CO_2 and to H_2O. By the time the gases reach the second converter (the second box closest to the end of the exhaust pipe, furthest from the engine) the gases have cooled down a bit. The second converter changes (or dissociates) the NO into N_2 and O_2 and usually operates at a much lower temperature (the gases being cooler) than the first converter.

Inside the converters ("boxes") you will find a sheet of tiny "beads" arranged in such a way that the hot gases have to pass over the "beads" as they move out through the exhaust pipe.



A representation of the transition metal "beads" inside the converter.

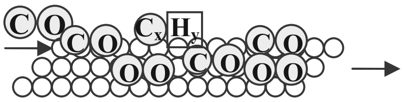
The beads contain platinum, or palladium, or some other transition metal or some other transition metal oxide (such as a combination of CuO and Cr_2O_3). Not all converters contain beads some might have a honeycomb structure made from alumina (Al_2O_3) which is saturated with the metal oxide. Usually the two converters in an exhaust system (the two "boxes") will have different transition metals or transition metal oxides (remember they do not operate at the same temperature).

Note that in the converters ("boxes") - the "beads" representing the catalyst (containing the transition metal or transition metal oxide), are solid and the gases passing over the converters are converted into other gases. Do you notice the different phases? The catalyst is a solid and the other chemical or compound is a gas. Therefore these catalysts are heterogeneous catalysts.

Notice the above is the answer to question (f):

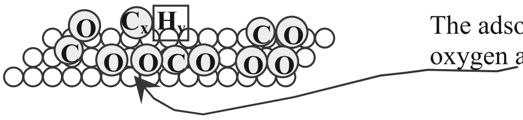
(f) *Is the catalytic converter regarded as a homogeneous or a heterogeneous catalyst?*

In heterogeneous catalysis, the surface of the solid catalyst is usually the site of the reaction, therefore such a catalyst usually has a huge surface area so that (in this case) the gas could make proper contact. The gas molecules get chemically adsorbed onto the surface of the catalysts. Adsorption means to adhere to (or to stick on) a surface. Adsorption and absorption are two different actions. (Absorption means to be taken into (the interior) of another substance, similar to how a spunge takes up water). In this case the gas molecules are adsorped onto the surface of the catalyst.



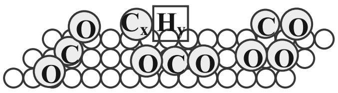
As the gas molecules (CO(g), O_2(g) and Hydrocarbons C_xH_y(g)) move over the surface of the "beads" they adsorp onto the surface until the whole surface could be full of gas molecules.

The hot gases from the engine are forced out through the exhaust pipe of the car. When these gases move through the first converter (the box-like thing closest to the engine) the carbon monoxide, oxygen and hydrocarbons get adsorped onto the metal surface.



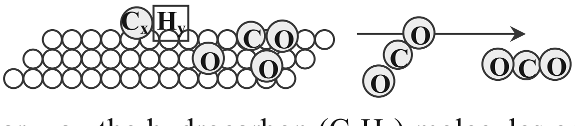
The adsorption weakens the O-O bond in O_2 and oxygen atoms become available.

The adsorption of the oxygen molecules weakens the O-O bonds and oxygen atoms form. They then combine with the adsorped CO molecules to form CO_2 molecules.



The oxygen atoms are now available to bond to the adsorbed carbon monoxide to form carbon dioxide.

The adsorption of the CO_2 molecules to the metal surface weakens and the CO_2(g) is released into the flow of the gases through the exhaust.



The adsorption of the molecules to the metal surface decreases and the carbon dioxide gas is released.

In a similar way the hydrocarbon (C_xH_y) molecules get adsorped onto the metal surface. The C-H bonds weaken and C atoms and H atoms form which bond to the oxygen atom to form carbon dioxide (CO_2) and water (H_2O) gas. These gases also get released into the flow of the gases through the exhaust pipe.

In the second converter (that functions at a lower temperature) the NO and NO_2 molecules get adsorped onto the metal- or metal oxide surface (the "beads"). The N-O bond weakens and N and

O atoms form which then combine to form N_2 and O_2 molecules. The adsorption of these molecules weakens and these gases are released.

Next question:

(g) *Explain what is meant by*

(i) "it oxidizes CO and the unburned hydrocarbons to CO_2 and H_2O" and

(ii) *"it reduces NO and NO_2 to N_2 and O_2".*

In Organic Chemistry the term oxidation is used to signify either the removal of the elements of hydrogen from a compound or the addition of oxygen to a compound. Often the symbol [O] is used to indicate an oxidation reaction without specifying the oxidation agent.
The chemical equation for the reaction could be written as:

$$2\,CO(g) + O_2(g) \rightarrow 2\,CO_2(g) \text{ and}$$

$$C_xH_y + m\,O_2 \rightarrow x\,CO_2 + \tfrac{y}{2}\,H_2O$$

(Note there is no visible addition of electrons. Nothing of the type: $A \rightarrow A^{2+} + 2e^-$, but if you calculate the oxidation number of the different atoms you find the following:

$$2\,\overset{+2}{C}\,\overset{-2}{O}(g) + \overset{0}{O_2}(g) \rightarrow 2\,\overset{+4}{C}\,\overset{-2}{O_2}(g) \qquad \text{and for} \qquad \overset{?}{C_x}\overset{+1}{H_y} + m\,\overset{0}{O_2} \rightarrow x\,\overset{+4}{C}\,\overset{-2}{O_2} + \tfrac{y}{2}\,\overset{+1}{H_2}\,\overset{-2}{O}$$

The oxidation number of the carbon atom has increased from +2 to +4, while the oxidation number of oxygen decreased from 0 to -2. Although it is not clear what the oxidation number of the carbon in the hydrocarbon is, the oxidation number of the carbon should have increased, since the oxidation number of the oxygen decreased. An increase in the oxidation number indicates that the substance was oxidized and a decrease indicates that that substance was reduced).

Conversely, if we add the elements of hydrogen to a compound or if we remove oxygen from a compound, we say that compound has been reduced or has undergone reduction. In Organic Chemistry the symbol [R] is often used to indicate a process of reduction reaction without specifying the reducing agent.
Similarly the oxidation numbers of the various atoms could be calculated:

$$2\,\overset{+2}{N}\,\overset{-2}{O}(g) \rightarrow \overset{0}{N_2}(g) + \overset{0}{O_2}(g)$$

The oxidation number of nitrogen decreased from +2 to 0, indicating that nitrogen was reduced. The nitrogen monoxide, NO, also lost an oxygen atom to become N_2, indicating reduction.

Notes

Notes