

IB Physics – Theme A: Space, Time and Motion

IB Physics SL & HL (2016+ / 2023 syllabus) · Total marks: 54 · Answers on the last page

Questions on kinematics, forces and momentum, work/energy/power, and rigid body mechanics (HL only, marked). Use $g = 9.81 \text{ m s}^{-2}$ and a calculator throughout; give final answers to 3 significant figures unless stated otherwise.

Section A – Kinematics (SL and HL)

1. A ball is thrown vertically upwards at 15 m s^{-1} from a height of 1.2 m above the ground.
 - (a) Calculate the maximum height reached above the ground.
 - (b) Calculate the total time taken for the ball to hit the ground. [5]
2. A projectile is launched from level ground at 20 m s^{-1} at 30° above the horizontal. Air resistance is negligible.
 - (a) Calculate the time of flight.
 - (b) Calculate the horizontal range.
 - (c) Calculate the maximum height reached. [6]
3. Explain, in terms of forces, why a skydiver falling through air reaches a terminal velocity. [3]
4. Sketch, by description, the shape of a displacement-time graph and the corresponding velocity-time graph for an object released from rest and falling freely under gravity (no air resistance) for 3 seconds. [3]

Section B – Forces, Momentum, Work and Energy (SL and HL)

5. An Atwood machine consists of a light, inextensible string over a frictionless pulley connecting a mass $m_1 = 5.0 \text{ kg}$ to a mass $m_2 = 3.0 \text{ kg}$, both hanging freely.
 - (a) Calculate the magnitude of the acceleration of the system.
 - (b) Calculate the tension in the string. [5]
6. A trolley of mass 2.0 kg travelling at 6.0 m s^{-1} collides with, and sticks to, a stationary trolley of mass 4.0 kg .
 - (a) Calculate the common velocity after the collision.
 - (b) Calculate the kinetic energy lost in the collision.
 - (c) State the name given to a collision in which kinetic energy is not conserved. [6]
7. A car of mass 1200 kg accelerates from rest to 25 m s^{-1} in 8.0 s on a level road. Friction and air resistance are negligible.
 - (a) Calculate the work done on the car.
 - (b) Calculate the average power output of the engine. [4]
8. State the principle of conservation of momentum, and explain why it applies to a system of two colliding objects even when kinetic energy is not conserved. [2]

Section C – Rigid Body Mechanics (HL) (HL only)

9. A uniform rod of mass 4.0 kg and length 2.0 m is pivoted at one end and held horizontally, then released from rest. The moment of inertia of a uniform rod about an end is $I = \frac{1}{3}ML^2$.

- (a) Calculate the moment of inertia of the rod about the pivot.
 - (b) Calculate the torque due to gravity about the pivot at the instant of release.
 - (c) Calculate the initial angular acceleration of the rod. [6]
10. A uniform disc of mass 0.50 kg and radius 0.20 m spins about its central axis at an angular velocity of 20 rad s^{-1} . The moment of inertia of a disc about its central axis is $I = \frac{1}{2}MR^2$.
- (a) Calculate the moment of inertia of the disc.
 - (b) Calculate its angular momentum.
 - (c) Calculate its rotational kinetic energy. [5]
11. A solid sphere (moment of inertia $I = \frac{2}{5}MR^2$) is released from rest and rolls without slipping down a slope, descending a vertical height of 0.80 m. Using conservation of energy, calculate the speed of the sphere's centre of mass at the bottom of the slope. [4]
12. An ice skater spinning with moment of inertia 4.0 kg m^2 at an angular velocity of 2.0 rad s^{-1} pulls her arms in, reducing her moment of inertia to 1.6 kg m^2 .
- (a) Calculate her new angular velocity.
 - (b) Calculate the kinetic energy before and after, and explain the source of any increase. [5]

Answers

Check your working against these. If an answer does not match, try the question again before looking for the method.

- Time to top: $t = \frac{u}{g} = \frac{15}{9.81} = 1.53 \text{ s}$. Maximum height $= 1.2 + \frac{15^2}{2(9.81)} = 12.7 \text{ m}$.
 - Using $1.2 + 15t - 4.905t^2 = 0$ gives $t = 3.14 \text{ s}$.
- $v_x = 20 \cos 30^\circ = 17.3 \text{ m s}^{-1}$, $v_y = 20 \sin 30^\circ = 10.0 \text{ m s}^{-1}$.
 - $T = \frac{2v_y}{g} = 2.04 \text{ s}$.
 - $R = v_x T = 35.3 \text{ m}$.
 - $H = \frac{v_y^2}{2g} = 5.10 \text{ m}$.
- As speed increases, air resistance (drag) increases; when drag becomes equal in magnitude to the weight, the resultant force on the skydiver is zero, so the acceleration is zero and the skydiver falls at a constant (terminal) velocity.
- Displacement-time graph: a curve starting at the origin with increasing (steepening) gradient – a parabola, since $s \propto t^2$. Velocity-time graph: a straight line through the origin with constant positive gradient equal to g , since $v = gt$.
- $a = \frac{(m_1 - m_2)g}{m_1 + m_2} = \frac{2.0(9.81)}{8.0} = 2.45 \text{ m s}^{-2}$.
 - $T = m_1(g - a) = 5.0(9.81 - 2.45) = 36.8 \text{ N}$ (also $T = m_2(g + a) = 36.8 \text{ N}$, confirming consistency).
- By conservation of momentum, $v = \frac{(2.0)(6.0)}{6.0} = 2.0 \text{ m s}^{-1}$.
 - $E_{K,i} = \frac{1}{2}(2.0)(6.0)^2 = 36 \text{ J}$; $E_{K,f} = \frac{1}{2}(6.0)(2.0)^2 = 12 \text{ J}$; loss $= 24 \text{ J}$.
 - Inelastic collision.
- $W = \Delta E_K = \frac{1}{2}(1200)(25)^2 = 3.75 \times 10^5 \text{ J}$.
 - $P = \frac{W}{t} = \frac{3.75 \times 10^5}{8.0} = 4.69 \times 10^4 \text{ W}$.
- The total momentum of an isolated system (no external resultant force) is constant. Momentum conservation follows from Newton's third law (equal and opposite internal forces act for equal times during the collision) and holds regardless of whether the collision is elastic or inelastic, since kinetic energy loss (e.g. to heat or sound) does not affect the vector sum of momentum.
- $I = \frac{1}{3}(4.0)(2.0)^2 = 5.33 \text{ kg m}^2$.
 - The weight acts at the centre of mass, 1.0 m from the pivot: $\tau = Mg \left(\frac{L}{2}\right) = 4.0(9.81)(1.0) = 39.2 \text{ N m}$.
 - $\alpha = \frac{\tau}{I} = \frac{39.2}{5.33} = 7.36 \text{ rad s}^{-2}$.
- $I = \frac{1}{2}(0.50)(0.20)^2 = 0.0100 \text{ kg m}^2$.
 - $L = I\omega = 0.0100(20) = 0.200 \text{ kg m}^2 \text{ s}^{-1}$.
 - $E_K = \frac{1}{2}I\omega^2 = \frac{1}{2}(0.0100)(20)^2 = 2.00 \text{ J}$.
- $Mgh = \frac{1}{2}Mv^2 + \frac{1}{2}I\omega^2$ with $\omega = \frac{v}{R}$ gives $Mgh = \frac{7}{10}Mv^2$, so $v = \sqrt{\frac{10gh}{7}} = \sqrt{\frac{10(9.81)(0.80)}{7}} = 3.35 \text{ m s}^{-1}$.

12. (a) By conservation of angular momentum, $\omega_2 = \frac{I_1\omega_1}{I_2} = \frac{4.0(2.0)}{1.6} = 5.0 \text{ rad s}^{-1}$.
- (b) $E_{K,1} = \frac{1}{2}(4.0)(2.0)^2 = 8.0 \text{ J}$; $E_{K,2} = \frac{1}{2}(1.6)(5.0)^2 = 20.0 \text{ J}$. The kinetic energy increases because the skater does positive work pulling her arms inward against the centripetal force, converting internal (muscular/chemical) energy into rotational kinetic energy.

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