

NEWTON'S CANNON

Teaching Guidelines

Summary: Students are introduced to the concept of orbital velocity through the Futures Channel movie, *The Ares Launch Vehicles*, and a discussion of Newton's cannon, then work in teams to carry out an investigation of the relationship between horizontal velocity of an object and distance traveled before falling to Earth. As an optional final step, the class derives a formula for computation of orbital velocity at the surface of the earth.

Subject: Science

Topics: Physics (Motion)

Grades: 9 - 12

Concepts

- Force
- Velocity
- Orbital Velocity

Knowledge and Skills:

- The speed of an object increases when force is applied along the direction of its motion; the longer the force is applied, and the greater the force, the greater the speed.
- An object will go into stable orbit around the earth if given sufficient speed in the right direction while outside of the earth's atmosphere.

Materials Needed (per team)

- Ruler (the type with a channel down the center along which a marble can travel)
- Marble
- Tape Measure
- Protractor

Procedure

Segment One: Introduction

Prepare for presentation the Futures Channel movie, *The Ares Launch Vehicles*.

Ask students to consider this question (which should be posted) and write down their answers. You may wish to have them do this with partners.

Do you think it's possible to throw a baseball so fast that it never falls to the earth? Explain your answer.

Ask for and accept some answers as a class discussion, for a minute or two.

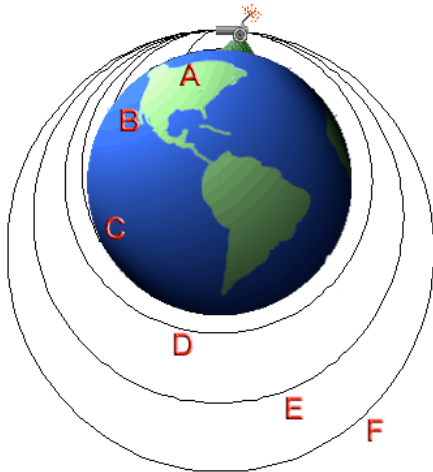
Play the movie, *The Ares Launch Vehicles*, all the way through.

Now ask students if what they learned in the movie either reinforced or changed their minds about their earlier answers, and accept and discuss their responses briefly.

Segment Two: Newton's Cannon

Tell students that, around 300 years ago, Isaac Newton wondered about exactly the same question (if they are not familiar with Newton and his place in the history of physics, you may want to take a few minutes to review that). But Newton didn't have the advantage of knowing that rockets had carried men and women off of the surface of the earth, so he had to try to answer the question using only his imagination, as a "thought experiment."

Use a diagram like the one below to explain Newton's thought experiment.

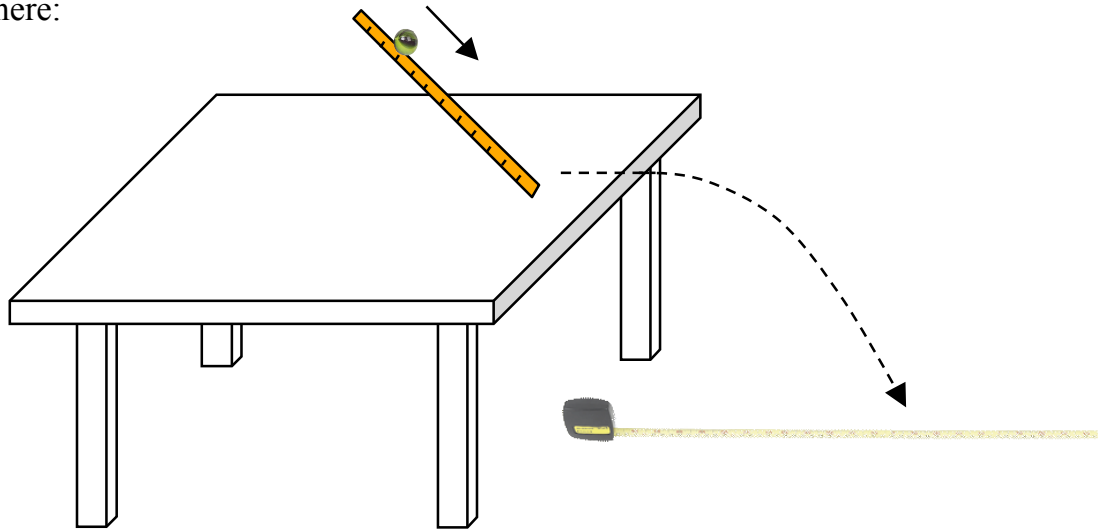


Newton's Thought Experiment

"Imagine a huge cannon located on the surface of the earth, firing a cannonball at greater and greater speeds. Ignore the effects of air resistance. As the speed increases, the cannonball will fall at greater and greater distances from the cannon (A, B, C). At some point (D), the speed will be so great that by the time the cannonball "falls" to the earth, the surface of the earth will have curved away from it! Instead of striking the earth, the ball swings all the way around the earth. Now the cannonball is in orbit! If you continue to give the cannonball more and more speed (D, E, F), its path will carry it farther and farther away from the earth as it travels around it."

Segment Three: Testing the Thought Experiment - The Investigation

Explain to students that they can actually test some aspects of this thought experiment, and, in doing so, get an idea of how fast the cannonball would have to travel to get into orbit. Arrange students into investigation teams and show them their investigation set-up, as diagrammed here:



Explain to students that they are to investigate what happens to the distance traveled by the marble before it hits the floor as the marble comes down the ramp faster and faster, and ensure that they understand the similarities between this investigation and Newton's Cannon.

With the class, work out a statement of the investigation question, which might be something like this:

How can we understand more about Newton's thought experiment?

As a class discussion, identify the variables of this investigation—not just the variables of interest (speed of marble, distance traveled), but also other variables that might affect results. Make a list of all variables and guide the discussion so that it includes at least these:

- Angle of ruler.
- Position of marble on ruler before it is released.
- Speed of marble as it comes to bottom of ruler.
- Distance marble travels across table before it reaches the edge.
- Speed of marble as it leaves the table.
- Friction between marble and ruler.
- Friction between marble and table.
- Height of table.
- Direction the marble is traveling as it leaves the table: Is it moving straight out or at an angle?
- How far the marble travels in the air before it strikes the ground.

Once your list is complete, ask students to identify the two key variables as "speed of marble as it leaves the table" and "how far the marble travels in the air before it strikes the ground." Then discuss how the other variables might affect these. (Note that this discussion is in some ways the most important part of this lesson, because it affords an opportunity to highlight relationships between the various forces acting on the ball and its resultant motion.)

Tell students that all teams should set the angle of their rulers at 45 degrees and the distance between the bottom of the ruler and edge of table as 10 centimeters. (It is also essential that all tables be the same height and have the same type of surface.)

As a class discussion, work out the steps of the procedure that students will follow. Guide the discussion to ensure that it includes the steps below.

- 1) Set up ruler at the correct angle, at the correct distance from edge of table, and perpendicular to the edge of table.
- 2) Have one student prepared to put his finger on the spot where the marble strikes the floor.
- 3) Place the marble at one of the centimeter markers on the ruler, and release it.
- 4) Measure how far the marble travels from the edge of table to the point where it strikes the floor.
- 5) Repeat the measurement twice more; always making sure ruler is at a 45-degree angle with the table.
- 6) Place the marble at a different centimeter marker on the ruler, and release it.

Next, have each team make a prediction as to what they expect will happen in the investigation. These predictions should not only state that "the marble will go farther when it is released higher on the ruler," but should also state how much—for example, if the marble is released at twice the distance on the ruler, will it go twice as far, less than that, or more?

Ask all students to copy the investigation question, the agreed-upon procedure and their predictions on a right-hand sheet in their science journals; on the facing page, they should draw a diagram of the experimental setup, including measurements of the height of table and distance between the bottom of the ruler and the table's edge.

Before students begin, ask them to think about how they will record their data in an organized way. You may wish to generate a common data collection format for the entire class, or allow each team to work this out for themselves.

Student teams should collect data for at least 6 different placements of the marble on the ruler.

Segment Four: Testing the Thought Experiment - The Analysis

Each student team should be given time to graph and analyze the data collected, following the protocols you have established for the investigations; that analysis should include their statements of conclusions. Ask each team to answer these questions:

- *Did the investigation help them to answer the question they started with?*
- *Were their predictions correct?*
- *Did they notice anything surprising?*
- *Do they think the results are valid or not, and why?*

Segment Five: Estimating Escape Velocity (optional for more advanced classes)

Tell students that they can use the data that they gathered to determine how fast the marble would have to go to get into orbit around the earth. Work through these calculations as a class:

First, you will work out how far the marble would have to travel so that by the time it fell 75 centimeters, the ground was no longer "there"—that is, the earth had curved enough so that the marble would still be the same distance above the ground as when it started. This can be determined geometrically to follow this formula:

$$d = \sqrt{2r_e h}$$

h = vertical distance of the fall of the marble

d = horizontal distance traveled along surface

r_e = radius of earth

Assuming that the height of the table is 75 centimeters, the formula gives a distance of a little over 3 kilometers.

Ask students to use the data they collected to estimate how far up the ruler the marble would have had to be placed to travel that 3 km distance before falling 75 centimeters. Allow them to use whatever methods they wish to do so. Then discuss those estimates, using the opportunity to discuss the validity of extrapolation so far beyond the domain and range of the actual experimental measurements.

Next, work out how fast the marble would have to be traveling to go that distance as it falls by 75 centimeters. This is not as difficult as it might seem, because the time of travel can be determined from the distance the marble "falls" through a simple relationship between distance and time for a falling object at the surface of the earth:

$$t = \sqrt{\frac{2d}{g}}$$

t = time

g = acceleration at surface of earth due to gravity,

= 980 cm per second per second

d = distance fallen

If d is 75 centimeters (typical height of a table), this gives a time of around 0.4 seconds.

Now you have the distance the marble must travel across the earth (3 kilometers) and the time in which it must travel that distance (0.4 seconds); the velocity can be computed as distance divided by time:

$$\begin{aligned} \text{velocity} &= \text{distance}/\text{time} \\ &= 3 \text{ kilometers}/0.4 \text{ seconds} \\ &= 7.5 \text{ kilometers per second.} \end{aligned}$$

As a final step, point out to students that even if they could get their marble moving that fast, it would not go into orbit, and ask them if they can tell you why. Guide the discussion to recognition of the effects of air resistance and the realization that that is why rockets must carry satellites and crew vehicles up above the earth's atmosphere in order to place them into stable orbits.

Note: You may have noticed that these equations can be solved simultaneously, yielding a simple relationship between the theoretical orbital velocity at the earth's surface, radius of the earth and constant of gravitational acceleration at the surface of the earth:

$$v = \sqrt{2gr_e}$$