Topic 4: Momentum, Impulse and Collisions

Advanced Placement Physics 1

Dr. Timothy Leung

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Olympiads School

Momentum

Momentum

Linear momentum[1] is a quantity of motion defined as the product of mass m and velocity $\mathbf{v}$. The unit of momentum is **kilogram meter per second** ($\mathrm{kg\,m/s}$):

$$\boxed{\mathbf{p} = m\mathbf{v}}$$

- Momentum is a *vector* quantity; the direction of $\mathbf{p}$ is the same as $\mathbf{v}$
- For rotational motion of rigid bodies, there is also a similar concept called **angular momentum** which will be studied in a later topic

[1] or **translational momentum**, or just **momentum**

General Form of Second Law of Motion

From an inertial frame of reference, for a constant mass m, the average rate of change of momentum gives a familiar result:

$$\frac{\Delta \mathbf{p}}{\Delta t} = \frac{\Delta \left(m\mathbf{v} \right)}{\Delta t} = m\frac{\Delta \mathbf{v}}{\Delta t} = m\mathbf{a} = \bar{\mathbf{F}}_{\text{net}}$$

which is the familiar form of the second law of motion. In fact, the *general form* of the first and second laws of motion is that **the average net external force on an object is the change of its momentum over a finite time interval**:

$$\boxed{\bar{\mathbf{F}}_{\text{net}} = \frac{\Delta \mathbf{p}}{\Delta t}}$$

First Law of Motion & Conservation of Momentum

$$\boxed{\mathbf{F}_{\text{net}} = \frac{\Delta \mathbf{p}}{\Delta t}}$$

First law of motion: The momentum state of an object is conserved unless a net unbalanced external force acts on it

- Without net external forces, the **conservation of momentum** states that the initial and final momentum must be constant:

$$\sum \mathbf{p}_i = \sum \mathbf{p}'_i$$

- This is applied to collision and explosion problems.

Impulse

Rearranging the variables in the general form of the second law of motion, we obtain the **impulse-momentum theorem**:

$$\bar{\mathbf{F}}_{\text{net}} = \frac{\Delta \mathbf{p}}{\Delta t} \rightarrow \boxed{\mathbf{J}_{\text{net}} = \bar{\mathbf{F}}_{\text{net}} \Delta t = \Delta \mathbf{p}}$$

where $\mathbf{J}_{\text{net}}$ is called the **net impulse**. Since $\mathbf{F}$, $\mathbf{p}$ and $\mathbf{J}_{\text{net}}$ are all vectors, impulse can be evaluated separately in each of the $\hat{\imath}$, $\hat{\jmath}$ and $\hat{\mathrm{k}}$ directions.

$$\mathbf{J} = J_x \hat{\imath} + J_x \hat{\jmath} + J_z \hat{\mathrm{k}}$$

For the $\hat{\imath}$ direction:

$$J_x = F_x \Delta t = \Delta p_x$$

Impulse

Any average force $\bar{\mathbf{F}}$ acting on an object over a time Δt generates an impulse $\mathbf{J}$, regardless of whether or not there is a change in momentum:

$$\boxed{\mathbf{J} = \bar{\mathbf{F}}\Delta t}$$

The change in momentum only depends on *net* impulse $\mathbf{J}_{\text{net}}$. The force is a *time-averaged* vector that generates the same impulse. It is often used in introductory physics courses to avoid calculus

Impulse: An Example

Example 1: Jim pushes a box with mass 1.0 kg with a 5.0 N force for 10 s while the box stays on the same place. Find the impulse of the pushing force, friction force, the gravitational force, and the net force.

Rocket Propulsion Problem

Example 2: A rocket generates a thrust force by ejecting hot gases from an engine. If it takes 1 ms to combust 1.0 kg of fuel, ejecting it at a speed of 1000 m / s, what thrust is generated?

A. 1000 N
B. 10 000 N
C. 100 000 N
D. 1 000 000 N

Another Space Example

Example 3: A rocket for mining the asteroid belt is designed like a large scoop. It is approaching asteroids at a velocity of 10^4 m/s. The asteroids are much smaller than the rocket. If the rocket scoops asteroids at a rate of 100 kg/s, what thrust (force) must the rocket's engine provide in order for the rocket to maintain constant velocity? Ignore any variation in the rocket's mass due to the burning fuel.

A. 10^3 N
B. 10^6 N
C. 10^9 N
D. 10^{12} N

Collisions

Conservation of Momentum

- From the third law of motion, we know that the action and reaction forces are always equal in magnitude and in opposite direction. Thus, their total impulse would be zero.
- When there is no external force, the momentum of the total system will always be constant. We saw that a few slides ago:

$$\sum_i \mathbf{p} = \sum_i \mathbf{p}'$$

Classifications of Collisions

- Elastic Collision:
  - Total kinetic energy is conserved
  - Momentum is conserved
- Inelastic collision:
  - Kinetic energy is **not** conserved
  - Momentum is conserved
- Completely inelastic collision:
  - “Perfectly inelastic collision”
  - A special case of inelastic collision
  - The objects move together after the collision
  - Kinetic energy is **not** conserved
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How to Solve Conservation of Momentum Problem

1. Check whether the condition for the conservation of momentum is satisfied (i.e. are there any external forces?)
2. If so, write out expressions for initial momentum and final momentum, and equate the two. You will get 1 to 3 equations (one for each direction).
3. Solve these equations, find the quantity you need to find.

Remember that momentum is a vector. If there is no external force component in some direction, then the momentum component in this direction is still conserved.

Before We Dive Into Some Exercises

The most typical applications of momentum conservation are collision and explosions

- **Collision: A hits B**
  - Regardless of whether they move together or not afterwards, momentum is conserved
  - Head-on collisions are usually 1D
  - Glancing collisions are usually 2D or 3D
- **Explosion: A explodes and becomes B and C (and D and E...)**
  - A perfectly inelastic collision in reverse
  - Total momentum of B and C (and D and E...) is the same as A in the beginning
  - Usually a 2D or 3D problem

Example

Example 4: Two blocks A and B, both have mass 1.0 kg. Block A has velocity 3.0 m/s and block B is at rest. Their distance is 1.0 m. The surface is has kinetic friction coefficient 0.02. After they collide, they move together, what would be the final velocity of these two blocks? How far can they go after the collision?

Collision Problem

Example 5: Two objects with equal mass are heading toward each other with equal speeds, undergo a head-on collision. Which one of the following statement is correct?

A. Their final velocities are zero
B. Their final velocities may be zero
C. Each must have a final velocity equal to the other's initial velocity
D. Their velocities must be reduced in magnitude

Glancing Collision

Example 7: A billiard ball of mass 0.155 kg ("cue ball") moves with a velocity of 1.25 m/s toward a stationary billiard ball ("eight ball") of identical mass and strikes it with a glancing blow. The cue ball moves off at an angle of 29.7° clockwise from its original direction, with a speed of 0.956 m/s. What is the final velocity of the eight ball?

Elastic Collisions

Elastic Collision Problems

In elastic collisions, *both* momentum and kinetic energy is conserved. In a 1D collision, both equations below have to be satisfied:

$$\sum m_i v_i = \sum m_i v_i'$$
$$\sum \frac{1}{2} m_i v_i^2 = \sum \frac{1}{2} m_i v_i'^2$$

How kinetic energy is conserved: In an elastic collision, energy is first converted into a potential energy (e.g. elastic potential energy in a spring), and then all the energy is released back as kinetic energy.

Conservation of Momentum & Energy in Elastic Collisions

For collision of two objects, the conservation of momentum equation can be expressed as:

$$\boxed{m_1(v_1 - v_1') = m_2(v_2' - v_2)} \tag{1}$$

By moving m_1 terms to the left, and m_2 terms to the right. Likewise, the conservation of energy can also be arranged as:

$$\boxed{m_1(v_1^2 - v_1'^2) = m_2(v_2'^2 - v_2^2)} \tag{2}$$

By multiplying every term by 2, and again, moving m_1 terms to the left, and v_2 terms to the right.

Conservation of Momentum & Energy in Elastic Collisions

Dividing the equations (2) by (1) from the last slide, we get:

$$\frac{(2)}{(1)} \quad \rightarrow \quad \frac{m_1(v_1^2 - v_1'^2)}{m_1(v_1 - v_1')} = \frac{m_2(v_2'^2 - v_2^2)}{m_2(v_2' - v_2)}$$

m_1 and m_2 terms cancel out, while the terms in the numerator can be expanded as the difference of two squares which is then simplified:

$$\frac{(v_1 + v_1')(v_1 - v_1')}{(v_1 - v_1')} = \frac{(v_2' + v_2)(v_2' - v_2)}{(v_2' - v_2)}$$

Leading to the final expression, which is substituted back into (1)

$$v_1 + v_1' = v_2 + v_2'$$

Final Velocities in an Elastic Collision

When two objects 1 and 2 of mass m_1 and m_2 and initial velocities v_1 and v_2 collide elastically, their final velocities will be:

$$v_1' = \frac{v_1(m_1 - m_2) + 2m_2v_2}{m_1 + m_2}$$
$$v_2' = \frac{v_2(m_2 - m_1) + 2m_1v_1}{m_1 + m_2}$$

These equations are not provided in the AP exam equation sheet, which means that we are more interested in the behavior qualitatively rather than quantitatively.

Special Cases

If both objects have equal mass ($m_1 = m_2 = m$) and the second object is initially at rest ($v_2 = 0$), then the equations simplifies to

$$v_1' = \frac{v_1(m-m) + 2mv_2}{m+m} = 0$$
$$v_2' = \frac{v_2(m-m) + 2mv_1}{m+m} = v_1$$

All the momentum and energy from m_1 is transferred to m_2. Object 1 stops all together, while object 2 continues with the initial momentum and velocity of Object 1.

Special Cases

Another special case is when $m_1 \gg m_2$ and $v_2 = 0$ (i.e. a large object colliding with a small stationary object) then we can effectively "ignore" m_2:

$$v_1' = \frac{v_1(m_1 - m_2) + 2m_2v_2}{m_1 + m_2} \approx \frac{m_1v_1}{m_1} = v_1$$
$$v_2' = \frac{v_2(m_2 - m_1) + 2m_1v_1}{m_1 + m_2} \approx \frac{2m_1v_1}{m_1} = 2v_1$$

Object 1 continues to move like nothing happened, but object 2 is pushed to move at *twice* the initial speed of object 1.

Special Cases

In the reverse case, if $m_1 \ll m_2$, and $v_2 = 0$ (a small object colliding with a large stationary object), then we can "ignore" the m_1 term:

$$v_1' = \frac{v_1(m_1 - m_2) + 2m_2v_2}{m_1 + m_2} \approx \frac{-m_2v_1}{m_2} = -v_1$$

$$v_2' = \frac{v_2(m_2 - m_1) + 2m_1v_1}{m_1 + m_2} \approx 0$$

Object 1 bounces off object 2, and travels in the opposite direction with the same velocity magnitude, while object 2 does not move.

Elastic Collision Example

Example 8: Blocks A and B have the same mass; A hits B with a speed of 5.0 m / s while B is initially at rest. If the collision is elastic, what would be the final speed of these two objects?

Elastic Collision Example

Example 9: Blocks A and B with the same mass; A has a velocity 3.0 m / s to the east while B has 2 m / s to the west. If the collision is elastic, after the collision, what would the velocity of the two blocks be?

Elastic Collision Example

Example 10: Throw a ball to a really big wall, when the ball reaches the wall, it has a velocity $10\,\mathrm{m/s}$ toward the wall. If the collision is elastic, what would the final velocity of the ball be?

Elastic Collision Example

Example 11: Throw a ball with a velocity 4.0 m/s toward a train with a velocity 40 m/s toward the ball. If the collision is elastic, what would the final velocity of the ball be?

Inelastic Collision: Calculating Energy Loss

Example 12: Two blocks A and B with mass 2.0 kg, block A hits B with velocity 4.0 m / s while B is at rest.

A. Suppose the collision is completely inelastic, what would the final velocity of A and B be?
B. What is the loss of energy?