

Momentum and Impulse

PH11-9

ORIENTATION

Lesson goal: build accurate physics fluency for momentum and impulse and use that fluency to support clear HSC-style scientific writing.

This page is materialised into the MentorMind course shell from existing teaching, textbook, and eduKG material. Use it as the main lesson surface; use the tutor for targeted repair, worked examples, and concise writing feedback.

SYLLABUS INQUIRY QUESTION

- How can momentum models predict outcomes of interactions?

From The Feynman Lectures on Physics, Vol I, Chapter 10:

Momentum is a conserved quantity that often reveals the final motion even when the detailed forces are unknown.

LEARNING OBJECTIVES

- Define momentum and impulse with units.
 - Apply the impulse-momentum theorem.
 - Use conservation of momentum in one dimension.
 - Distinguish elastic and inelastic collisions.
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CONTENT

Momentum

Momentum is the product of mass and velocity:

$$\vec{p} = m\vec{v}$$

- Momentum is a **vector** (has direction)
- SI units: kg·m/s (or N·s)
- A fast, heavy object has large momentum
- A stationary object has zero momentum

Momentum is conserved in collisions, making it a powerful tool for predicting outcomes without knowing the detailed forces.

Interactive: Comparing Momentum

Different objects with the same momentum:

Impulse

Impulse is the change in momentum caused by a force acting over time:

$$\vec{J} = \vec{F}\Delta t = \Delta\vec{p} = m\vec{v}_f - m\vec{v}_i$$

This is the **impulse-momentum theorem**: the impulse equals the change in momentum.

$$\vec{J} = \vec{F}_{avg}\Delta t = \Delta\vec{p}$$

A large force for a short time, or a small force for a long time, can produce the same impulse.

Units of impulse: N·s (equivalent to kg·m/s)

Why Impulse Matters

Impulse explains why:

- **Airbags** reduce injury: same impulse over longer time → smaller force
- **Following through** in sport: contact time increases → greater impulse
- **Crumple zones** save lives: extending collision time reduces peak force

Conservation of Momentum

In an **isolated system** (no external forces), total momentum is conserved:

$$\vec{p}_{before} = \vec{p}_{after}$$

$$m_1\vec{v}_{1i} + m_2\vec{v}_{2i} = m_1\vec{v}_{1f} + m_2\vec{v}_{2f}$$

Interactive: Collision Before and After

Two objects collide and exchange momentum:

Before: Total momentum = $3 \times 4 + 2 \times 0 = 12 \text{ kg}\cdot\text{m/s}$

After (if they stick): $(3 + 2) \times v_f = 12 \rightarrow v_f = 2.4 \text{ m/s}$

Types of Collisions

| TYPE | MOMENTUM | KINETIC ENERGY | EXAMPLE |
|---------------------|-----------|-----------------|-----------------------------------|
| Elastic | Conserved | Conserved | Billiard balls, atomic collisions |
| Inelastic | Conserved | NOT conserved | Car crash, ball catches |
| Perfectly inelastic | Conserved | Maximum KE lost | Objects stick together |

Momentum is ALWAYS conserved in collisions (if the system is isolated). Kinetic energy is only conserved in elastic collisions.

Interactive: Elastic vs Inelastic Collision

Compare the outcomes of different collision types:

In an elastic collision between equal masses where one is at rest, the moving object stops and the stationary object moves with the original velocity.

WORKED EXAMPLES

Example 1: Calculate momentum

A 0.25 kg ball moves at 18 m/s.

Solution:

1. Use $p = mv$
2. $p = 0.25 \times 18 = 4.5 \text{ kg}\cdot\text{m/s}$
3. Momentum is in the direction of motion

Example 2: Impulse and velocity change

A 1.5 kg cart experiences a 12 N force for 0.50 s.

Solution:

1. Calculate impulse: $J = F\Delta t = 12 \times 0.50 = 6.0 \text{ N}\cdot\text{s}$
2. Impulse equals change in momentum: $J = \Delta p = m\Delta v$
3. Velocity change: $\Delta v = \frac{J}{m} = \frac{6.0}{1.5} = 4.0 \text{ m/s}$

The cart's velocity increases by 4.0 m/s in the direction of the force.

Example 3: Perfectly inelastic collision

A 2.0 kg cart moving at 3.0 m/s collides and sticks to a 1.0 kg cart at rest.

Solution:

1. Initial momentum: $p_i = m_1v_1 + m_2v_2 = 2.0 \times 3.0 + 1.0 \times 0 = 6.0 \text{ kg}\cdot\text{m/s}$
2. Final mass (stuck together): $m_f = 2.0 + 1.0 = 3.0 \text{ kg}$
3. Conservation: $p_f = p_i$
4. Final velocity: $v_f = \frac{p_i}{m_f} = \frac{6.0}{3.0} = 2.0 \text{ m/s}$

Example 4: Force from impulse

A 0.40 kg ball changes velocity from 12 m/s (right) to 8 m/s (left) in 0.020 s. Find the average force.

Solution:

1. Taking right as positive:
 - Initial velocity: $v_i = +12 \text{ m/s}$
 - Final velocity: $v_f = -8 \text{ m/s}$

2. Change in momentum:

$$\Delta p = m(v_f - v_i) = 0.40 \times (-8 - 12) = 0.40 \times (-20) = -8.0 \text{ kg}\cdot\text{m/s}$$

3. Average force:

$$F = \frac{\Delta p}{\Delta t} = \frac{-8.0}{0.020} = -400 \text{ N}$$

4. The force is 400 N to the left (negative direction)

Example 5: Elastic collision

A 1.0 kg cart moving at 4.0 m/s collides elastically with a 2.0 kg cart at rest. Find the final velocities.

Solution:

For elastic collisions between two objects (object 2 initially at rest):

$$v_{1f} = \frac{m_1 - m_2}{m_1 + m_2} v_{1i} = \frac{1.0 - 2.0}{1.0 + 2.0} \times 4.0 = \frac{-1}{3} \times 4.0 = -1.33 \text{ m/s}$$
$$v_{2f} = \frac{2m_1}{m_1 + m_2} v_{1i} = \frac{2 \times 1.0}{1.0 + 2.0} \times 4.0 = \frac{2}{3} \times 4.0 = 2.67 \text{ m/s}$$

Cart 1 bounces back at 1.33 m/s; Cart 2 moves forward at 2.67 m/s.

Verification: Check momentum is conserved:

- Before: $1.0 \times 4.0 = 4.0 \text{ kg}\cdot\text{m/s}$
- After: $1.0 \times (-1.33) + 2.0 \times 2.67 = -1.33 + 5.33 = 4.0 \text{ kg}\cdot\text{m/s} \checkmark$

COMMON MISCONCEPTIONS

- **Misconception:** Momentum depends only on speed. **Correction:** Momentum is $p = mv$. Both mass AND velocity matter. A slow truck can have more momentum than a fast bicycle.
- **Misconception:** Impulse equals force. **Correction:** Impulse is $J = F\Delta t$. The same force applied for different times produces different impulses.
- **Misconception:** Momentum is always conserved. **Correction:** Only in **isolated systems** with no external forces. External forces change total momentum.
- **Misconception:** Kinetic energy is always conserved in collisions. **Correction:** Only in **elastic** collisions. In inelastic collisions, some KE is converted to other forms (sound, heat, deformation).
- **Misconception:** Heavier objects always have more momentum. **Correction:** A light, fast object can have more momentum than a heavy, slow object.

PRACTICE QUESTIONS

Easy (2 marks)

Find the momentum of a 3.0 kg object moving at 2.5 m/s.

- Use $p = mv$ (1)
- Correct value: $p = 3.0 \times 2.5 = 7.5 \text{ kg}\cdot\text{m/s}$ with units (1)

Answer: 7.5 kg·m/s

Medium (4 marks)

A 0.40 kg ball changes velocity from 12 m/s (east) to 8 m/s (west) in 0.020 s. Find the average force.

- Correct change in velocity: $\Delta v = -8 - (+12) = -20 \text{ m/s}$ (1)
- Change in momentum: $\Delta p = 0.40 \times (-20) = -8.0 \text{ kg}\cdot\text{m/s}$ (1)
- Force calculation: $F = \Delta p / \Delta t = -8.0 / 0.020 = -400 \text{ N}$ (1)
- Direction: 400 N west (1)

Answer: 400 N west

Hard (5 marks)

A 1.0 kg cart moving at 4.0 m/s collides elastically with a 2.0 kg cart at rest. Find the final velocities.

- State conservation of momentum (1)
- State conservation of kinetic energy for elastic collision (1)
- Apply elastic collision formulas or solve simultaneous equations (1)
- Correct final velocity of cart 1: $v_{1f} = -1.33 \text{ m/s}$ (1)
- Correct final velocity of cart 2: $v_{2f} = 2.67 \text{ m/s}$ (1)

Solution:

Using elastic collision formulas:

- $v_{1f} = \frac{m_1 - m_2}{m_1 + m_2} v_{1i} = \frac{-1}{3} \times 4.0 = -1.33 \text{ m/s}$
- $v_{2f} = \frac{2m_1}{m_1 + m_2} v_{1i} = \frac{2}{3} \times 4.0 = 2.67 \text{ m/s}$

Answer: Cart 1: 1.33 m/s backward; Cart 2: 2.67 m/s forward

MULTIPLE CHOICE QUESTIONS

Test your understanding with these interactive questions:

SUMMARY

- Momentum: $\vec{p} = m\vec{v}$ (units: kg·m/s)
 - Impulse: $\vec{J} = \vec{F}\Delta t = \Delta\vec{p}$ (units: N·s)
 - Conservation: In isolated systems, $|\vec{p}\{\text{before}\}| = |\vec{p}\{\text{after}\}|$
 - Elastic collisions: Both momentum AND kinetic energy conserved
 - Inelastic collisions: Only momentum conserved; KE is lost
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SELF-ASSESSMENT

Check your understanding:

After studying this section, you should be able to:

- Calculate momentum using $p = mv$
 - Apply the impulse-momentum theorem
 - Use conservation of momentum in collisions
 - Distinguish elastic from inelastic collisions
 - Explain why airbags reduce injury forces
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SCIENTIFIC WRITING AND EXAM SUPPORT

When answering questions from this lesson, separate:

- the physical quantity being discussed,
- the model or law being applied,
- the mathematical relationship, including units,
- the conclusion in words.

For explanation questions, write in the pattern: **claim -> physics reason -> consequence.**

For calculation questions, state the formula, substitute with units, calculate, then interpret the answer.

MAINTENANCE LOOP

One-minute retrieval:

1. State the key law, model, or relationship used in this lesson.
2. Identify one common misconception that would lead to a wrong answer.
3. Write one sentence that links the calculation or evidence back to the physical meaning.

STUDENT WORKING
