611-0395 (45-045) "Exploring the Mystery of the Tower" Kit

Bill of Materials for the Leaning Tower of Pisa

Quantity	Description	Item Number
6	Leaning Tower of Pisa	30-205
6	protractor	038011
Exploring the Mystery of the Tower, Student Instructions		24-5045
Exploring the Mystery of the Tower, Journal Page		24-5045
Exploring the Mystery of the Tower, Teacher Edition		24-5045

Warranty and Parts:

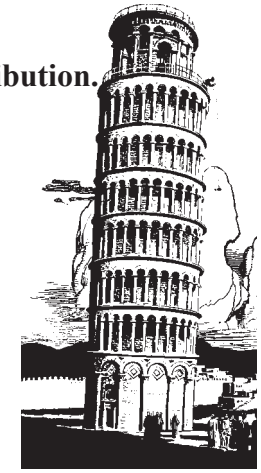
We replace all missing or defective parts free of charge. For additional parts, use part numbers above. We accept Mastercard, Visa, checks, school P.O.'s. All products guaranteed free from defect for 90 days after sale, defined as 90 days after date of invoice. This guarantee does not include accident, misuse, or normal wear and tear.

P/N 24-5045

Exploring the Mystery of the Tower

Objectives

- **To experimentally determine the center of gravity of a structure.**
- **To observe how location of center of gravity changes with changing mass distribution.**
- **To explore how location of center of gravity affects structure stability.**



Materials

Leaning Tower of Pisa
Protractor
Hard cover book (not included)
Balance (not included)
Ruler (not included)
Index card (not included)
Tape (not included)

Background

Look at the illustration on the right. Do you notice anything remarkable? If you said that the building seems tilted, you're right! That tilted tower is none other than Italy's most famous bell tower, the Tower of Pisa!

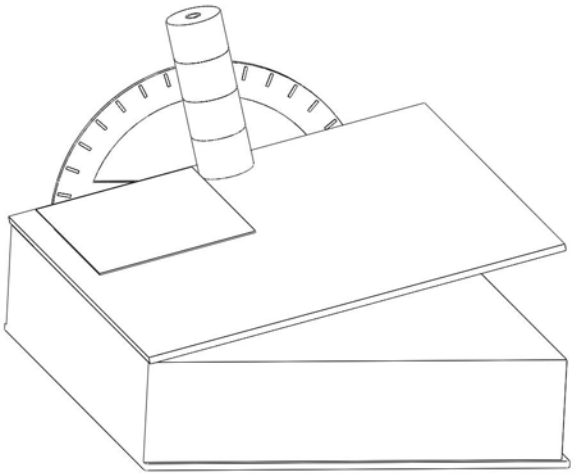
Billed as one of the seven wonders of the Middle Ages (about 476-1485 AD), the tower has been leaning in one direction or another almost since construction began in August 1173 AD. Each new generation of engineers tried to correct the tower's lean by adjusting the design of the storeys as they were added. In the beginning, engineers tried to correct a northward lean. When construction resumed in 1272, design changes were included to balance the tower's tilt toward the south. During the third and final construction phase in the 1360s, the bell chamber was added and angled northward. The end result of all of this design tweaking is a 58-meter (192 foot) tall marble tower with a Roman architectural flavor and banana shape that leans more and more south with each passing year!

Scientists estimate that the Tower of Pisa is moving at a rate of more than 1 millimeter a year. Many attempts have been made to try to stop the tower's slow decent or reverse its direction. Most early attempts not only did not fix the situation but, instead, made it worse. Why the 800-year-old tower hasn't fallen is a modern mystery. How does the location of the center of gravity affect how far a tower can lean before it topples? Do the following investigation to find out.

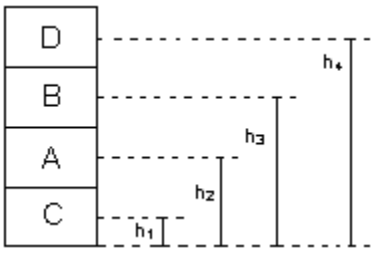
Procedure

1. Select one slug. Observe and describe this slug recording your description in Table 1 on your Journal Page. Measure its mass and diameter. Record all measurements in Table 1.
2. Record descriptions and measurements for each remaining slug.
3. Stack the slugs forming a tower. Use the steel pin that came with the slugs to hold them in place. You may arrange the slugs in any order that you choose. Label the slugs in the tower diagram shown for trial 1 in **Table 2** so that the order matches the tower you built.
4. Measure the distance from the bottom of the tower that *you built*—not the one in the picture—to the halfway point on the bottom slug. This is height one (h_1). Record this measurement on your tower diagram next to h_1.
5. Measure the distance *from the <u>bottom of the tower</u> that you built to the halfway point on the second slug*. This is height two (h_2). Record this measurement on your diagram next to h_2.

6. Measure and record heights for height three (h_3) and height (h_4).
7. Tape an index card to the back of a hardcover book.
8. Place your tower so that the bottom of the tower is in contact with the edge of the index card. The card will keep your tower from sliding.
9. Line up the ends of the protractor scale with the edge of the book cover so that the protractor is behind your tower. The edge of the protractor should be parallel to the tabletop.
10. While holding the protractor in place to measure the changing angle, slowly lift the book cover until the tower topples over. See below. Repeat steps 9 and 10 several times. Record the average angle at which your tower toppled in table 2.
11. Using the equation shown in table 2 and the data collected for mass and height in table 1 and table 2, calculate the distance of the center of gravity (C_g) from the bottom of your tower. This equation is not as scary as it looks. M_A, M_B, M_C, M_D are masses for each slug recorded in table 1. Values for h_1, h_2, h_3, and h_4 are recorded on the diagram in table 2.



The mass of each M_x depends on the order in which the slugs are organized in your tower. For example, the diagram shows one possible arrangement of slugs.



Plugging this information into the equation changes the equation as shown below.

$$C_g = \frac{M_x h_4 + M_x h_3 + M_x h_2 + M_x h_1}{M_A + M_B + M_C + M_D} \quad \rightarrow\rightarrow\rightarrow \quad \frac{M_D h_4 + M_B h_3 + M_A h_2 + M_C h_1}{M_A + M_B + M_C + M_D}$$

When you plug your mass and height measurements into your equation, you are ready to solve the equation and find the center of gravity of your tower.

12. Using a filled circle or other symbol, mark the location of the center of gravity on your tower diagram for **Trial 1** in **Table 2**. Don't forget to label this point on your diagram.
13. Take your tower apart. Build a new tower with the slugs in a different order. Label the slugs in the tower shown for **Trial 2** in **Table 2** so that it matches your new tower. Repeat **Steps 8 through 12** calculating the distance of the center of gravity of your new tower from the bottom of the tower. Mark and label the location of the center of gravity of your second tower on your second tower diagram.
14. Complete the questions on your **Journal Page**.

To learn more about center of gravity, Pisa's Leaning Tower, and efforts to save it, check out the following sites on the World Wide Web:

http://webphysics.ph.msstate.edu/javamirror/ntnujava/block/block.html
http://news.bbc.co.uk.1hi.world/europe/793432.stm
http://www.cisiau.unipi.it/~pierotti/Torre/Torre/1995/scientific.html

Name _____ Date _____

Class _____

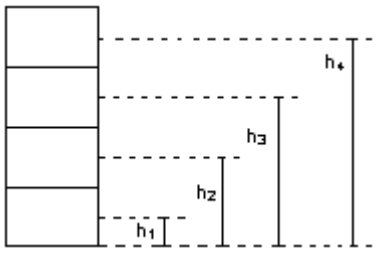
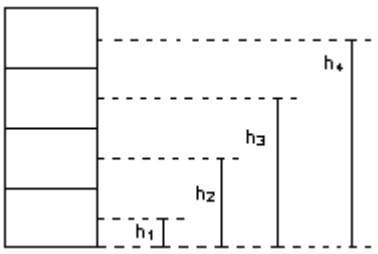
Exploring the Mystery of the Tower

Journal Page

Table 1

Slug	Description	Mass of Slug (g)	Diameter of Slug (cm)
A			
B			
C			
D			

Table 2

Trial	Tower	Tower Topple Angle	Center of Gravity
			$C_g = \frac{M_x h_4 + M_x h_3 + M_x h_2 + M_x h_1}{M_A + M_B + M_C + M_D}$
			$C_g = \frac{M_x h_4 + M_x h_3 + M_x h_2 + M_x h_1}{M_A + M_B + M_C + M_D}$

Think It Over

1. Describe how the slugs used to build your tower are alike. How are they different?

2. How did changing the order of the slugs affect the location of the center of gravity of the towers you built? Explain your answer. (**Hint:** Think of the slugs in terms of mass.)

3. How would you describe the relationship between the location of the center of gravity of a tower and the angle at which a tower will topple? In other words, how can the location of a tower's center of gravity be used to predict a tilting tower's relative stability? Explain your answer.

4. Using your diagrams in **Table 2**, select the tower that has the highest center of gravity. Rebuild this tower placing the slugs in the same order as the diagram. Measure the height of the center of gravity and place a very small piece of tape on the tower at that height.

   Imagine that the tape is a tiny window in your tower. You are holding the end of the very, very long string attached to a yo-yo out the window. How does the position of the center of gravity of your tower compare to the base of your tower when the tower is perpendicular to the ground? Write your answer in a complete sentence.

5. Place the tower on the book cover next to the index card just as you did before. Slowly raise the book cover. Describe how the position of the center of gravity compared to the center of the base changes as the tower tilts. (**Tip:** You are still holding onto the string of the yo-yo as the tower tilts.)

6. What can you conclude about the relationship between the angle at which the tower topples and the location of the center of gravity when compared to the base of the tower?

Take a few minutes to think about this one. Test your ideas about this system using your model and materials used during your investigation before writing your answer.

Challenge

1. Why do you think that the Tower of Pisa has not toppled?

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Teacher Pages

Time

Two 45-minute class periods

Benchmarks and Standards

This investigation provides support for the *Benchmarks for Science Literacy* and *National Science Education Standards* shown in the table below.

<table>
<tr><th colspan="3">Benchmarks for Science Literacy</th><th colspan="3">National Science Education Standard</th></tr>
<tr><td rowspan="2">Nature of Technology</td><td>3A.3</td><td>Engineers, architects, and others who engage in design and technology use scientific knowledge to solve practical problems.</td><td rowspan="2">Unifying Concepts and Processes</td><td>Systems, Order and Organization</td><td>A system is an organized group of related objects or components that form a whole.</td></tr>
<tr><td>3B.4</td><td>Systems fail because they have faulty or poorly matched parts, are used in ways that exceed what was intended by the design, or were poorly designed to begin with.</td><td>Evidence, Models and Explanation</td><td>Models are tentative schemes or structures that correspond to real objects, events, or classes of events, and that have explanatory power.</td></tr>
<tr><td rowspan="2">Nature of Mathematics</td><td rowspan="2">2C.2</td><td rowspan="2">Using mathematics to solve a problem requires doing computations.</td><td rowspan="2">Science as Inquiry</td><td colspan="2">Think critically and logically to make the relationships between evidence and explanations.</td></tr>
<tr><td colspan="2">Use mathematics in all aspects of scientific inquiry.</td></tr>
<tr><td>Physical Setting</td><td>4F.3</td><td>An unbalanced force acting on an object changes its speed or direction of motion, or both.</td><td>Science and Technology</td><td>Understanding About Science and Technology</td><td>Technologies exist within nature and so they cannot contravene physical or biological principles.</td></tr>
</table>

Before the Class Begins:

Have the students read the Background section of their labs highlighting important terms and concepts. Review concepts and vocabulary associated with mass, gravity and weight.

After the investigation:

As students answer questions on their Journal Pages, encourage students to use data collected during their experiments and their observations to help explain their answers. Encourage students to repeat the testing/toppling steps as often as necessary as to answer the questions.

Answers to Think It Over:

1. Student responses should indicate that the slugs are alike in that they are similarly sized and shaped. The primary difference that they should notice is that the slugs all have different masses. Other notable observations may include: different colors; different materials etc.
2. Student responses should indicate that changing the order of the slugs caused the center of gravity to be either higher or lower than was in the first tower built. For example, the center of gravity was lower in the tower when the heaviest slug was on the bottom than when the slug was higher up in the tower. Accept all reasonable lines of logic.
3. Student responses should suggest that the further away the center of gravity is from the base of the tower, the smaller the angle at which a tower will topple.
4. Student responses should indicate that when the tower is perpendicular to the ground, the center of gravity of the tower is directly over the center of the base. Student responses should be in complete sentences.
5. Student responses should indicate that as the tower tilts, the center of gravity of the tower is no longer directly over the center of the base. Accept all reasonable answers.
6. Student responses should suggest something along the lines of the following: the angle at which a tower topples indicates the position at which the center of gravity of the tower is no longer over the base.

Challenge Questions:

Accept all reasonable answers that include application of concepts explored in this investigation. For example, the tower has not toppled because the center of gravity of the tower is still over the base.

Assessment:

Collect and grade student Journal Pages. For ESL or Special Education students, have students draw diagrams of towers at different angles while holding yo-yos with long strings out the windows. Have students label windows as center of gravity. Have students label the bases of their towers. OR, Team ESL students with non-ESL students. Have student teams explain their observations and conclusions to the class such that the ESL students point to pertinent portions of the diagrams while non-ESL teammates explain their findings.