OCR A Physics | Conservation of momentum and collisions solutions

AS core solutions + optional second-year AL extension | 56 marks total

Specification points covered

- 3.5.2(a) State and apply the principle of conservation of momentum.
- 3.5.2(b) Describe and analyse collisions and interactions of bodies in one and two dimensions.
- 3.5.2(c) Distinguish between perfectly elastic and inelastic collisions.

Course level guide
Questions 1-7 are the 37-mark AS route; questions 8-10 are AL content. Define the system, choose a positive direction and conserve total momentum before using kinetic energy to classify the collision.

1. Principles and collision types [4 marks]

Use precise wording that identifies the system and the quantity that is conserved.

(a) State the principle of conservation of momentum, including the condition required for it to apply. **[2 marks]**

(b) State what is meant by a perfectly elastic collision. **[1 mark]**

(c) State what is meant by an inelastic collision. **[1 mark]**

Answer / mark points: (a) The total momentum of a system remains constant [1] provided the resultant external force on the system is zero. [1]
(b) The total kinetic energy of the system is conserved in a perfectly elastic collision. [1]
(c) The total kinetic energy of the system is not conserved in an inelastic collision. [1] Total energy is still conserved.

Teacher prompt / common error: Do not accept 'momentum before equals momentum after' without identifying total momentum of the system and the absence of a resultant external force. Inelastic does not mean that energy disappears.

2. A joined one-dimensional collision [4 marks]

Take motion to the right as positive. Cart A has mass 0.40 kg and velocity +3.0 m s^{-1}. It collides with stationary cart B of mass 0.60 kg. The carts stick together.

(a) Calculate the velocity of the joined carts immediately after the collision. **[2 marks]**

(b) Calculate the kinetic energy transferred from the kinetic store during the collision. **[2 marks]**

Answer / mark points: (a) $0.40 \times 3.0 + 0.60 \times 0 = (0.40 + 0.60)v$ [1], so $v = +1.20$ m s^{-1}. [1]
(b) $E_{k,before} = ½ \times 0.40 \times 3.0^2 = 1.80$ J and $E_{k,after} = ½ \times 1.00 \times 1.20^2 = 0.720$ J. [1] Energy transferred = 1.80 - 0.720 = 1.08 J (about 1.1 J). [1]

Teacher prompt / common error: Do not average the initial velocities. Use total momentum; any decrease in kinetic energy is transferred to internal energy, sound and deformation.

3. A rebound collision [7 marks]

Take motion to the right as positive. Cart A has mass 0.20 kg and initial velocity +3.0 m s^{-1}. It collides head-on with stationary cart B of mass 0.30 kg. After the collision, A has velocity -0.60 m s^{-1}.

(a) Calculate the velocity of cart B after the collision. **[3 marks]**

(b) Calculate the total kinetic energy before and after the collision. **[2 marks]**

(c) Classify the collision and justify your answer. **[1 mark]**

(d) State the relationship between the changes in momentum of carts A and B. **[1 mark]**

Answer / mark points: (a) 0.20 × 3.0 + 0 = 0.20 × (-0.60) + 0.30v_B. [1] Therefore 0.30v_B = 0.720 [1], so v_B = +2.40 m s^{-1}. [1]

(b) $E_{k,before}$ = ½ × 0.20 × 3.0^2 = 0.900 J. [1] $E_{k,after}$ = ½ × 0.20 × 0.60^2 + ½ × 0.30 × 2.40^2 = 0.036 + 0.864 = 0.900 J. [1]

(c) The collision is perfectly elastic because total kinetic energy is conserved. [1]

(d) Δp_A = 0.20(-0.60 - 3.0) = -0.720 kg m s^{-1} and Δp_B = +0.720 kg m s^{-1}: the changes are equal in magnitude and opposite in direction. [1]

Teacher prompt / common error: A rebound velocity must carry a negative sign when right is positive. Compare total kinetic energy, not the kinetic energy of one cart.

4. An internal separation [4 marks]

Two carts are initially stationary and held together by a compressed spring. When released, cart A of mass 0.45 kg moves left at 2.2 m s^{-1}. Cart B has mass 0.75 kg. External horizontal forces are negligible.

(a) Calculate the velocity of cart B. **[2 marks]**

(b) Explain why the total kinetic energy increases while total momentum remains zero. **[2 marks]**

Answer / mark points: (a) 0 = 0.45 × (-2.2) + 0.75v_B [1], so v_B = +1.32 m s^{-1} (to the right). [1]

(b) Elastic potential energy in the compressed spring is transferred to kinetic energy. [1] The spring forces are internal and the resultant external horizontal force is zero, so the equal and opposite momenta keep the total momentum at zero. [1]

Teacher prompt / common error: Momentum conservation applies to interactions as well as collisions. Energy can change store while total energy and total momentum remain conserved.

5. Rebound and contact force [6 marks]

Take motion to the right as positive. Autonomous parcel carrier A has mass 1.50 kg and moves at +2.40 m s^{-1}. It collides with stationary carrier B of mass 2.50 kg. After the collision A rebounds at -0.40 m s^{-1}. The carriers are in contact for 0.080 s. External horizontal forces are negligible during the collision.

(a) Calculate the velocity of carrier B immediately after the collision. **[3 marks]**

(b) Calculate the change in momentum of carrier A. **[1 mark]**

(c) Calculate the average force exerted on carrier A during the collision. **[1 mark]**

(d) State the average force exerted on carrier B, including its direction. **[1 mark]**

Answer / mark points: (a) 1.50 × 2.40 + 0 = 1.50 × (-0.40) + 2.50v_B. [1] Therefore 2.50v_B = 4.20 kg m s^{-1} [1], so v_B = +1.68 m s^{-1}. [1]

(b) Δp_A = 1.50[-0.40 - (+2.40)] = -4.20 kg m s^{-1}. [1]

(c) $F_{average\ on\ A}$ = $\Delta p_A/\Delta t$ = -4.20/0.080 = -52.5 N. [1] The negative sign means the force is to the left.

(d) The average force on B is 52.5 N to the right. [1] It is equal in magnitude and opposite in direction to the force on A.

Teacher prompt / common error: Keep the rebound velocity negative throughout. The force pair acts on different carriers; equal and opposite forces produce equal and opposite momentum changes during the same contact time.

6. A sequence of one-dimensional collisions [8 marks]

Three test carts P, Q and R move along the same straight, level track. Take motion to the right as positive. Cart P has mass 0.40 kg and initially moves at +3.0 m s^{-1}; cart Q of mass 0.80 kg is stationary. After P collides with Q, P continues to the right at +0.40 m s^{-1}. Cart Q then collides with stationary cart R of mass 0.50 kg and the two carts couple together. External horizontal forces are negligible during both collisions.

(a) Calculate the velocity of cart Q immediately after the first collision. **[2 marks]**

(b) Calculate the kinetic energy transferred from the kinetic store in the first collision and classify this collision. **[3 marks]**

(c) Calculate the velocity of the coupled Q-R carts after the second collision. **[2 marks]**

(d) Calculate the total kinetic energy transferred from the start of the sequence to the end of the second collision. **[1 mark]**

Answer / mark points: (a) 0.40 × 3.0 = 0.40 × 0.40 + 0.80v_Q. [1] Hence v_Q = (1.20 - 0.160)/0.80 = +1.30 m s^{-1}. [1]

(b) $E_{k,before}$ = ½ × 0.40 × 3.0^2 = 1.80 J. $E_{k,after}$ = ½ × 0.40 × 0.40^2 + ½ × 0.80 × 1.30^2 = 0.032 + 0.676 = 0.708 J. [1] Energy transferred = 1.80 - 0.708 = 1.09 J. [1] The collision is inelastic because total kinetic energy decreases. [1]

(c) 0.80 × 1.30 + 0 = (0.80 + 0.50)v. [1] Therefore v = +0.800 m s^{-1}. [1]

(d) Final E_k = ½ × 0.40 × 0.40^2 + ½ × 1.30 × 0.800^2 = 0.032 + 0.416 = 0.448 J, so total energy transferred = 1.80 - 0.448 = 1.35 J. [1]

Teacher prompt / common error: Treat the two collisions separately for momentum, then include every moving cart when comparing the initial and final kinetic energy of the complete P-Q-R system.

7. Collision language corrections [4 marks]

For each statement, give a precise scientific correction.

(a) "The collision lost momentum because the kinetic energy decreased." **[2 marks]**

(b) "An inelastic collision always makes the objects stick together." **[2 marks]**

Answer / mark points: (a) The total momentum of the complete collision system is conserved because the resultant external force is negligible. [1] Kinetic energy is transferred to other stores, such as internal energy, deformation and sound; it is not momentum that is lost. [1]

(b) Inelastic means that total kinetic energy is not conserved. [1] The objects may separate after the collision; sticking together is only one possible inelastic outcome. [1]

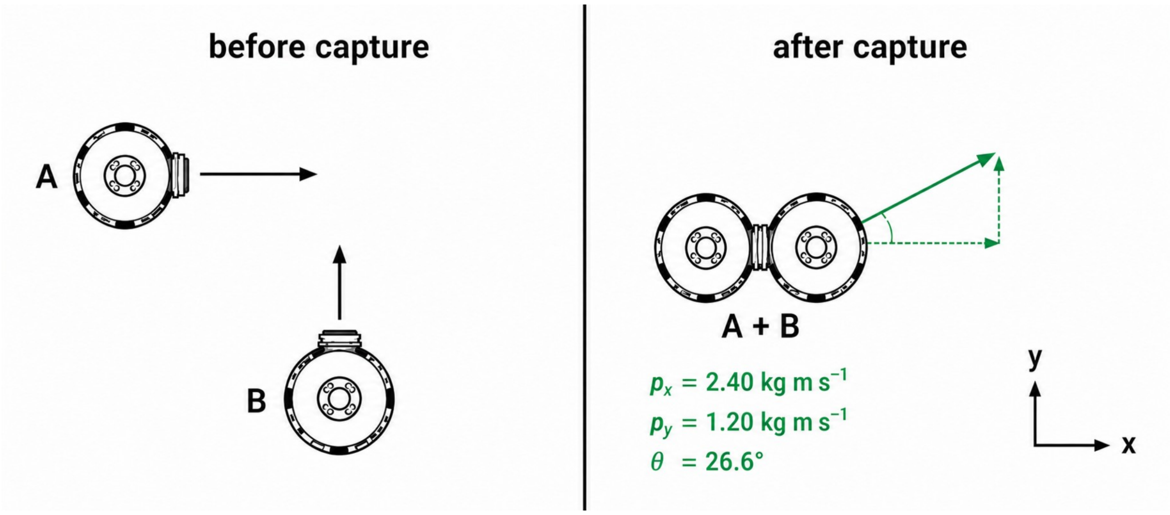
Teacher prompt / common error: Require pupils to name 'total momentum of the system' and 'total kinetic energy'. Momentum is a vector quantity; kinetic energy is a scalar energy store.

AL CONTENT - SECOND-YEAR ONLY

Questions 8-10 use conservation of momentum in two dimensions. This content is assessed at A Level and is not part of the AS assessment route.

Scenario: air-bearing satellite capture simulator

Engineers test two round satellite modules on a horizontal air-bearing platform. The platform reproduces near-frictionless motion in two dimensions. Module A has mass 0.80 kg and moves east at 3.0 m s^{-1}. Module B has mass 1.20 kg and moves north at 1.0 m s^{-1}. Resultant external horizontal forces are negligible. The diagram is not to scale.



8. AL content - initial momentum of the two-module system [4 marks]

(a) Calculate the eastward x-component of the total momentum before capture. [1 mark]

(b) Calculate the northward y-component of the total momentum before capture. [1 mark]

(c) Calculate the magnitude of the total momentum before capture. [1 mark]

(d) Calculate the direction of the total momentum, measured north of east. [1 mark]

Answer / mark points: (a) $p_x = 0.80 \times 3.0 = 2.40$ kg m s^{-1} east. [1]

(b) $p_y = 1.20 \times 1.0 = 1.20$ kg m s^{-1} north. [1]

(c) $p = \sqrt{(2.40^2 + 1.20^2)} = 2.68$ kg m s^{-1}. [1]

(d) $\theta = \tan^{-1}(1.20/2.40) = 26.6°$ north of east. [1]

Teacher prompt / common error: Momentum is a vector. Conserve and combine the perpendicular components before finding a magnitude or direction.

9. AL content - trial 1: modules dock and remain joined [7 marks]

The modules lock together during capture. Their combined mass is 2.00 kg.

(a) Calculate the x- and y-components of the velocity of the joined modules. **[2 marks]**

(b) Calculate the speed of the joined modules. **[1 mark]**

(c) Calculate the total kinetic energy before and after capture, and hence determine the energy transferred from the kinetic store. **[3 marks]**

(d) Classify the collision and justify your answer. **[1 mark]**

Answer / mark points: (a) $v_x = 2.40/2.00 = 1.20$ m s^{-1} [1] and $v_y = 1.20/2.00 = 0.600$ m s^{-1}. [1]

(b) $v = \sqrt{(1.20^2 + 0.600^2)} = 1.34$ m s^{-1}. [1]

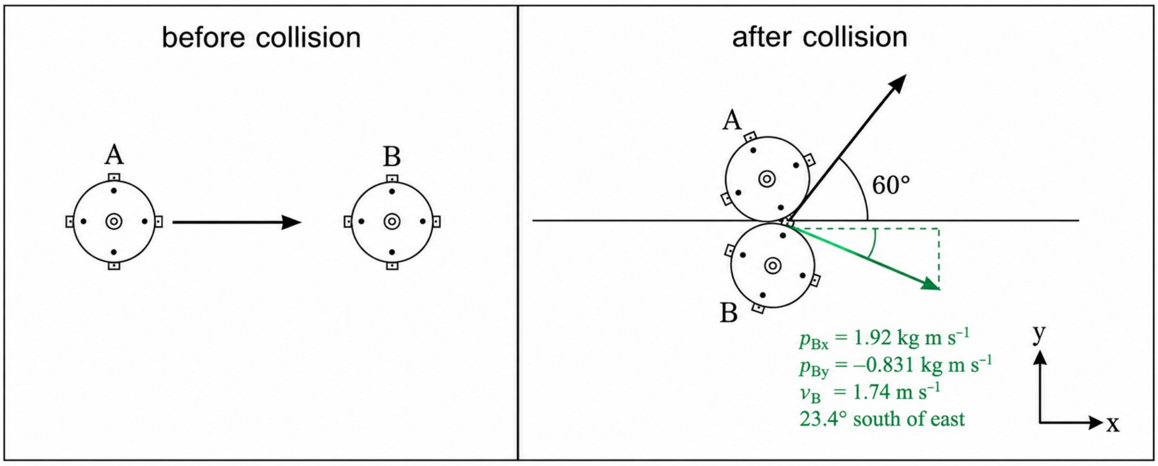
(c) $E_{k,before} = ½ \times 0.80 \times 3.0^2 + ½ \times 1.20 \times 1.0^2 = 4.20$ J. [1] $E_{k,after} = ½ \times 2.00 \times 1.34^2 = 1.80$ J. [1] Energy transferred = 4.20 - 1.80 = 2.40 J. [1]

(d) The collision is inelastic because total kinetic energy decreases. [1]

Teacher prompt / common error: The joined velocity has the same direction as the total momentum, but dividing a vector by the combined mass is most safely done component by component.

10. AL content - trial 2: the docking mechanism deflects the modules [8 marks]

In a separate trial, module B is initially stationary. Module A again moves east at 3.0 m s^{-1}. After the collision A moves at 1.20 m s^{-1}, 60° north of east. Module B moves south of east. The diagram is not to scale.



(a) Calculate the x- and y-components of the momentum of A after the collision. **[2 marks]**

(b) Use conservation of momentum to determine the x- and y-components of the momentum of B after the collision. **[2 marks]**

(c) Calculate the speed and direction of B after the collision. **[2 marks]**

(d) The initial kinetic energy is 3.60 J. Calculate the total kinetic energy after the collision and classify the collision. **[2 marks]**

Answer / mark points: (a) The momentum of A after is 0.80 × 1.20 = 0.960 kg m s^{-1}. p_{Ax} = 0.960 cos 60° = 0.480 kg m s^{-1} [1]; p_{Ay} = 0.960 sin 60° = +0.831 kg m s^{-1}. [1]

(b) Initially, total momentum is (2.40, 0). Therefore p_{Bx} = 2.40 - 0.480 = 1.92 kg m s^{-1} [1] and p_{By} = 0 - 0.831 = -0.831 kg m s^{-1}. [1]

(c) v_{Bx} = 1.92/1.20 = 1.60 m s^{-1} and v_{By} = -0.831/1.20 = -0.693 m s^{-1}. Speed = $\sqrt{(1.60^2 + 0.693^2)}$ = 1.74 m s^{-1} [1], at $\tan^{-1}$(0.693/1.60) = 23.4° south of east. [1]

(d) $E_{k,after}$ = ½ × 0.80 × 1.20^2 + ½ × 1.20 × 1.74^2 = 0.576 + 1.82 = 2.40 J. [1] This is less than 3.60 J, so the collision is inelastic. [1]

Teacher prompt / common error: Conserve momentum independently in x and y. The negative y-component for B is required to cancel A's positive y-component; inelastic objects do not have to remain joined.