

Momentum and Collisions:

Overview and Learning Goals



Build working understanding of momentum, impulse, and collisions



Define momentum as a vector:
 $p = mv$



Apply the impulse-momentum theorem: $J = \Delta p$



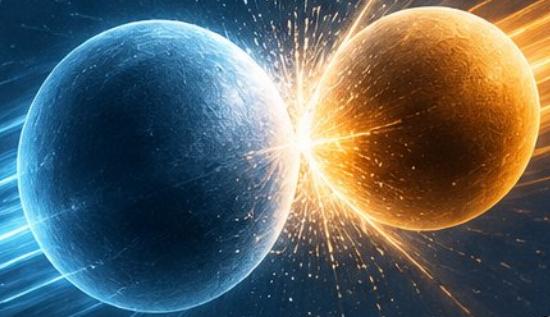
Distinguish elastic from inelastic collisions, conserve momentum in 1D and 2D



Real-world payoff: vehicle safety, sports, DART asteroid deflection



Opening question: if an airbag doesn't change total momentum change, how does it reduce injury?

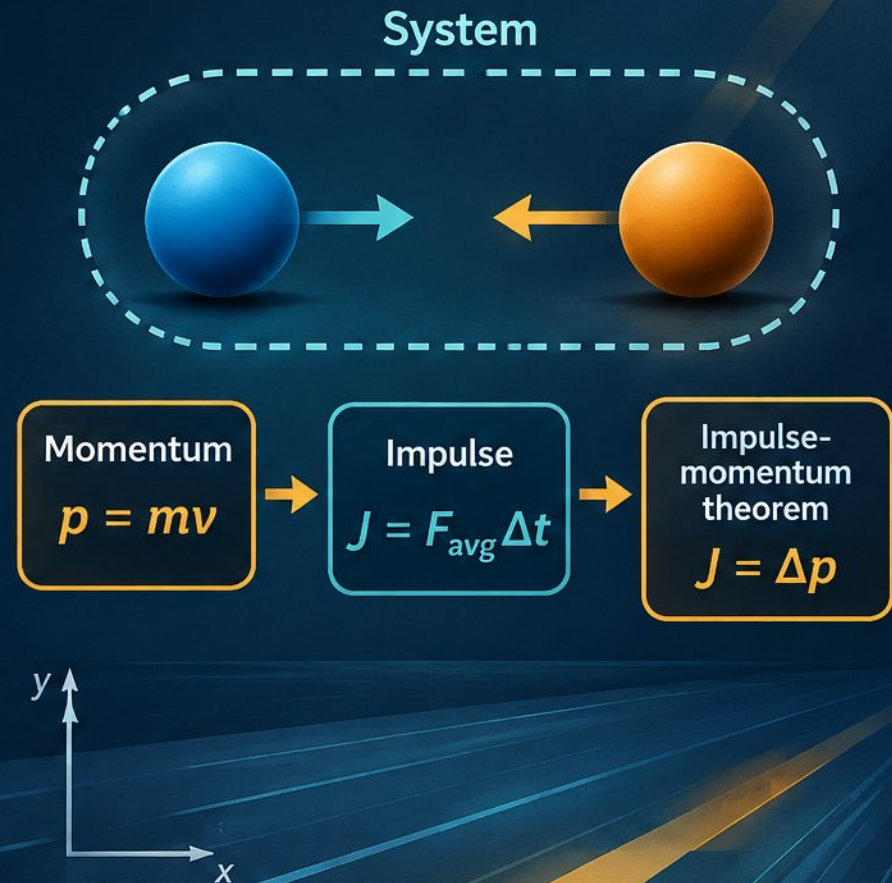


Core Vocabulary:

Momentum, Impulse, and Systems

The three ideas behind every collision problem

- Momentum is a vector: $\mathbf{p} = m\mathbf{v}$
pointing with velocity
- Impulse is force over time: $\mathbf{J} = F_{\text{avg}}\Delta t$
in N·s
- Impulse-momentum theorem: $\mathbf{J} = \Delta\mathbf{p}$
impulse changes momentum
- A system is the objects you choose to analyze
- Internal forces cancel; only external impulse changes total momentum



Why Momentum Matters: **Safety**, **Sports**, and Space



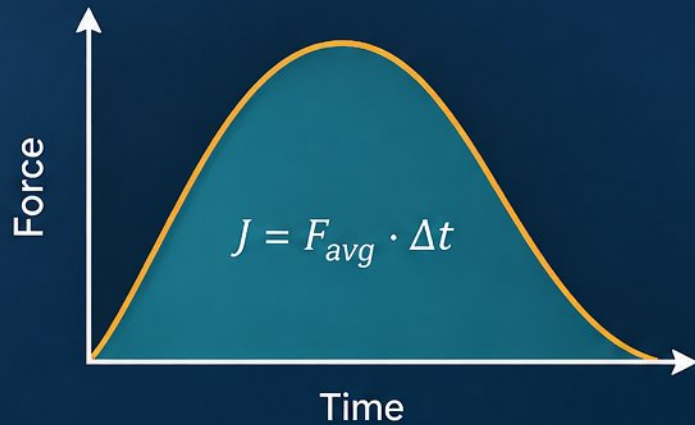
- Airbags and crumple zones extend collision time, lowering peak force and injury
- Same momentum change, longer time: smaller average force on occupants
- Sports: bat-ball impacts, soft-hand catches, and safer tackling techniques
- DART impact (2022) shortened Dimorphos's orbit by about 33 minutes
- Ejected debris doubled the punch: momentum enhancement factor near 2
- Key reminder: momentum is a vector; kinetic energy is a scalar



The Impulse-Momentum Theorem

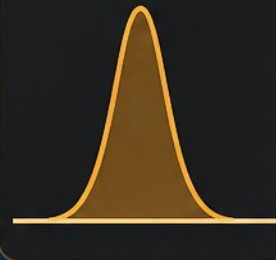
- Newton's second law in momentum form: $F_{net} = \frac{\Delta p}{\Delta t}$
- Impulse is the area under a force-time graph; $J = F_{avg} \cdot \Delta t$
- Safety design: $F_{avg} = \frac{\Delta p}{\Delta t}$ — longer stopping time, smaller force
- 70 kg driver at 15 m/s: $\Delta p = 1050 \text{ kg} \cdot \text{m/s}$; 0.05 s gives ~21,000 N; 0.30 s gives ~3,500 N
- Catching with relaxed hands lengthens contact time and reduces force

Impulse as Area Under the Curve



Same Momentum Change, Different Stopping Time

0.05 s
~21,000 N



0.30 s
~3,500 N



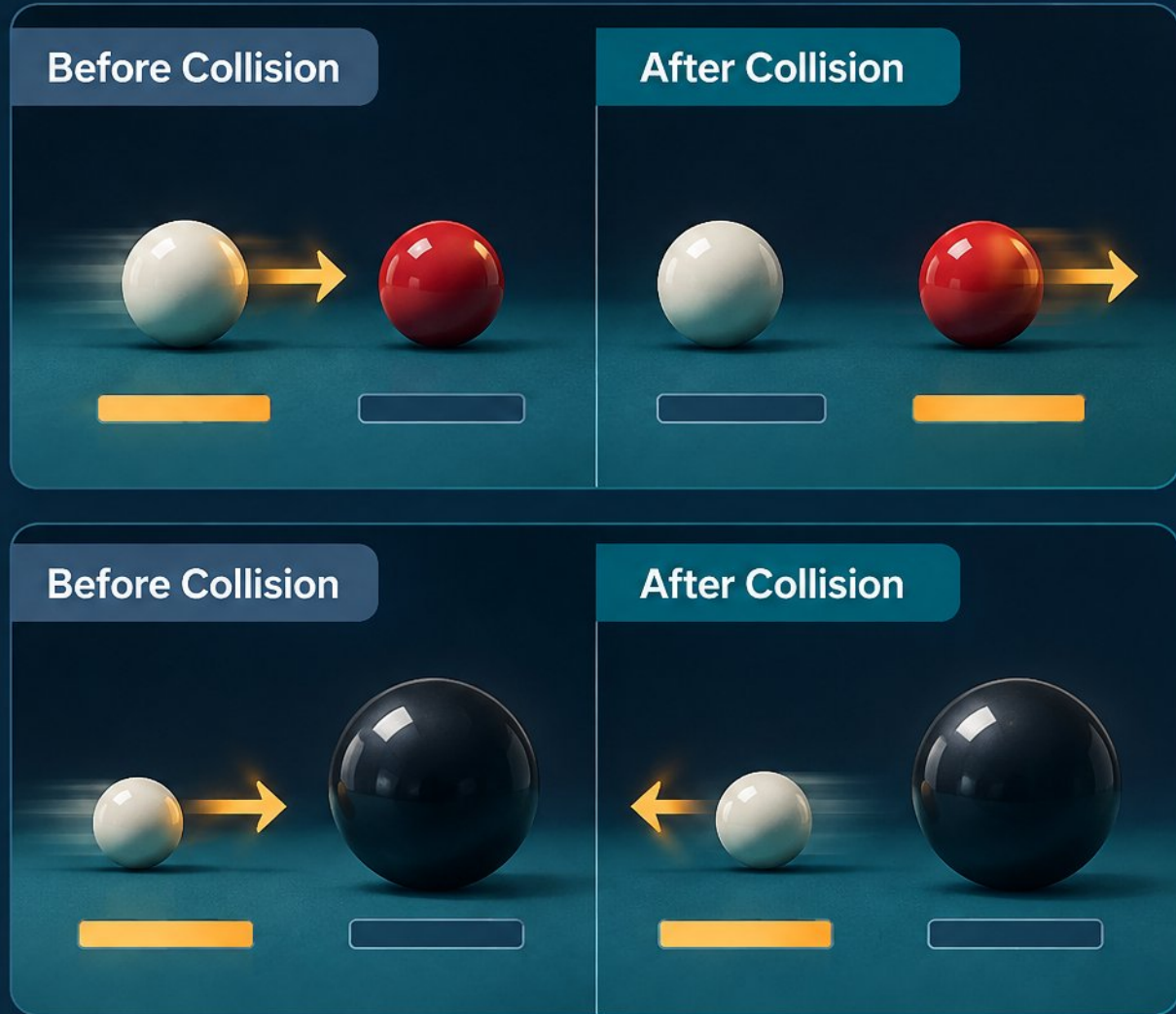
Catching with Relaxed Hands

Lengthens contact time
and reduces force



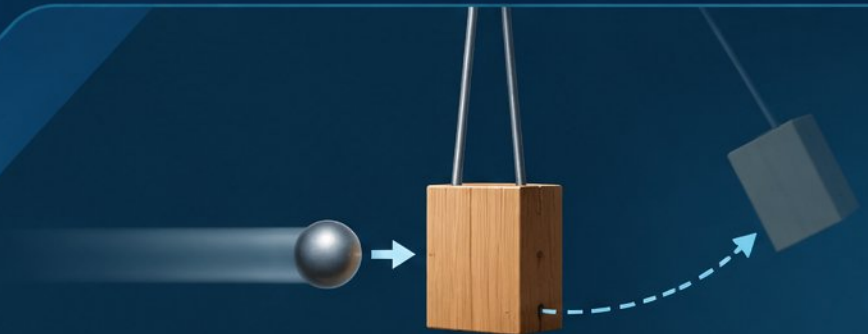
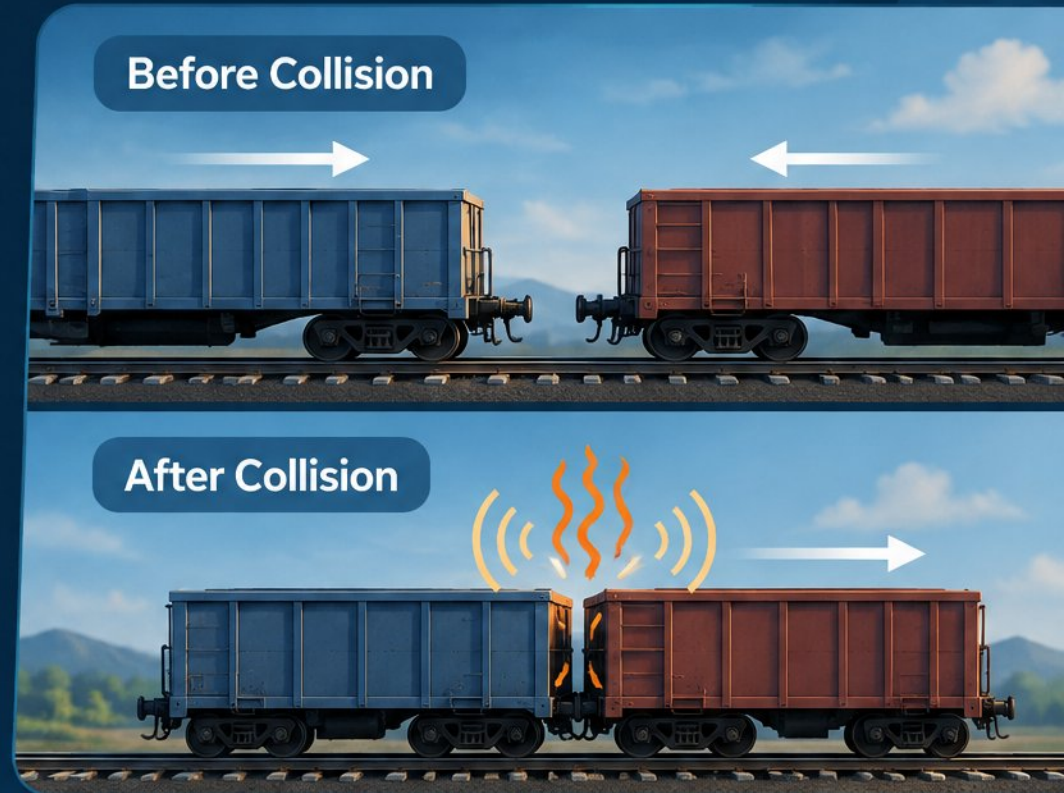
Elastic Collisions: Momentum and Kinetic Energy Conserved

- Elastic collision: total momentum and total kinetic energy both conserved
- Equal masses swap velocities; cue ball stops, struck ball rolls off
- Light ball rebounds near full speed off a massive target
- Billiard balls, gas molecules, neutron scattering: near-elastic approximations
- Real collisions are rarely perfect; restitution near 1 means nearly elastic



Inelastic and **Perfectly Inelastic** Collisions

- **Inelastic collision:** momentum conserved, kinetic energy not
- Energy lost to heat, sound, and permanent deformation
- **Perfectly inelastic:** objects stick together, share one final velocity
- **Examples:** car crashes, catching a ball, railroad cars coupling
- **Ballistic pendulum:** momentum during impact, energy during swing



The Ballistic Pendulum: Combining Momentum and Energy

- A projectile embeds in a hanging block; the combined mass swings up

- Stage 1, collision: momentum conserved,

$$mv = (M + m)V$$

- Stage 2, swing: mechanical energy conserved,

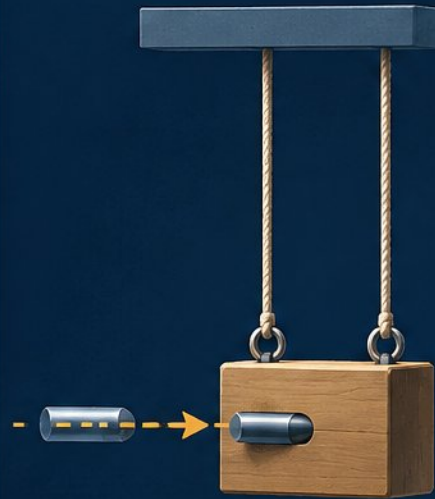
$$\frac{1}{2}(M + m)V^2 = (M + m)gh$$

- Combined result:

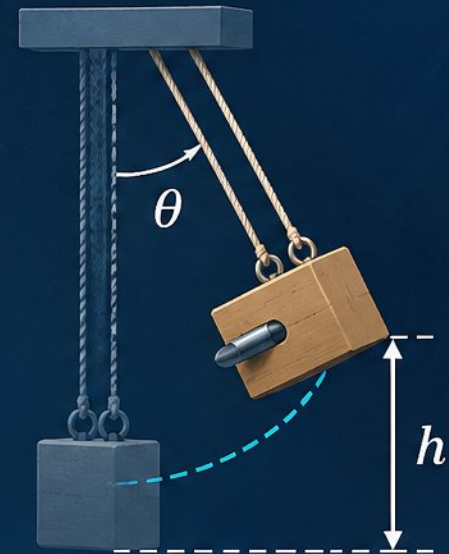
$$v = ((M + m)/m)\sqrt{2gh}$$

- Key insight: momentum and energy are conserved at different stages, not at once

Stage 1: Collision



Stage 2: Swing



Conservation of Momentum in One Dimension

- In an isolated system, total momentum before equals total momentum after:

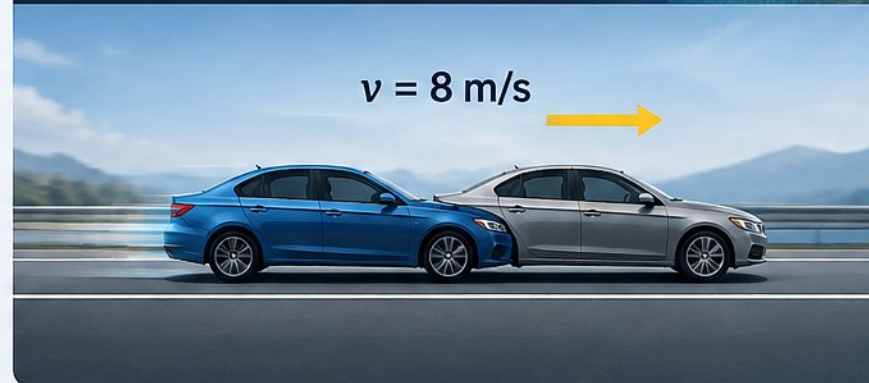
$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

- Momentum is a vector—choose a positive direction and assign signs to each velocity
- For objects that stick together:
$$m_1u_1 + m_2u_2 = (m_1 + m_2)v$$
- Explosions and recoil are time-reversed collisions; total momentum stays at its initial value
- Worked example: 1000 kg car at 20 m/s hits stationary 1500 kg car, sticks together $\rightarrow v = 8$ m/s

Before Collision



After Collision (Stuck Together)



SAME TOTAL MOMENTUM
BEFORE AND AFTER

MOTION CONNECTS
IDEAS

Momentum in Two Dimensions

- Momentum conserved independently along x and y axes
- Component method: two 1D problems solved at once
- Choose axes along incoming velocity; usually one object at rest
- Resolve each velocity using sine and cosine components
- Sticking cars: 1325 kg north at 27.0 m/s, 2165 kg east at 17.0 m/s → 14.7 m/s at 44° north of east



Two-Dimensional Problem Workshop

FROM DIAGRAMS TO SOLUTIONS

VECTOR ANALYSIS
CONSERVATION LAWS
REAL-WORLD PROBLEMS

1

Step 1:

Draw before-and-after diagrams with velocity vectors and axes.

2

Step 2:

Resolve each velocity into x and y components using sine and cosine.

3

Step 3:

Write separate conservation equations for x and y; keep signs consistent.

4

Step 4:

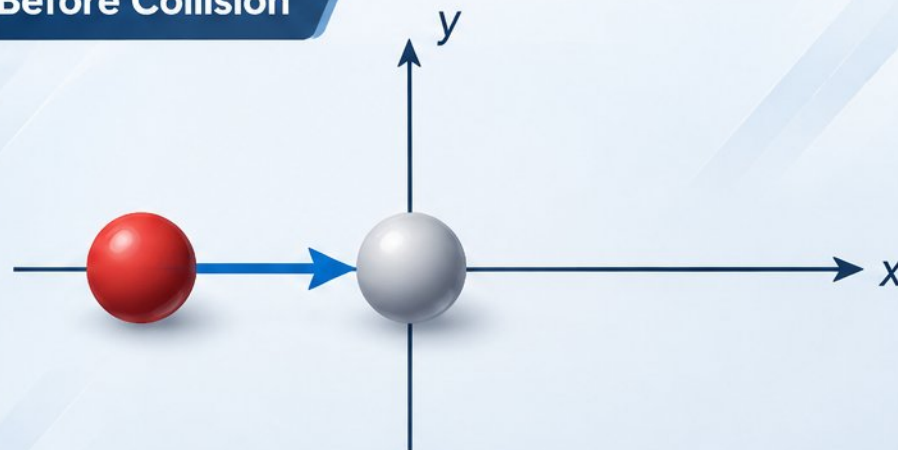
Solve the two equations to find unknown speed and direction.



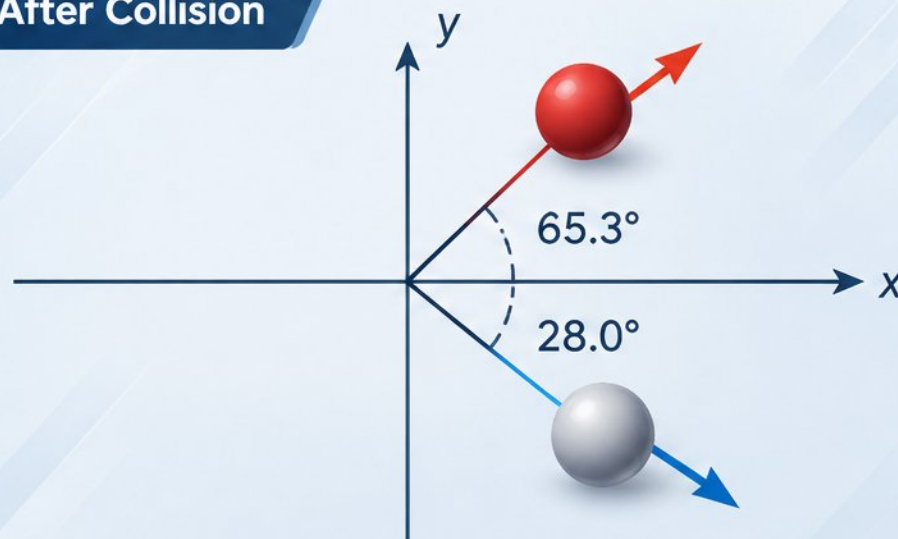
Example:

161 g ball at 1.50 m/s strikes stationary 169 g ball; separation angles 65.3° and 28.0° .

Before Collision

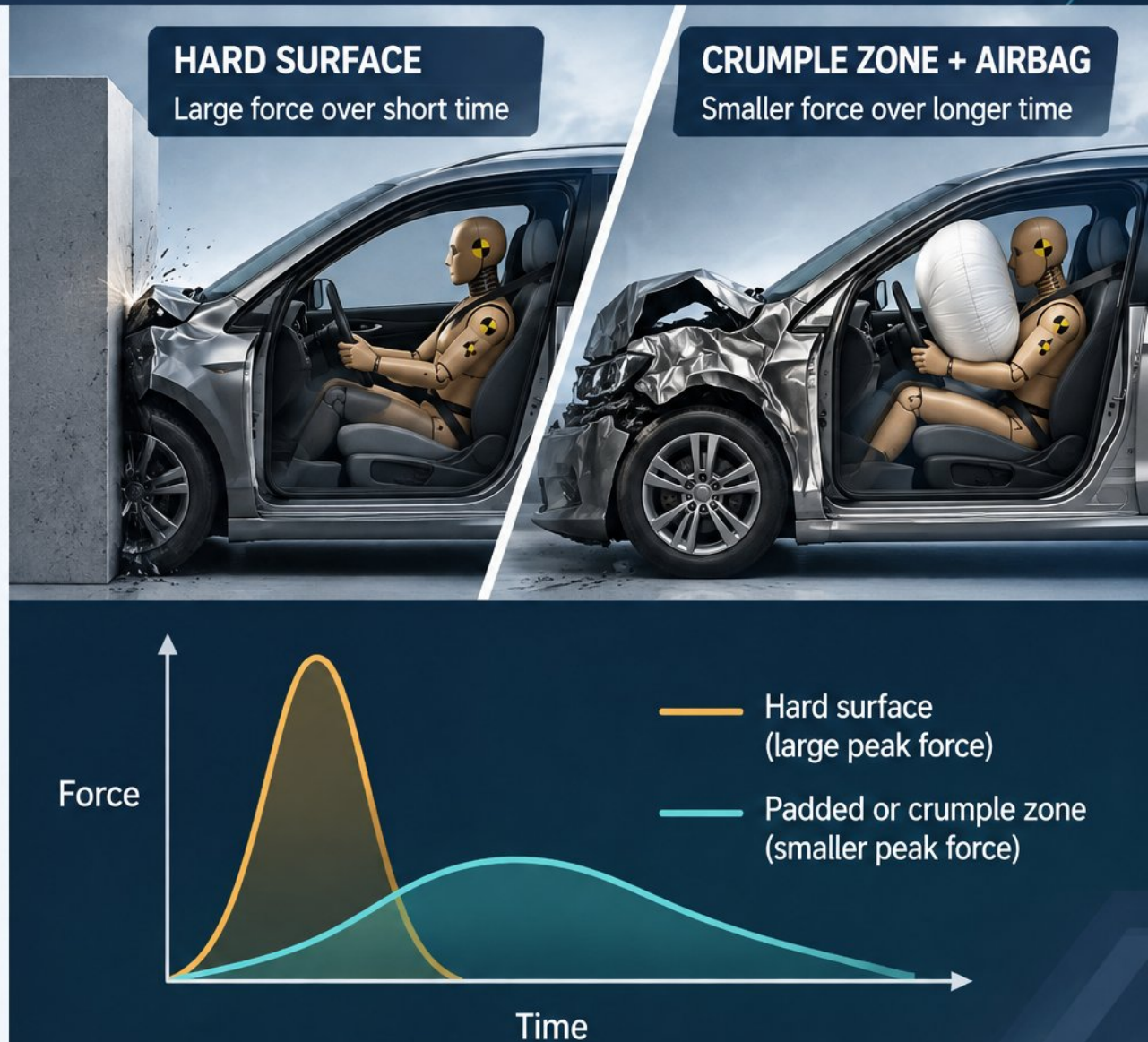


After Collision



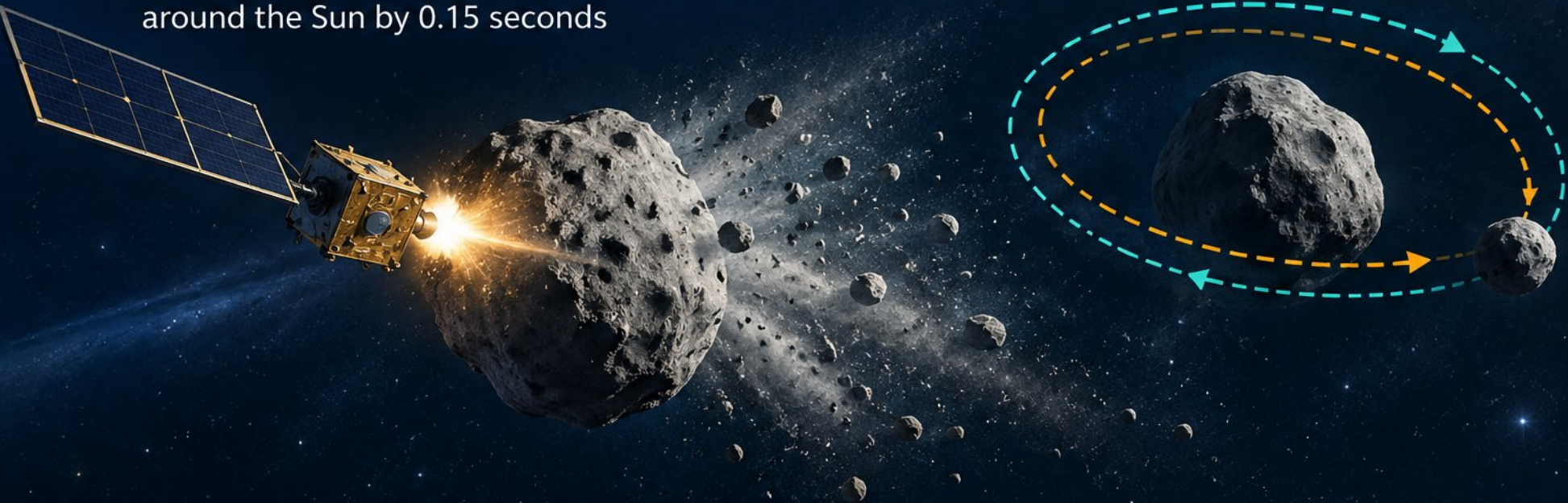
Safety Engineering: Impulse, Force, and Time

- Same momentum change: large force over short time, or smaller force over longer time
- Crumple zones extend collision time, lowering peak deceleration on occupants
- Airbags spread force over larger area and lengthen stopping time
- Modern systems adapt deployment to seat position and occupant size
- Padded surfaces stop the same object with smaller average force than hard surfaces
- Formula: $F_{avg} = \Delta p / \Delta t$



Case Study: **DART and** Momentum Transfer in Space

- NASA's DART spacecraft impacted asteroid moonlet Dimorphos on September 26, 2022
- Impact shortened Dimorphos's 12-hour orbit around Didymos by about 33 minutes
- Momentum enhancement factor β reached roughly 2–3.6 from escaping ejecta debris
- Debris carried extra momentum, so kinetic impact deflected the asteroid more effectively
- New research: impact shifted the Didymos system's orbit around the Sun by 0.15 seconds



A Five-Step Method for Collision Problems

1



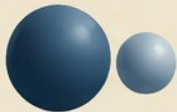
Step 1: Define the system;
confirm external impulse is negligible

2



Step 2: Choose a positive direction
and coordinate axes; assign signs

3



Step 3: List known masses and
velocities before and after

4



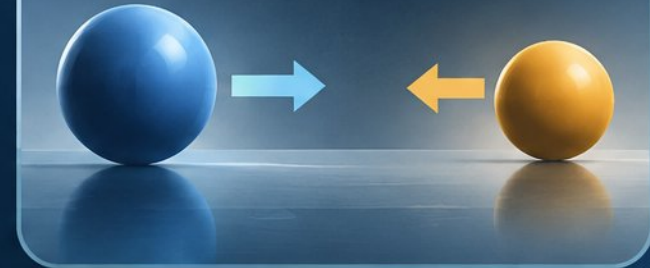
Step 4: Apply conservation of
momentum; use kinetic energy only
for elastic collisions

5

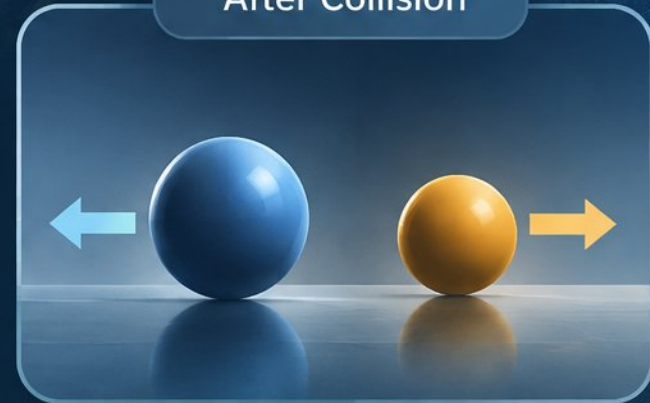


Step 5: Solve, check units, verify signs,
confirm the result makes sense

Before Collision



After Collision



Misconceptions, Assessment, and Next Steps

Common Misconceptions and Facts



- **Misconception: momentum and kinetic energy are the same concept**

- Momentum is a vector; kinetic energy is a scalar
- Momentum is conserved in all collisions; kinetic energy only in elastic



- **Misconception: heavier objects always have more momentum**

- Momentum also depends on velocity, not mass alone



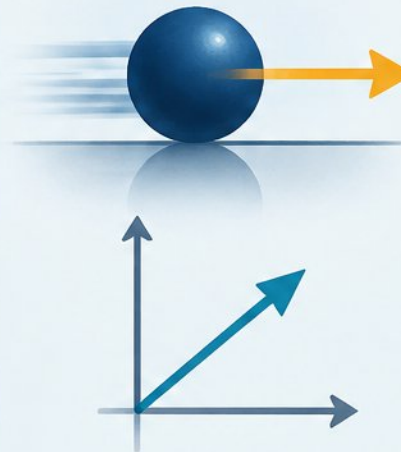
- **Misconception: collisions always lose kinetic energy**

- Elastic collisions conserve kinetic energy

Momentum vs. Kinetic Energy

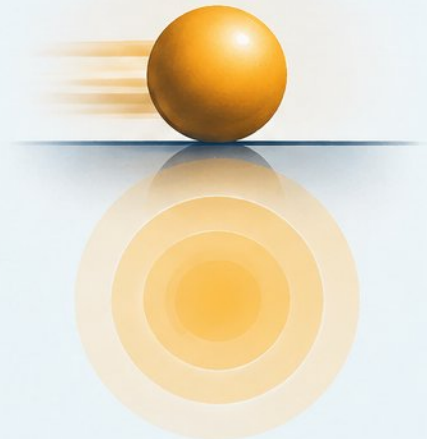
Momentum

Vector quantity



Kinetic Energy

Scalar quantity



Formative Assessment



- Formative assessment: predict before calculating, interpret force-time graphs
- Explain safety features using the impulse-momentum theorem

Next Steps



- **Next steps:** practice sets, collision simulators, ballistic pendulum, DART data

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