Einstein's equivalence principle

FizziQ activity · High school · 30 min

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A smartphone accelerometer records rest, uniform motion and free fall; with FizziQ, high school students test Einstein's equivalence principle from the data.

Learning objectives

- Compare accelerometer readings in three scenarios: stationary, uniform motion, and vertical acceleration
- Observe that the accelerometer cannot distinguish between gravitational acceleration and inertial acceleration
- Understand Einstein's equivalence principle through direct measurement
- Analyze accelerometer data to identify different states of motion
- Connect the experimental observations to the conceptual foundations of general relativity

Instruments and sensors

Absolute acceleration (accelerometer-based) · Accelerometer

Materials

- Smartphone with the FizziQ application
- A flat surface for static measurements
- A rigid box or pocket to hold the smartphone
- FizziQ experience notebook
- Note: the protocol remains adaptable to any comparable acceleration measurement tool.

Protocol

1. Open FizziQ and select the Accelerometer sensor. Choose absolute acceleration for the clearest demonstration.
2. Scenario 1 (At rest): Place the smartphone flat on a stable table. Start recording for 10 seconds. Observe that the reading is approximately 9.81 m/s^2 (1g), even though the phone is not moving.
3. Save this recording and note the average value. Discuss: why does a stationary object register an acceleration?
4. Scenario 2 (Uniform motion): Hold the smartphone steadily and walk at a constant pace in a straight line. Record for 10 seconds. The reading should remain close to 9.81 m/s^2, just as in the stationary case.
5. Save this recording. Note that uniform rectilinear motion and rest are indistinguishable to the accelerometer, consistent with Galilean relativity.
6. Scenario 3 (Brief free fall): Place the smartphone in a protective padded box. Hold it at waist height over a thick pillow or cushion.
7. Start the recording, wait 2 seconds, then release the box so it falls onto the cushion. Let it record for 2 more seconds after impact.
8. Retrieve the smartphone and examine the graph. During the fall, the acceleration should drop to approximately 0 m/s^2 (weightlessness), then spike sharply upon impact.
9. Measure the duration of the free fall from the graph (the time interval where acceleration ≈ 0).
10. Calculate the expected fall duration from the height: $t = \sqrt{2h/g}$. Compare with the measured duration.
11. Scenario 4 (Elevator or car): If possible, record the accelerometer in an elevator. Note the increased reading during upward acceleration (>1g) and decreased reading during downward acceleration (<1g).

12. Summarize your observations: the accelerometer measures g + a_inertial, and cannot distinguish the gravitational contribution from the inertial one. This is the essence of the equivalence principle.

Expected results

In the stationary and uniform motion scenarios, the accelerometer should read approximately 9.81 m/s^2 (±0.05 m/s^2), demonstrating that these two states are indistinguishable to the sensor. During free fall, the reading should drop to near 0 m/s^2 (typically 0.1-0.5 m/s^2 due to air resistance and rotation). The free-fall duration for a 1-meter drop should be approximately 0.45 seconds. Upon impact with the pillow, a brief acceleration spike of 20-50 m/s^2 (2-5g) is typical. In an elevator, students should observe readings of approximately 10.5-11 m/s^2 during upward acceleration and 9.0-9.5 m/s^2 during downward acceleration, with 9.81 m/s^2 during constant-speed travel.

Questions

- Why does a stationary smartphone read 9.81 m/s^2 on its accelerometer even though it is not accelerating?
- What would the accelerometer read inside a freely orbiting spacecraft? Why?
- Einstein said his happiest thought was about a person in free fall. What did he realize?
- How does the equivalence principle lead to the prediction that light bends near massive objects?
- Can you design an experiment inside a closed box that distinguishes between gravitational acceleration and uniform acceleration?
- What is the connection between weightlessness and free fall?

Going further

- Compare the free fall readings for drops from different heights and verify that the duration matches the theoretical prediction
- Throw the protected smartphone gently upward and identify the free-fall phase during the entire upward-and-downward trajectory
- Record the accelerometer during a car ride and identify acceleration, braking, and turning events
- Compare the readings of two different smartphones during identical scenarios to assess sensor consistency
- Investigate the accelerometer behavior during a roller coaster ride or a swing to find moments of apparent weightlessness