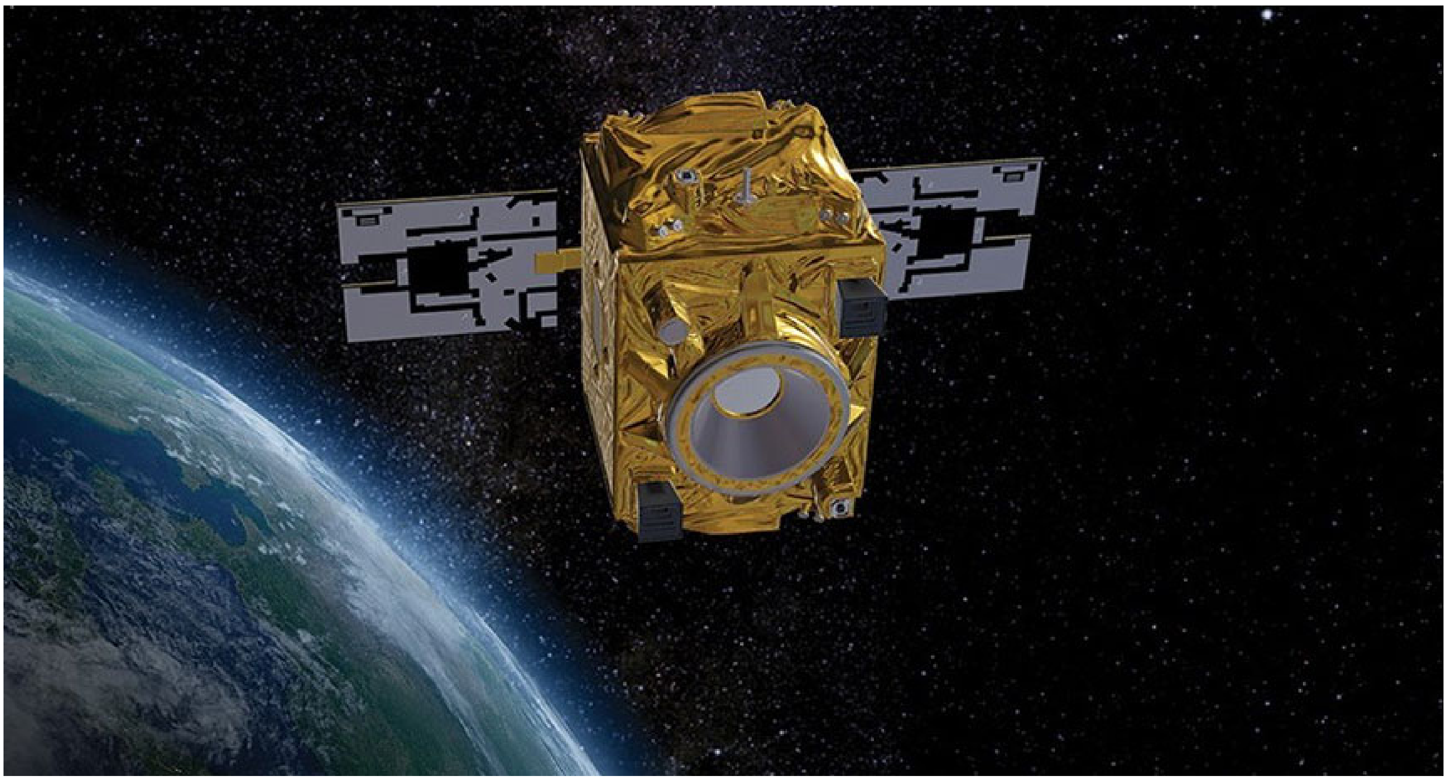
Science News
IN HIGH SCHOOLS | EDUCATOR GUIDE



January 20, 2018

Galileo Experiment Re-created in Space

SOCIETY FOR SCIENCE & THE PUBLIC

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EDUCATOR GUIDE
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About the Issue

Science News **article(s):** "Galileo experiment re-created in space"

Readability score: 12.8

Science News for Students **article(s):** "Major gravity experiment recreated aboard a satellite"

Readability score: 8.6

The article "Galileo experiment re-created in space" describes how scientists used cylinders in a satellite to show with very high precision that the equivalence principle, a foundation of Einstein's general theory of relativity, holds up in space. Students can focus on details reported in the article, follow connections to earlier articles about gravitational measurements and pursue cross-curricular connections to other major science topics in physics, biology and engineering. In a related activity, students can drop balls of various densities and measure the balls' gravitational acceleration.

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Article-based observation: Questions focus on how scientists used cylinders in a satellite to show that the equivalence principle, a foundation of Einstein's general theory of relativity, holds up in space.

Quest through the archives: Use this short section to explore and compare other articles about measurements of the equivalence principle as reported by *Science News* since 1924.

Cross-curricular discussion:

Physical Sciences questions concern the equivalence principle and factors that could alter it.

Chemical and Biological Sciences questions discuss the effects of low-gravity space environments on materials and on the human body.

Engineering and Experimental Design questions deal with the basic experimental design of the MICROSCOPE experiment and other potential uses of measuring gravitational acceleration with high precision.

Activity: Free-Fallin'

Purpose: To serve as an introduction to gravitational acceleration and the equivalence principle. Students will determine if an object's composition and the height at which an object is dropped affects its gravitational acceleration.

Procedural overview: Students will measure the masses and sizes of different balls to determine the balls' densities. The students will drop each ball from a certain height, measure the time required for the balls to fall and calculate each ball's gravitational acceleration. Additionally, students may drop a ball from different heights to determine if the ball's distance from the ground affects its gravitational acceleration, given that the balls will all be dropped from distances of 15 meters or less from the ground.

Approximate class time: 30-60 minutes or longer, depending on the modifications made to the given procedure.

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Standards

Next Generation Science	Common Core ELA
Motion and Stability: Forces and Interactions: HS-PS2-1, HS-PS2-4	Reading Informational Text (RI): 1, 2, 4, 5, 7
Energy: HS-PS3-1, HS-PS3-2	Writing (W): 1, 2, 3, 4, 6, 7, 8, 9
Earth's Place in the Universe: HS-ESS1-4	Speaking and Listening (SL): 1, 2, 4, 5, 6
Engineering Design: HS-ETS1-1, HS-ETS1-2, HS-ETS1-3	Reading for Literacy in Science and Technical Subjects (RST): 1, 2, 3, 4, 5, 7, 8, 9
	Writing Literacy in History/Social Studies and Science and Technical Subjects (WHST): 1, 2, 4, 7, 8, 9

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Article-Based Observation: Q&A

Directions: Read the article "Galileo experiment re-created in space" and then answer these questions.

1. Summarize the article by making brief statements defining "who," "what," "where," "when" and "why."

Possible student response:

Who: Manuel Rodrigues and other scientists working on the MICROSCOPE project.

What: Rodrigues and colleagues showed that two cylinders composed of different materials free-falling in space accelerated at rates matching within two trillionths of a percent.

Where: A satellite in orbit around Earth.

When: Scientists published their results on December 4, 2017.

Why: The MICROSCOPE experiment was testing the equivalence principle without certain pitfalls of land-based equivalence principle tests. The equivalence principle is a foundation of Einstein's theory of gravity, which is known as the general theory of relativity. To test if that theory is correct, scientists need to test the equivalence principle.

2. In what primary research journal did MICROSCOPE scientists report their findings?

Possible student response: *Physical Review Letters*

3. What was the experiment that inspired this space test, and who is sometimes said to have performed the experiment?

Possible student response: Galileo supposedly dropped two balls of different densities from the Leaning Tower of Pisa, showing that the balls accelerated at the same rate.

4. How did scientists determine if the two cylinders accelerated at the same rate during the experiment?

Possible student response: Electrical forces were used to keep the two cylinders aligned during free fall, with one cylinder centered inside the other. If the cylinders had different accelerations, their relative positions would change and adjustments would be made to correct their alignment. Any change in relative positions would vary with a regular frequency, tied to the rate at which the satellite rotated and orbited Earth.

5. How long were the cylinders in the experiment accelerating at the same rate?

Possible student response: The cylinders accelerated at the same rate for 120 orbits, or about eight days.

6. How precise were the results of this experiment? How much precision do the scientists hope to achieve in future experiments?

Possible student response: The cylinders' acceleration rates match within two-trillionths of a percent for this experiment, which is about 10 times more precise than previous tests. In future experiments, scientists hope to measure whether the cylinders' acceleration rates match within a tenth of a trillionth of a percent, or about 100 times more precise than previous tests.

7. Why are the results important?

Possible student response: A key element of Einstein's general theory of relativity is the equivalence principle, which states that an object's inertial mass (which sets the amount of force needed to accelerate the object) is equal to its gravitational mass (which determines how the object responds to a gravitational field). So free-falling objects accelerate at the same rate (at least in a vacuum, where air resistance is eliminated), regardless of their mass or composition. The results of this experiment give an even more precise measurement of the equivalence principle. Theoretical physicists are attempting to combine general relativity with quantum mechanics (the physics of the very small). Some theories of how to combine the two predict that there might be small differences between an object's inertial mass and its gravitational mass — a violation of the equivalence principle. But those differences have not been detected yet. If a violation of the equivalence principle were found, it could help scientists understand how to combine general relativity and quantum mechanics. So scientists want to test the equivalence principle with even greater precision.

8. What other questions do you still have after reading the article?

Possible student response: How could similar experiments be performed under more extreme conditions that might show where current theories start to break down and new theories are needed? Could scientists make astronomical observations of objects falling into a black hole, or conduct experiments in which the falling objects are particles with quantum behavior?

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Article-Based Observation: Q

Directions: Read the article "Galileo experiment re-created in space" and then answer these questions.

1. Summarize the article by making brief statements defining "who," "what," "where," "when" and "why."

2. In what primary research journal did MICROSCOPE scientists report their findings?

3. What was the experiment that inspired this space test, and who is sometimes said to have performed the experiment?

4. How did scientists determine if the two cylinders accelerated at the same rate during the experiment?

5. How long were the cylinders in the experiment accelerating at the same rate?

6. How precise were the results of this experiment? How much precision do the scientists hope to achieve in future experiments?

7. Why are the results important?

8. What other questions do you still have after reading the article?

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Quest Through the Archives: Q&A

1. "Galileo experiment re-created in space" considered the equivalence principle only for cylinders that behaved like classical objects, which aren't subject to the rules of quantum mechanics. Can you find an article testing the equivalence principle for particles in quantum particles? Summarize the article below.

Possible student response: The *Science News* article "Key Einstein principle survives quantum test," published 5/27/2017, describes how the equivalence principle was tested with atoms in quantum states. Scientists used lasers to give clouds of rubidium atoms an upward kick and observed how gravity pulled the atoms down. They compared the acceleration rates of atom clouds in superposition — a kind of limbo in which an atom does not have a definite energy but occupies a combination of two energy levels — with the rates of atom clouds in a normal energy state. Gravity pulled on the atom clouds in a superposition at the same rate as it did the atom clouds in a normal energy state, at least to the level of sensitivity the scientists were able to probe — within 5 parts in 100 million.

2. Adjust the search filters to include articles from the last 30 years. Find and explain the content in an article about measuring the equivalence principle using the moon?

Possible student response: The *Science News* article "Stronger support for equivalence principle," published 9/22/1990, discusses how scientists measured the gravitational acceleration of the moon in response to the Earth and sun. Scientists found that the moon's inertial mass and gravitational mass were equal within 14 parts in 10^{12}. Within the limits of precision of the experiment, there was no sign of any violations of the equivalence principle or of a fifth fundamental force other than gravity, electromagnetism and the strong and weak nuclear forces.

3. Find and summarize an article about measuring the equivalence principle using stars.

Possible student response: The *Science News* article "Unusual three-star system promises new test of gravity," published 2/22/2014, describes how astronomers found a pulsar and two white dwarfs that orbit each other very closely. All three objects are dense and have strong gravitational fields, and as the pulsar rotates 366 times per second, its electromagnetic waves sweep through space like a lighthouse beam. By closely monitoring the timing of the pulsar's beam and making other measurements of the three-star system, scientists hope to test the equivalence principle. Alternative theories of gravity other than general relativity predict that there could be small deviations from the equivalence principle.

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Quest Through the Archives: Q

Directions: After reading the article "Galileo experiment re-created in space," log in to your *Science News* in High Schools account and use the Search page to answer these questions. Make sure you adjust the filters to include articles written before 1999, if the question requires you to do so.

1. "Galileo experiment re-created in space" considered the equivalence principle only for cylinders that behaved like classical objects, which aren't subject to the rules of quantum mechanics. Can you find an article testing the equivalence principle for particles in quantum particles? Summarize the article below.

2. Adjust the search filters to include articles from the last 30 years. Find and explain the content in an article about measuring the equivalence principle using the moon?

3. Find and summarize an article about measuring the equivalence principle using stars.

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Cross-Curricular Discussion: Q&A

Directions: After students have had a chance to review the article "Galileo experiment re-created in space," lead a classroom discussion based on the questions that follow. Before you begin the discussion, show students "Apollo 15 proves Galileo correct" on YouTube.

PHYSICAL SCIENCES

Discussion questions:

1. What is the equivalence principle?

The equivalence principle states that an object's inertial mass ($M_{inertia}$*) and its gravitational mass (*M_{grav}*) are equal,* $M_{inertia} = M_{grav}$*. How much a force (*F*) makes an object accelerate (*a*) depends on the object's inertial mass,* $F = M_{inertia}\, a$*. How much gravitational force pulls on an object depends on the object's gravitational mass (*M_{grav}*) and the gravitational acceleration (*g*),* $F_{grav} = M_{grav}\, g$*. Considering only gravitational force on an object,* $F = F_{grav}$*, gives* $M_{inertia}\, a = M_{grav}\, g$*. If* $M_{inertia} = M_{grav}$*, an object's gravitational acceleration does not depend on its mass,* $a = g$*.*

2. What are aerodynamic drag and terminal velocity?

Aerodynamic drag is the force air molecules exert on an object as it moves through the air. Drag generally increases with the square of an object's velocity: If the object goes faster, it experiences much more drag. Terminal velocity is the speed at which the aerodynamic drag on a falling object becomes so large that the force balances the opposing gravitational force, so the object stops accelerating and falls at a constant velocity. An object's terminal velocity depends on aerodynamic drag and the object's mass. For example, terminal velocity is low for parachutes and higher for cell phones.

Extension prompts:

3. What is quantum gravity?

Quantum gravity is a class of unproven theories that combine both general relativity (which describes gravitational fields) and quantum physics (which describes very small particles). These theories attempt to describe the behavior of things that are both very small and subjected to strong gravitational fields. Very small things that are subjected to weak gravitational fields, generally behave by Newtonian gravitational principles.

CHEMICAL AND BIOLOGICAL SCIENCES

Discussion questions:

1. The article mentioned that the two cylinders are made of alloys of platinum and titanium. What are the densities of pure platinum and pure titanium? Why is it possible that scientists used these materials for this experiment?

Because these substances are alloys of two different elements, they have different physical and chemical properties. The difference in their composition alone could lead to an equivalence principle violation. Platinum has a density of 21.45 g/cm^3, whereas titanium has a density of 4.51 g/cm^3. A large difference between their densities may be useful for an experiment in which composition is the independent variable.

Extension prompts:

2. What are some ways that microgravity (the condition in which people or objects can achieve weightlessness) could be used for chemistry and materials science applications?

In microgravity, molten metal would form spheres (due to surface tension) and could cool that way to make ball bearings. Semiconductor crystals and optical crystals in microgravity could form lattices with fewer defects. Phase change processes ranging from boiling to condensation would work differently, as would chemical processes such as combustion.

3. What are the effects of long-term weightlessness on the human body? How is artificial gravity created for the astronauts on the space station?

Prolonged weightlessness in a microgravity environment can cause health problems including bone loss, muscle atrophy and decreases in red and white blood cells. Getting lots of exercise while on a space station helps to minimize those problems. And artificial gravity can be created by spinning the station.

ENGINEERING AND EXPERIMENTAL DESIGN

Discussion questions:

1. Name the independent and dependent variables in the MICROSCOPE experiment described in "Galileo experiment re-created in space."

The independent variables are the compositions of the two cylinders — one cylinder is made of a platinum alloy and the other is made of a titanium alloy. The dependent variables are the cylinders' rates of acceleration.

2. What sorts of confounding variables can limit the precision of the MICROSCOPE experiment and other previous experiments testing the equivalence principle?

On Earth, groundwater flow can alter the mass, and hence, the gravitational pull of surrounding terrain. On Earth and in space, temperature changes can make things expand and contract, limiting the precision of measurements. If the experiment is not performed in a perfect vacuum, air resistance may alter the acceleration of objects based on their structure and geometry.

3. On Earth, you can measure the mass of an object using a two-pan balance, a triple-beam balance, a spring scale or a digital scale. If you used those same tools on the moon or Mars, would you get the same results?

Gravity on the moon is roughly one-sixth that of Earth, and gravity on Mars is roughly one-third that of Earth. The mass of objects measured using a two-pan balance or triple-beam balance would be the same on the moon and Mars as it is on Earth because gravity pulls on objects on both sides of the balance. A spring scale or digital scale assumes the Earth's usual gravitational force is pulling an object down, and measures the distance the object is pulled down. There would be less downward pull on the moon or Mars, so the mass readout would be erroneously low.

Extension prompts:

4. How else might measuring gravitational acceleration with high precision be useful?

Sensors such as gravity gradiometers are used to map small changes in the Earth's gravitational acceleration. Those acceleration changes can indicate alterations in the density of matter nearby, and could be used to locate dense mineral deposits, measure changes in groundwater, spot underground cavities and distinguish between loaded and unloaded vessels, for example.

5. Imagine that you could use some process to alter the inertial mass (or possibly the gravitational mass) of an object. How would those alterations affect the object's acceleration?

If the inertial mass were reduced, the same amount of applied force could cause a larger acceleration.

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Cross-Curricular Discussion: Q

Directions: The following list of discussion questions is provided to help you take notes, brainstorm ideas and test your thinking in order to be more actively engaged in class discussions related to this article. All questions in this section are related to topics covered in "Galileo experiment re-created in space."

PHYSICAL SCIENCES

Discussion questions:

1. What is the equivalence principle?

2. What are aerodynamic drag and terminal velocity?

Extension prompts:

3. What is quantum gravity?

CHEMICAL AND BIOLOGICAL SCIENCES

Discussion questions:

1. The article mentioned that the two cylinders are made of alloys of platinum and titanium. What are the densities of pure platinum and pure titanium? Why is it possible that scientists used these materials for this experiment?

Extension prompts:

2. What are some ways that microgravity (the condition in which people or objects can achieve weightlessness) could be used for chemistry and materials science applications?

3. What are the effects of long-term weightlessness on the human body? How is artificial gravity created for the astronauts on the space station?

ENGINEERING AND EXPERIMENTAL DESIGN

Discussion questions:

1. Name the independent and dependent variables in the MICROSCOPE experiment described in "Galileo experiment re-created in space."

2. What sorts of confounding variables can limit the precision of the MICROSCOPE experiment and other previous experiments testing the equivalence principle?

3. On Earth, you can measure the mass of an object using a two-pan balance, a triple-beam balance, a spring scale or a digital scale. If you used those same tools on the moon or Mars, would you get the same results?

Extension prompts:

4. How else might measuring gravitational acceleration with high precision be useful?

5. Imagine that you could use some process to alter the inertial mass (or possibly the gravitational mass) of an object. How would those alterations affect the object's acceleration?

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Activity Guide for Teachers: Free-Fallin'

Activity: Free-Fallin'

Purpose: To serve as an introduction to gravitational acceleration and the equivalence principle. Students will determine if a ball's composition and the height at which an object is dropped affects its gravitational acceleration.

Procedural overview: Students will measure the masses and sizes of different balls to determine the balls' densities. The students will drop each ball from a certain height, measure the time required for the balls to fall and calculate each ball's gravitational acceleration. Additionally, students may drop a ball from different heights to determine if the ball's distance from the ground affects its gravitational acceleration.

Approximate class time: 30-60 minutes or longer, depending on the modifications made to the given procedure.

Materials:

- Activity guides, data tables and graphs for students
- Various round balls of different masses, sizes and densities. Each group should have at least four different balls. Try to avoid very hard, dense balls to avoid injury should a ball hit someone.
- Balances for measuring the mass in grams of each ball
- Rulers for measuring the diameter in centimeters of each ball
- Calculators
- A good location to drop balls, such as a stairwell. Higher drops (many meters) make it easier to measure the time of the fall.
- Tape measures to measure the distance in meters balls are dropped
- Stopwatches or cell phone timers that show fractions of a second, to time the fall of each ball

Notes to the teacher:

This activity may be used as an introduction to gravitational acceleration and the equivalence principle. The given procedure will depend on materials you collect and the physical space you have available for dropping the balls. As the instructions are written, students are asked to determine how many different types of balls they are testing and from what heights they are dropping the balls. Students will then need to determine which ball they are selecting to drop from multiple heights, and the specific heights the ball will be dropped from. If you have time, allow your students to help determine other parts of the procedure — see the "Make this activity more inquiry-based for students" suggestions below. This is a good activity for teaching students how to design an experiment.

The acceleration due to gravity on Earth's surface is 9.8 m/sec^2. The equivalence principle states that objects of different densities experience the same gravitational acceleration when dropped, apart from aerodynamic drag effects. Since students will not be dropping the balls in a vacuum, aerodynamic drag will affect their results.

If students measure the time of fall very carefully (which is easier for longer distances and longer times), average several results together and use dense balls with little aerodynamic drag, they can get quite close to that result. It is recommended that students choose distances that give fall times between 1.0 second (approximately 5 meters) and 1.5 seconds (approximately 11.25 meters). Students can also try dropping balls shorter distances.

Make this activity more inquiry-based for students:

Choose one or more of the suggestions below to allow students to take more initiative in designing their experiment.

- Rather than giving students the accompanying data table, require them to create their own prior to executing the experiment.
- Have students create their own graphs of acceleration versus distance and acceleration versus density, or show students how to use a computer program to graph their data.
- Take out all or some of the equations given in the instructions and on the data table.
- Remove instructions No. 1–3 below, and allow students to determine how to find the density of an object. If the objects or balls that are being dropped are small enough, provide graduated cylinders to find the volume of the objects by water displacement.
- Remove the distance suggestion given in instruction No. 5 and encourage students to do a few initial tests to determine a distance.
- Remove instruction No. 10 and allow students to determine the number of trials they want to perform for each ball at each distance. Ask them to explain their thought process for the number of trials chosen.
- Remove the given procedure and the procedural overview, and give students the purpose of the experiment. Based on your students' background knowledge, give them equations as needed. Ask students to define variables, write a hypothesis and create their own procedure.

Procedure:

1. Using a balance or scale, measure the mass M of a ball. Record the result in your data table, making sure to include units of measure.

2. Using a ruler, measure the diameter D [in centimeters] of the ball. Record the result in your data table, making sure to include units of measure.

3. Calculate the volume $V = (\pi/6)D^3$ of the ball. Record the result in your data table, making sure to include units of measure.

4. Calculate the density $\rho = M/V$ of the ball. Record the result in your data table, making sure to include units of measure.

5. Decide how far you will let the ball fall, and use a tape measure to measure the distance d [in meters]. Record the result in your data table. It is recommended that you choose distances that give fall times between 1.0 second (approximately 5 meters) and 1.5 seconds (approximately 11.25 meters).

6. Drop the ball and use a stopwatch or cell phone timer to measure the time t [in seconds] for it to travel that distance. It is important to release the ball and not throw it, and to measure the time as accurately as possible. Record the result in your data table.

7. Calculate the average velocity during the fall, $v_{avg} = d/t$. Record the result in your data table, making sure to include units of measure.

8. Assuming the ball accelerates at a uniform rate, the average velocity should be half of the final velocity. Calculate the final velocity $v_{final} = 2v_{avg} = 2\ d/t$. Record the result in your data table, making sure to include units of measure.

9. Calculate the acceleration during the fall, $a = v_{final}/t = 2d/t^2$. Record the result in your data table, making sure to include units of measure.

10. Repeat steps No. 6–9 to make a total of five measurements for the same ball and same distance. Record the results in your data table, making sure to include units of measure.

11. Find the average of your five acceleration measurements for that ball, $a_{avg} = (a_1 + a_2 + a_3 + a_4 + a_5)/5$. Record the result in your data table, making sure to include units of measure.

12. Repeat steps No. 1–11 for other balls of different densities. Record the results in your data table, making sure to include units of measure.

13. Plot your data points for acceleration versus ball density on the accompanying graph. How does density affect the acceleration of a ball, and why?

> *The ball's density should not affect its measured acceleration. As previously noted, the equivalence principle predicts that objects of different densities should experience the same gravitational acceleration when dropped, apart from aerodynamic drag effects.*

14. How does aerodynamic drag affect the time it takes for an object to fall. Based on your data, which balls appear to be affected the most by aerodynamic drag? Explain how aerodynamic drag would affect the calculated acceleration for an object.

> *The greater the aerodynamic drag on an object, the longer it will take for that object to fall to the ground. The calculated acceleration would be smaller when the aerodynamic drag is greater, because in order to calculate the acceleration, you are dividing 2d by t^2.*

15. Repeat steps No. 1–11 using the same ball, but dropping it over four different distances. Measure the time and acceleration five times for each distance, and take the average of those five measurements. Record the results in your data table, making sure to include units of measure.

16. Plot your data points for acceleration versus distance on the accompanying graph. How does distance affect the acceleration of a ball, and why?

> *Acceleration should be around 9.8 m/sec^2 regardless of distance. For short distances, the calculated acceleration may come out different, since it is more difficult for students to accurately measure the time of the fall when it is so short. Acceleration over longer distances may be less than 9.8 m/sec^2 because aerodynamic drag becomes larger at higher velocities.*

17. How would you expect your experimental results to change if you conducted the experiment in a vacuum?

Without aerodynamic drag, ball density should not affect the acceleration, and all balls should fall with an acceleration of 9.8 m/sec^2.

18. How would you expect your experimental results to change if you conducted this experiment on the moon or on another planet?

The objects' acceleration would be smaller on the moon because the moon's gravity is about one-sixth that of Earth's. Acceleration on another planet would also be different depending on the planet's gravity. Aerodynamic drag could be different too, depending on whether the planet has an atmosphere and how thick that atmosphere is.

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Activity Guide for Students: Free Fallin'

Purpose: To serve as an introduction to gravitational acceleration and the equivalence principle. To determine if an object's composition or the height at which an object is dropped affects its gravitational acceleration.

Procedural overview: Measure the masses and sizes of different balls to determine their densities. Drop each ball from a certain height and record the time required for each ball to fall. Using this data, calculate each ball's gravitational acceleration. Additionally, a ball may be dropped from different heights to determine if the ball's distance from the ground affects its gravitational acceleration.

Procedure:

1. Using a balance or scale, measure the mass M of a ball. Record the result in your data table, making sure to include units of measurement.

2. Using a ruler, measure the diameter D [in centimeters] of the ball. Record the result in your data table, making sure to include units of measurement.

3. Calculate the volume $V = (\pi/6)D^3$ of the ball. Record the result in your data table, making sure to include units of measurement.

4. Calculate the density $\rho = M/V$ of the ball. Record the result in your data table, making sure to include units of measurement.

5. Decide how far you will let the ball fall, and use a tape measure to measure the distance d [in meters]. Record the result in your data table. It is recommended that you choose distances that give fall times between 1.0 second (approximately 5 meters) and 1.5 seconds (approximately 11.25 meters).

6. Drop the ball and use a stopwatch or cell phone timer to measure the time t [in seconds] for it to travel that distance. It is important to release the ball and not throw it, and to measure the time as accurately as possible. Record the result in your data table.

7. Calculate the average velocity during the fall, $v_{avg} = d/t$. Record the result in your data table, making sure to include units of measurement.

8. Assuming the ball accelerates at a uniform rate, the average velocity should be half of the final velocity. Calculate the final velocity $v_{final} = 2v_{avg} = 2\ d/t$. Record the result in your data table, making sure to include units of measurement.

9. Calculate the acceleration during the fall, $a = v_{final}/t = 2d/t^2$. Record the result in your data table, making sure to include units of measurement.

10. Repeat steps No. 6–9 to make a total of five measurements for the same ball and same distance. Record the results in your data table, making sure to include units of measurement.

11. Find the average of your five acceleration measurements for that ball, $a_{avg} = (a_1 + a_2 + a_3 + a_4 + a_5)/5$. Record the result in your data table, making sure to include units of measurement.

12. Repeat steps No. 1–11 for other balls of different densities. Record the results in your data table, making sure to include units of measurement.

13. Plot your data points for acceleration versus ball density on the accompanying graph. How does density affect the acceleration of a ball, and why?

14. How does aerodynamic drag affect the time it takes for an object to fall. Based on your data, which balls appear to be affected the most by aerodynamic drag? Explain how aerodynamic drag would affect the calculated acceleration for an object.

15. Repeat steps No. 1–11 using the same ball, but dropping it over four different distances. Measure the time and acceleration five times for each distance, and take the average of those five measurements. Record the results in your data table, making sure to include units of measurement.

16. Plot your data points for acceleration versus distance on the accompanying graph. How does distance affect the acceleration of a ball, and why?

17. How would you expect your experimental results to change if you conducted the experiment in a vacuum?

18. How would you expect your experimental results to change if you conducted this experiment on the moon or on another planet?

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Other Related Articles

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