

ME 206 – Statics and Dynamics

Experiment 3 - Demonstration of the Linear Impulse–Momentum Principle

Experiment Topic - Studying the Linear Impulse–Momentum Relationship through Collision of Two Equal-Mass Air Hockey Pushers on a Low-Friction Surface.

Group 12

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Introduction:

The impulse and momentum principle is one of the most basic ideas in dynamics. It essentially explains how a force acting for a short period can alter the motion of a body. In many real-life situations, such as when two objects collide or hit each other, the forces act only for a very short time. Instead of measuring the force at every instant, it is easier to describe the overall effect by considering the impulse that the force imparts during contact.

Mathematically, the relation can be written as

$$J = \int_{t_1}^{t_2} F(t) dt = m(v_2 - v_1)$$

where J is the impulse, $F(t)$ is the time-dependent force, and $m(v_2 - v_1)$ is the change in linear momentum of the body.

In this experiment, we tried to demonstrate this principle using a simple setup with **two equal-mass air hockey pushers** colliding on an air hockey table. Because the surface has an air cushion, friction becomes almost negligible, and momentum transfer occurs mostly along a single straight line. One of the pushers was kept still while the other one was pushed with a known speed to hit it. The entire motion and impact were recorded using a high-speed camera and later analysed frame by frame with motion-tracking software.

The idea was to investigate how the impulse acts as the quantity that transfers momentum from one pusher to another and to verify whether the total momentum of the system remains nearly constant. This experiment helps us actually see what we study in theory — how short-time forces cause motion changes and how impulse connects force, time, and momentum in a real physical situation.

Experimental Design:

Aim of the Experiment

To design and perform a simple experimental demonstration of the linear impulse-momentum principle using two colliding air hockey pushers of equal mass, and to calculate the impulse and momentum transfer during the collision event.

Apparatus and Equipment

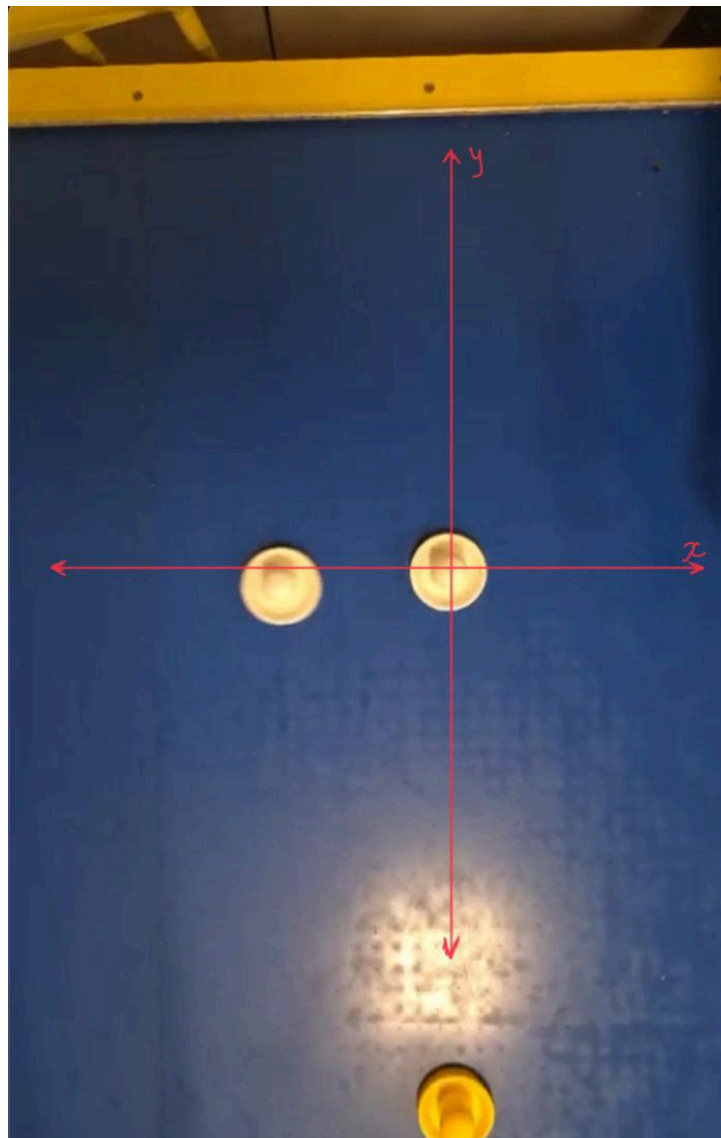
- Air hockey table (smooth, air-cushioned surface to minimise friction)
- Two identical air hockey pushers (equal mass m)
- Smartphone camera (240 fps recording capability)
- Ruler or calibration scale (for distance measurement in the video frame)
- A Laptop with **Tracker** software and **Python (NumPy, Pandas, Matplotlib)** for analysis
- Measuring tape

Setup Description

The setup for our experiment was made using a normal air hockey table. On the table, we placed two identical pushers in a straight line so that they could move directly toward each other. In the beginning, Pusher A was kept still at one end, and Pusher B was pushed by hand with some initial speed straight along the line that joined the two pushers.

When Pusher B hit Pusher A, they both moved after the collision and exchanged their momentum. Because both pushers have almost the same mass and the air surface reduces friction to a very small value, the collision was close to a one-dimensional and nearly elastic one. The smooth air layer allowed the pushers to glide freely with minimal energy loss.

We recorded the whole collision using a mobile phone camera placed above the table. The phone was positioned at a height that allowed for a clear top view, showing both pushers during the entire event. To ensure we could measure distances accurately later, we kept a ruler on the table along the path of motion. This ruler helped in converting pixel values from the video into actual real-world distances in meters.



Fabrication Details:

There was not much fabrication needed for this experiment, as the air hockey table already provides a smooth and almost frictionless surface to work on. Still, we made a few minor adjustments to ensure everything worked properly.

First, we marked a straight line through the centre of the table so that both pushers move only in one direction and don't drift sideways. We also checked that the table was levelled properly, because even a small tilt could make one pusher move by itself. The mobile camera was fixed on a tripod just above the setup to keep the view steady and exactly from the top.

The entire experiment was conducted in a simple and cost-effective manner. It was completed, primarily with items such as the calibration scale, marker tape, and tripod stand. The air hockey setup was borrowed from the lounge's game section, making it easy and inexpensive to carry out the test. This way, the setup can be repeated at any time without incurring additional costs.

Measurement Techniques:

- **Video Capture:**

The collision was recorded using a smartphone camera at around 240 frames per second. The phone was positioned directly above the air hockey table, allowing both pushers to be clearly visible during the motion. The high frame rate enabled us to capture even the briefest moment of impact more clearly, without missing any details.

- **Motion Tracking:**

After recording, we imported the video into the *Tracker* software. In the software, we manually marked the centre of both pushers in each frame, one by one, so that their positions over time could be determined. It took some patience to mark all the frames properly, but it gave us accurate position data.

- **Velocity Calculation:**

From the position data, the software automatically calculated the velocity of both pushers before and after the collision. The time gap between the last frame before collision and the first frame after it was taken as the contact time during which the impulse acted.

- **Impulse and Force Estimation:**

Knowing the mass of each pusher and the change in their velocities, we calculated the impulse $J = m(v_2 - v_1)$. Dividing this impulse by the short contact time gave us the average impact force acting during the collision.

- **Data Validation:**

To ensure our readings were correct, we double-checked the velocity values by calculating them from the displacement between a few selected frames. This helped us minimise potential errors from the tracking software and made our results more reliable.

Result and Discussion:

The video of the air hockey collision was analysed using the Tracker software. The experiment was conducted by striking a stationary puck with the mallet.

1. **Mass Measurement:** The mass of the air hockey puck was measured using a digital scale.

- Mass (m) = 170 g

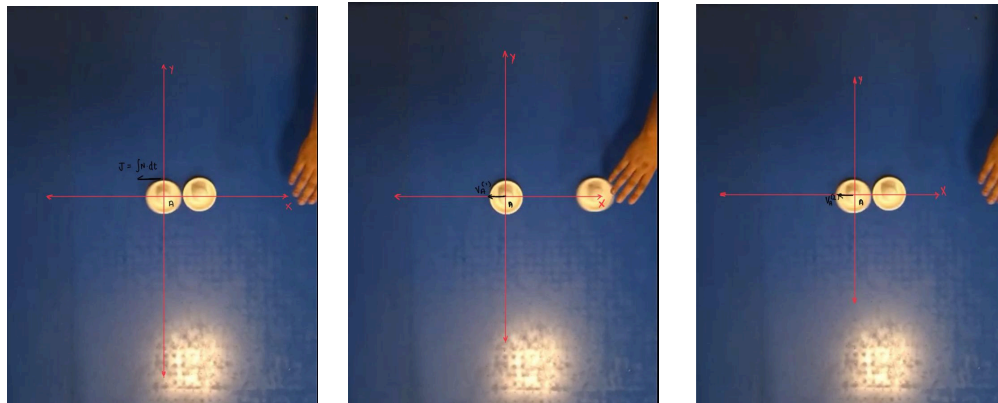
2. **Video Analysis:**

- a. The video was imported into Tracker and calibrated using the known diameter of the puck.
- b. The position of the puck's centre was tracked frame by frame, especially for the frames immediately before and after the collision.
- c. The Tracker software calculated the puck's velocity components (v_x, v_y) for each frame.

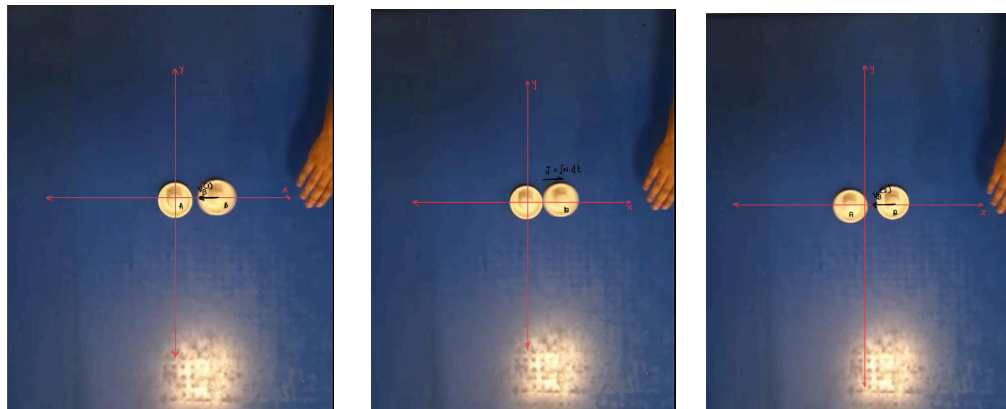
Calculation:

1. **Impulse Momentum diagram Diagram:**

- Mallet A:



- Mallet B:



2. Equation of Motion:

- Mallet A:

$$-m_A V_A^{(1)} \mathbf{i} - \int F(t) dt \mathbf{i} = -m_A V_A^{(2)} \mathbf{i} \quad \text{----- (1)}$$

- Mallet B:

$$-m_B V_B^{(1)} \mathbf{i} + \int F(t) dt \mathbf{i} = -m_B V_B^{(2)} \mathbf{i} \quad \text{----- (2)}$$

Combining Eqn (1) and (2):

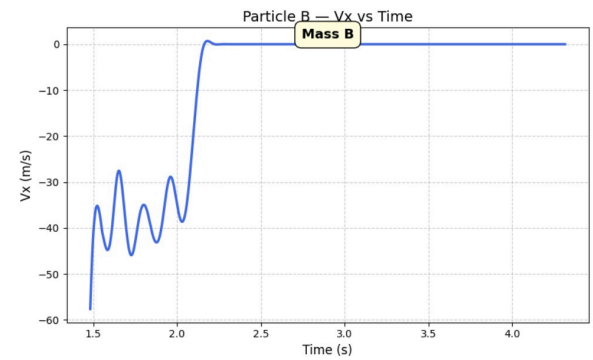
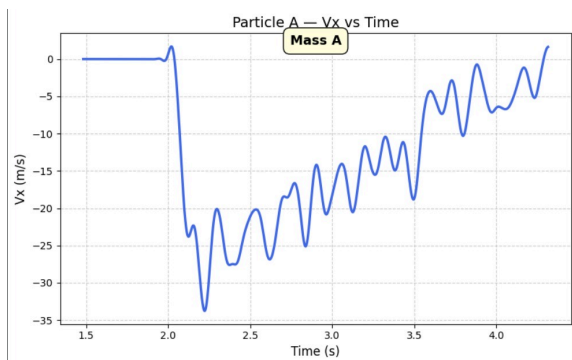
$$\therefore -m_A V_A^{(1)} - m_B V_B^{(1)} = -m_A V_A^{(2)} - m_B V_B^{(2)}$$

$$\therefore m_A V_A^{(1)} + m_B V_B^{(1)} = m_A V_A^{(2)} + m_B V_B^{(2)}$$

(Conservation of momentum Equation)

From the video tracker, we have $V_B^{(1)}$, $V_A^{(1)}$, $V_B^{(2)}$, $V_A^{(2)}$

\therefore We can plug in these values in equations (1) and (2) to get $J = \int F(t) dt$.



(The collision time is 2.063s to 2.128s making $\Delta t = 0.065s$, so will make an average value of $V_B^{(1)}$ and $V_A^{(2)}$)

As observed from the graph:

$$\therefore V_B^{(1)} = 22.23 \text{ m/s}$$

$$\therefore V_B^{(2)} = 0 \text{ m/s}$$

$$\therefore V_A^{(1)} = 0 \text{ m/s}$$

$$\therefore V_A^{(2)} = 22.23 \text{ m/s}$$

$$\therefore m_A = m_B = 170 \text{ g} = 0.17 \text{ kg}$$

In Eqn (1):

$$\therefore - (0.17)(0) - \int F(t) dt = - (0.17)(22.23)$$

$$\therefore \int F(t) dt = 3.7791 \text{ Ns}$$

Similarly in Eqn(2):

$$\therefore - (0.17)(22.23) + \int F(t) dt = - (0.17)(0)$$

$$\therefore \int F(t) dt = 3.7791 \text{ Ns}$$

Discussion:

The calculated value (J) represents the total impulse, or "kick," delivered by the mallet to the mallet to change its momentum from zero to p_f .

We can also estimate the average force of the impact. The video was recorded at 120 frames per second (fps), meaning each frame has a duration of $1/120$ seconds approximately.

The contact between the mallet and puck was extremely short, appearing to last for approximately 2 – 3 frames.

Sources of Discrepancy:

1. **Friction:** The air hockey table has low friction, but not zero friction. Air resistance and table friction begin to slow the puck immediately after it makes contact with the table. By using the velocity from the very first frame post-impact, we minimise this error, but any delay in measurement would underestimate v_f and thus underestimate the impulse.
2. **Impact Time (Δt):** The largest source of uncertainty. The standard video frame rate is too slow to accurately resolve the true contact time. Our estimate of Δt based on 2 – 3 frames a rough approximation. A more precise calculation F_{avg} would require a high-speed camera.
3. **Mass Measurement:** Standard error from the digital scale, though this is likely the smallest source of error.

Scope of Improvement:

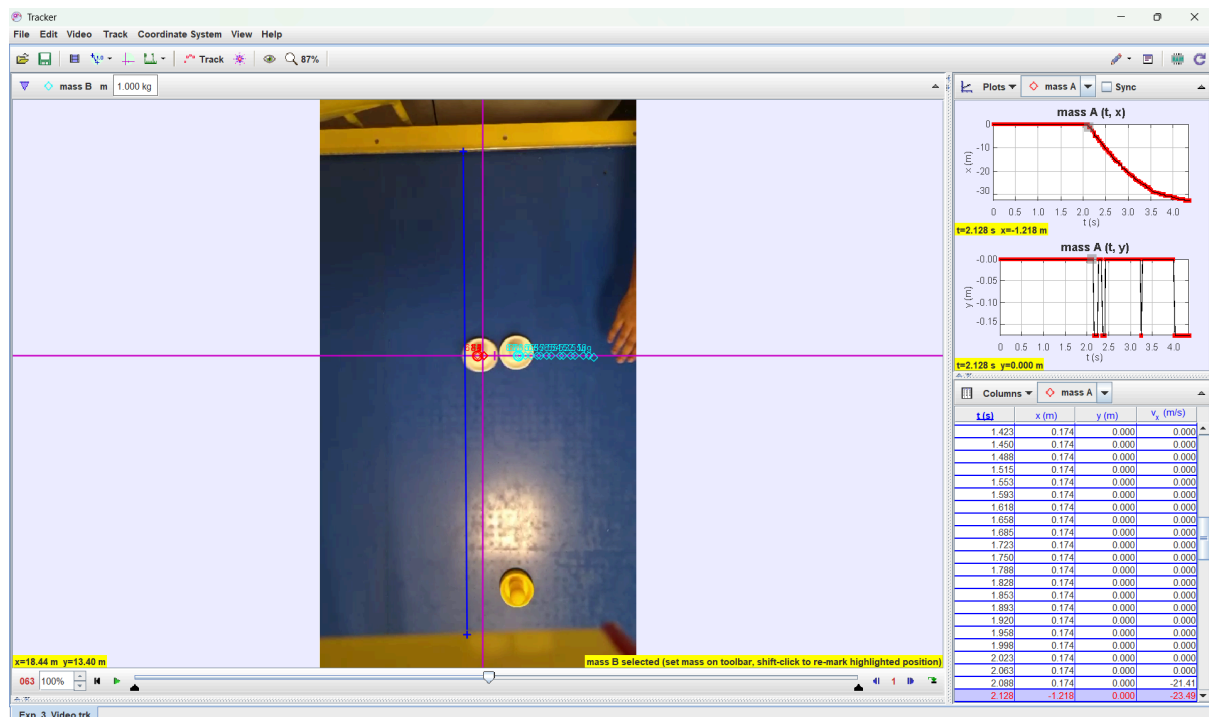
1. **High-Speed Camera:** The most significant improvement would be to use a high-frame-rate (e.g., 240 fps, 480 fps) camera; the video recorded for this

experiment was recorded at 120fps, so using a high fps camera would allow for:

- A much more accurate measurement of the impact duration Δt , as the contact would be spread across multiple frames.
 - A more precise measurement is achieved v_f by "freezing" the motion and reducing motion blur.
2. **Stable Camera Mount:** Using a tripod to mount the camera directly above the table (in a top-down view) would eliminate parallax error and ensure the motion is purely 2D from the camera's perspective.
 3. **Angular Impulse:** The prompt also mentions angular impulse. By hitting the puck *off-centre*, we could induce rotation. To study this, we would need to:
 - Mark two points on the puck.
 - Track both points in Tracker to find the angular velocity (ω).
 - Calculate the change in angular momentum ($L = I \cdot \omega$) to find the angular impulse J_θ .
 4. **Controlled Impact:** Instead of a handheld mallet, a spring-loaded launcher or a pendulum could be used to provide a more consistent and repeatable impulse for multiple trials.
 5. **2D Collisions:** The setup could be extended to study 2D conservation of momentum by colliding two pucks instead of a mallet and a puck.

Software/ tools Used:

- **Experimental Setup:**
 - Air hockey table with an air supply
 - Air hockey pucks and mallets
 - Digital camera (Smartphone)
 - Digital scale (for measuring puck mass)
- **Software:**
 - **Tracker (Open-Source Video Analysis Tool):** Used for Digital Particle Tracking Velocimetry (DPTV). Its core functions were to:
 - Import the .mp4 video file.
 - Calibrate the video (pixels to meters).
 - Manually track the center of the puck frame-by-frame.
 - Automatically generate position-time and velocity-time data.



- **Python (with libraries):** Used for any subsequent data cleaning, analysis, or plotting.
 - **NumPy:** For numerical operations on the velocity data.
 - **Pandas:** To organize and manage the data exported from Tracker.
 - **Matplotlib:** To create plots of position or velocity.

Acknowledgement:

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