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Catalog No. AP8054
Publication No. 8054

Build a Model Catapult

Flinn STEM Design Challenge™

Introduction

Catapults have been used to launch projectiles during battles from the time of the ancient Greeks to World War I. Today variations of the catapult are used to launch planes from ships and for recreational use such as clay targets. Make a model catapult out of simple materials and determine what variables affect launch distance and accuracy.

Concepts

- Engineering design
- Potential and kinetic energy
- Levers
- Projectile motion

Background

A catapult is based on the simple machine known as a *lever*. A lever is used for the transfer and modification of force and motion. The movement of objects can be made faster or slower, longer or shorter, and can occur in various patterns. In a lever system, the *lever* itself is always rigid, like a bar or plank, and turns or pivots on one point or axis called the *fulcrum*. The *load* is whatever is being moved—a rock, a load in a wheelbarrow, or other object. The *force* is applied to the lever by anything capable of doing mechanical work; it may be exerted by a person, a spring, a motor or any other item that can apply a force on the lever itself.

Lever systems in action are useful in gaining speed, distance, precision, or mechanical advantage. *Mechanical advantage* is defined as the ratio of force output to the force applied. Each lever system has its own unique properties and has trade-offs between force and distance or speed.

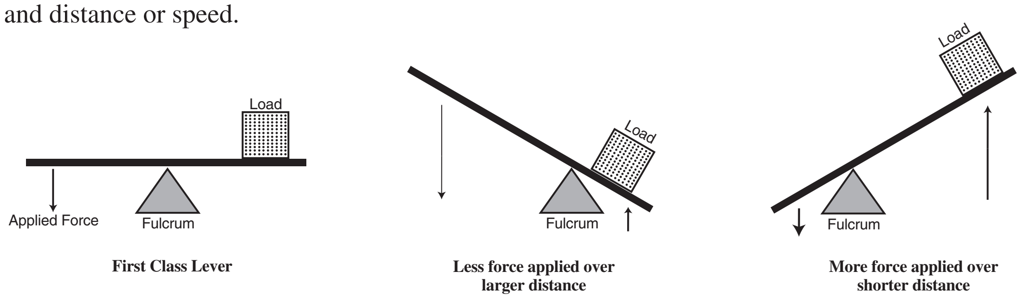

Figure 1a. **Figure 1b.** **Figure 1c.**

Many catapults are designed as first class levers, where the fulcrum is between the applied force and the load (see Figure 1a). When the load is closer to the fulcrum than the applied force, then less force is needed to lift the load than the weight of the load itself, but the applied force is exerted over a longer distance than the load moves (see Figure 1b). If the load is much farther from the fulcrum than the applied force, then the load moves a farther distance and with greater speed, but much more force is needed to move the load (see Figure 1c). In general, there is a reverse relationship between mechanical advantage and both the amount and speed of movement, however, there is no necessary relationship to precision. The precision of an instrument refers to how close several measurements are to each other. Accuracy, on the other hand, is how close a measurement is to a standard value.

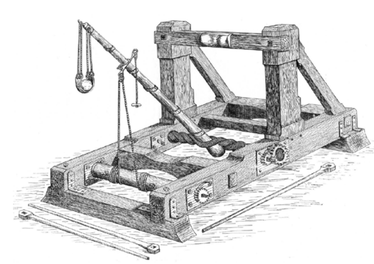

Figure 2.

One type of catapult, known as the onager, was used as a siege engine by the Romans beginning in the second century AD. A long lever arm was inserted into a bundle of ropes attached to a frame. A sling with a projectile, usually a large rock or several smaller stones, was attached to the end of the lever farthest from the rope bundle. Force was applied to twist the bundle, storing a great amount of *elastic potential energy* in the ropes. The bundle of ropes acted as the fulcrum (see Figure 2). The long arm of the lever was forced downward against the tension in the ropes. When the tension was released, the bundle's potential energy was converted to mechanical energy of the untwisting ropes, which pressed on the short end of the lever. As the lever rotated, the long end gained *kinetic energy* (energy of motion) and snapped upright, stopping at a crossbar and launching the projectile. Since the projectile was far from the fulcrum, it was launched with great speed. While not as accurate as some earlier siege weapons, the onager was quite effective at smashing walls or hurling missiles over protective barriers.

Several factors affect how far a projectile will travel, including the launch angle and the strength of the initial push or pull that sets the object in motion. The component forces acting on the projectile are the initial force that sets the object in motion and a vertical force of gravity pulling down. Once the projectile is launched, no horizontal force acts upon it, only gravity. Without gravity, the projectile would continue to travel upward, following the trajectory of the launch angle. The force of gravity makes the projectile fall beneath its intended path (see Figure 3). As a result, the path a projectile takes is a *parabola*. Figure 4 illustrates the path of a projectile launched at the same initial speed but at various angles. Neglecting air resistance, this pattern is the same for all projectiles launched with the same initial speed.

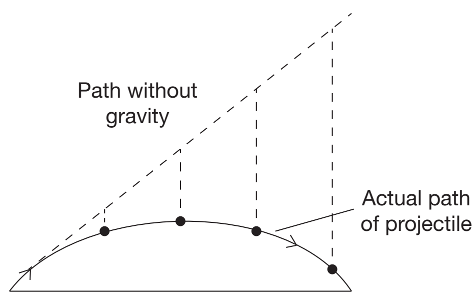

Figure 3.

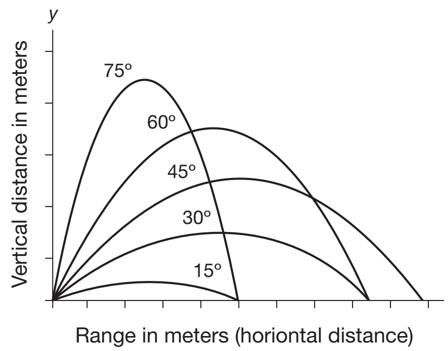

Figure 4.

Experiment Overview

The purpose of this activity is to construct a model catapult with the materials provided. Two projectiles of different masses will be tested and the distance each projectile travels will be measured. The procedure provides a model for guided-inquiry design of experiments to determine what modifications may be made to the catapult that provide the best solution to the given challenge.

Pre-Lab Questions

1. Examine Figure 4 in the *Background* section.
   a. At what angle should a projectile be launched to reach the greatest horizontal distance?
   b. Which pairs of angles reach the same horizontal distance but have different vertical components?
   c. What pattern do you see regarding the pairs of launch angles that result in the same horizontal distance?
   d. Based on your answer to 1c, at what other angle could a projectile be launched that would have the same horizontal range as when it was launched at a 25-degree angle? Assume the initial speed is the same.
2. "Bull's-eye" drawings are often used to illustrate the concepts of accuracy and precision. Which drawing in Figure 4 suggests projectiles that were launched at target x accurately but imprecisely? Which one illustrates precise but inaccurate catapult launches?

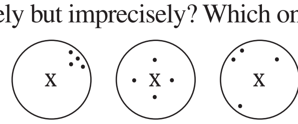

Figure 4.

3. Describe the safety hazards and precautions associated with this activity.

Materials

Balance	Rubber stopper, #2
Binder clip, medium	Ruler, metric
Bottle cap, plastic	Scissors or pliers
Cable ties, 4	Tongue depressors, 4
Cork, #6	Velcro® dot, hook
Meter stick or measuring tape	Velcro® dots, loop, 3
Protractor (optional)	

Safety Precautions

Use caution when launching projectile. Do not aim the catapult at anyone. Catapult launching should be performed only in the area specified by the instructor. Wear safety glasses at all times during this activity. Please follow all laboratory safety guidelines.

Procedure

Part I. Catapult Assembly

1. Align one tongue depressor on top of a second one and fasten them together with a cable tie 2.5–3 cm from one end (see Figure 5). Pull the cable tie as tight as possible.

Figure 5.

2. Insert one metal arm of the binder clip between the two tongue depressors, past the cable tie. Since the cable tie is very tight, the arm will fit snugly between the tongue depressors (see Figure 6).

Figure 6.

3. Repeat steps 1–2 with the other two tongue depressors and the second metal arm.
4. Insert a third cable tie through the binder clip and around two tongue depressors, pulling the cable tie as tightly as possible (see Figure 7).
5. Repeat step 4 with the fourth cable tie on the other side of the binder clip.
6. After making sure all four cable ties are as tight as possible, cut off the excess plastic. Alternately, grasp the excess cable tie near the fastener with pliers and twist several times until the excess plastic breaks off.
7. Attach the sticky side of the single Velcro hook dot to the bottom of the plastic bottle cap.
8. Press one of the Velcro loop dots onto the hook side of the bottle cap.
9. Attach the bottle cap to the top of one tongue depressor so the edge of the cap is about 1 cm from the end of the tongue depressor (see Figure 8). Press the cap down firmly.
10. The arm of the catapult with the bottle cap will be referred to as the lever arm and the other is the base of the catapult.

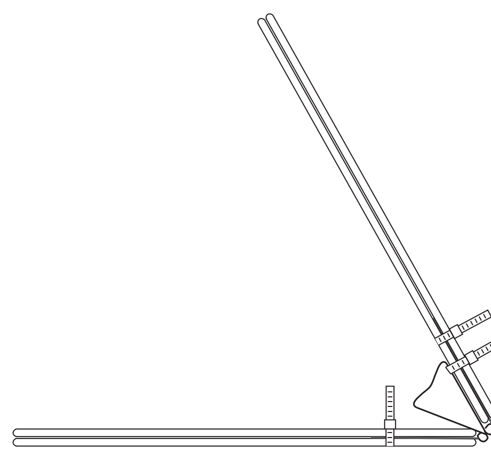

Figure 7.

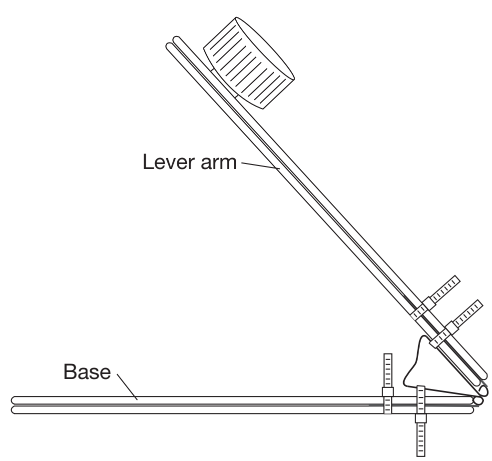

Figure 8.

Part II. Testing Variables

Be sure to wear safety glasses when any team is testing the catapult. Do not launch the projectile toward anyone.

A. Mass of Projectile

1. Choose either the cork or the rubber stopper as the projectile.
2. Weigh and record the mass of the projectile in Data Table A on the Build a Model Catapult worksheet.
3. Set the catapult on the floor and hold down the base.
4. Press the lever arm of the catapult down to the base and place the projectile in the bottle cap.

5. Making sure no one is in the path of the projectile, release the lever arm.
6. Note where the projectile lands. Measure and record the distance from the front of the catapult to that spot. *Note:* Do not include any distance the projectile moves after the initial landing.
7. Record any observations of the path of the projectile or the performance of the catapult.
8. Repeat steps 1-7 for a total of 10 trials.
9. Repeat steps 1-8 with the other projectile.

B. Length of Lever Arm

1. Attach the other two Velcro loop dots on the lever arm of the catapult so the distance from the center of one dot is 3 cm from the center of the next dot.
2. Measure and record the distance from the center of each dot to the fulcrum in Data Table B on the worksheet (Length of Lever Arm).
3. Use the data from Part A for the cork projectile to fill in the distances in Data Table B for the longest lever arm (dot near the end of the lever).
4. Remove the cap and place it on the center dot.
5. Repeat steps 3–8 from Part A above with the cork projectile.
6. Move the cap to the Velcro dot closest to the fulcrum.
7. Repeat steps 3–8 from Part A above with the cork projectile.

Part III. Design Challenge

Modify your catapult to hit a target a set distance provided by your instructor with either the rubber stopper or the cork with a minimum 80% accuracy, or at least 4 out of 5 times.

Form a working group with other students and discuss the following questions.

1. In Parts IIA and IIB, what was the average distance the projectile traveled for each set of 10 trials? Record the averages on the worksheet.
2. Consider the consistency of the distances of the projectiles, i.e., the precision of the catapult.
    a. Does the average distance indicate how precisely the catapult performed?
    b. What might be a good way to represent the precision of the catapult? In other words, by what method could you communicate how consistent the distances were for each set of 10 trials?
    c. Did the way the catapult was constructed appear to contribute to any inconsistencies? If so, how might the design be modified to minimize the problem?
3. One variable that was not tested was the launch angle.
    a. How should the angle be changed if the projectile travels farther than desired?
    b. Brainstorm ways to modify the catapult design to vary the launch angle.
4. What other variables may affect the distance the projectile travels?
5. What do you need to know about the target in order to choose the best design solution?

Name: ___________________________

Build a Model Catapult Worksheet

Data Table A. Mass of Projectile

Projectile	Rubber Stopper Mass:	Cork Mass:	Observations
Trial	**Distance (m)**		
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
Avg.			

Data Table B. Length of Lever Arm

Projectile:	Lever Arm: cm	Lever Arm: cm	Lever Arm: cm
Trial	**Distance (m)**		
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
Avg.			

Name: ______________________________

Post-Lab Questions

1. Consider the model catapult from Part 1.

   a. What acts as the fulcrum?

   b. When the lever arm is released, what is the load that is being moved?

   c. When the lever arm is released, what provides the applied force that moves the load?

2. How did the mass of the projectile affect the distance it traveled in Part IIA?

3. How did the length of the lever arm affect the distance the projectile traveled in Part IIB?

4. How does the relationship between the fulcrum and the load explain the results from Part IIB?

5. List the modifications made to the model catapult in Part III and the reason for each.

6. Explain why you chose the projectile used for the Design Challenge.

7. Which was more important in redesigning the model catapult—accuracy, precision, or both equally important?

8. Did the redesigned catapult achieve the desired results? If not, what other improvements might be made?

Teacher's Notes

Build a Model Catapult—Flinn STEM Design Challenge™

Materials Included in Kit *(for 15 groups of students)*

Binder clips, medium, 1 ¼″, 15
Bottle caps, plastic, 15
Cable ties, 8″, 60
Corks, size 6, 15
Stoppers, solid, #2, 15
Tongue depressors, 240
Velcro® dots, loops, 45
Velcro® dots, hooks, 15

Additional Materials Required *(for each lab group)*

Balance, 0.1-g (may be shared)
Meter sticks or measuring tape
Protractor (optional)
Ruler, metric
Scissors or pliers

Additional Material Required (for Pre-Lab Preparation)

Target (see *Lab Hints* on the next page for suggestions)

Pre-Lab Preparation

1. Make a target for the Design Challenge (see *Lab Hints* on the next page for suggestions).
2. Cut the Velcro dots apart, one hook side and three loop sides for each group.

Safety Precautions

Use caution when launching projectile. Do not aim the catapult at anyone. Catapult launching should be performed only in the area specified by the instructor. Wear safety glasses at all times during this activity. Please follow all laboratory safety guidelines.

NGSS Alignment

This laboratory activity relates to the following Next Generation Science Standards (2013):

Disciplinary Core Ideas: Middle School
- MS-PS2 Motion and Stability: Forces and Interactions
  - PS2.A: Forces and Motion
  - PS2.B: Types of Interactions
- MS-PS3 Energy
  - PS3.A: Definitions of Energy
  - PS3.B: Conservation of Energy and Energy Transfer
  - PS3.C: Relationship between Energy and Forces
- MS-ETS1 Engineering Design
  - ETS1.A: Defining and Delimiting Engineering Problems
  - ETS1.B: Developing Possible Solutions
  - ETS1.C: Optimizing the Design Solution

Disciplinary Core Ideas: High School
- HS-PS2 Motion and Stability: Forces and Interactions
  - PS2.A: Forces and Motion
  - PS2.B: Types of Interactions
- HS-PS3 Energy
  - PS3.A: Definitions of Energy
  - PS3.B: Conservation of Energy and Energy Transfer
- HS-ETS1 Engineering Design
  - ETS1.C: Optimizing the Design Solution

Science and Engineering Practices
- Asking questions and defining problems
- Developing and using models
- Planning and carrying out investigations
- Using mathematics and computational thinking
- Constructing explanations and designing solutions

Crosscutting Concepts
- Patterns
- Cause and effect
- Energy and matter
- Structure and function

Lab Hints

- Enough materials are provided in this kit for 30 students working in pairs, or for 15 groups of students. Extra tongue depressors are included for students to use in making modifications to their catapults. Parts I and II of this laboratory activity can reasonably be completed in two 50-minute class periods. The pre-laboratory assignment may be completed before coming to lab, and the data compilation and calculations may be completed the day after the lab. Allow more time for students to brainstorm and modify their designs for the Design Challenge.
- This model catapult was specifically chosen for ease in modification and to eliminate the need for hot glue or sharp cutting tools. Consider the experience and maturity of your students and set specific design constraints accordingly.
- Twisting the excess cable tie off with pliers leaves a smoother edge than cutting with scissors, which can leave a sharp edge. Alternately, sharp edges may be smoothed with sandpaper.
- A large open space, such as a gymnasium or even outdoors works best for this activity. Student groups may form a large circle with their catapults facing outward to avoid projectiles interfering with one another or hitting other students.
- Students will need to know what target they are shooting for in the design challenge—whether the projectile needs to land on a flat target or hit a "wall." For a flat target on the floor, a circle may be outlined in tape on the floor or use a paper plate for a greater challenge. For an upright target, a cardboard box may be used, or a large paper "building" may be taped on a wall. The size and distance of the target may be determined from the results from Part II of the activity so the design challenge is attainable.
- Students may wonder if gluing the cap to the lever arm might make a difference. This was tested in our lab with hot glue from a glue gun. The glue did not hold and the cap launched across the room with the projectile.
- Consider adding an adhesive label to each projectile and mark with each respective group's number so each group can easily identify its projectiles.

Teaching Tips

- This activity may be used with a unit on force and motion, energy transfer, or simple machines.
- Designate what materials students may use for their modified catapults. With more specific design constraints, variables are kept to a minimum, and students are better able to analyze the results. You may decide to limit the materials to the extra tongue depressors included in the kit and adhesive materials (wood glue, hot glue, masking tape, etc).
- While not required for this activity, students with knowledge of Newton's laws of motion will have a better understanding of projectile motion and why the launch distance is affected by the mass of the projectile.
- Some smart phones have a slow motion video feature. Allow students to record their launches in order to better analyze the motion of the catapult and projectile.
- If students are unsure why the angle between the lever arm and base is subtracted from 90 degrees to obtain the launch angle, show them that when the lever arm is pulled down all the way, the angle between the lever arm and base is zero. However, if the projectile could be launched in this position, it would travel straight up, a 90-degree angle.

Answers to Pre-Lab Questions *(Student answers will vary.)*

1. Examine Figure 4 in the *Background* section.
   a. At what angle should a projectile be launched to reach the greatest horizontal distance?

   A projectile launched at a 45-degree angle has the greatest horizontal range.

   b. Which pairs of angles reach the same horizontal distance but have different vertical components?

   Angles of 75 and 15 degrees have the same horizontal range and angles of 60 and 30 degrees have the same horizontal range.

   c. What pattern do you see regarding the pairs of launch angles that result in the same horizontal distance?

   Two angles that add up to 90 degrees have the same horizontal range, but different vertical components.

   d. Based on your answer to 1c, at what other angle could a projectile be launched that would have the same horizontal range as when it was launched at a 25-degree angle? Assume the initial speed is the same.

   A projectile launched at 65 degrees would reach the same horizontal distance as when it was launched at 25 degrees.

2. "Bull's-eye" drawings are often used to illustrate the concepts of accuracy and precision. Which drawing in Figure 4 suggests projectiles that were launched at target x accurately but imprecisely? Which one illustrates precise but inaccurate catapult launches?

   Drawing B suggests accurate but imprecise launches at target x. The marks are all close to x, but not to each other. Drawing A shows precise launches (they are close together) that are inaccurate (they are not close to x).

3. Describe the safety hazards and precautions associated with this activity.

   Projectiles launched from the catapults could hit someone. Do not aim the catapult at anyone. Catapult launching should be performed only in the area specified by the instructor. Wear safety glasses at all times during this activity.

Sample Data Tables *(Student data will vary.)*

Data Table A. Mass of Projectile

Projectile	**Rubber Stopper Mass:** *10 g*	**Cork Mass:** *1 g*	**Observations**
Trial	**Distance (m)**		
1	*2.97*	*5.10*	
2	*3.00*	*4.60*	
3	*2.49*	*5.20*	*Level arm release was not very smooth with the stopper.*
4	*2.96*	*4.96*	
5	*2.80*	*4.47*	*Lever arm vibrated a lot and cork didn't seem to go as high.*
6	*2.83*	*5.16*	
7	*2.83*	*5.00*	
8	*2.74*	*4.93*	
9	*2.83*	*4.89*	
10	*2.30*	*4.92*	*Catapult wobbled a lot and stopper did not travel straight.*
Avg.	*2.78*	*4.92*	

Data Table B. Length of Lever Arm

Projectile: *Cork*	**Lever Arm:** *12* **cm**	**Lever Arm:** *9* **cm**	**Lever Arm:** *6* **cm**
Trial	**Distance (m)**		
1	*5.10*	*4.98*	*4.20*
2	*4.60*	*4.69*	*3.90*
3	*5.20*	*4.96*	*3.30*
4	*4.96*	*4.86*	*4.30*
5	*4.47*	*5.70*	*3.77*
6	*5.16*	*5.40*	*3.26*
7	*5.00*	*4.99*	*3.30*
8	*4.93*	*4.70*	*3.52*
9	*4.89*	*4.93*	*2.81*
10	*4.92*	*5.19*	*3.30*
Avg.	*4.92*	*4.89*	*3.57*

Answers to Design Challenge Discussion Questions *(Student answers will vary.)*

1. In Parts IIA and IIB, what was the average distance the projectile traveled for each set of 10 trials? Record the averages on the worksheet.

   See sample Data Tables.

2. Consider the consistency of the distances of the projectiles, i.e., the precision of the catapult.

   a. Does the average distance indicate how precisely the catapult performed?

   No, the average does not indicate how much the distances varied.

   b. What might be a good way to represent the precision of the catapult? In other words, by what method could you communicate how consistent the distances were for each set of 10 trials?

   Possible ways include determining the standard deviation, the range from shortest to longest, or graphically representing frequency of distances with histograms.

   c. Did the way the catapult was constructed appear to contribute to any inconsistencies? If so, how might the design be modified to minimize the problem?

   The two tongue depressors making up the lever arm of the catapult vibrated quite a bit when it snapped back after the release. The cable tie on the base reduced the stability of the catapult. Gluing the pairs of tongue depressors together might reduce the vibrations and building a raised platform may increase the stability of the catapult during launch.

3. One variable that was not tested was the launch angle.

   a. How should the angle be changed if the projectile travels farther than desired?

   How the angle should be changed to reduce the horizontal distance of the projectile depends on the original launch angle. The angle could be either be increased or decreased from 45 degrees to shorten the horizontal distance. An angle greater than 45° would increase the vertical component and decrease the horizontal component of the projectile's motion. An angle less than 45° would decrease both the vertical and horizontal component of the projectile's motion. The catapult model that was tested had a launch angle of 35°. Therefore an angle less than 35° or greater than 55° (90-35) would be needed to shorten the horizontal distance of the projectile.

   b. Brainstorm ways to modify the catapult design to vary the launch angle.

   Answers may include designing a moveable cross bar to stop the lever arm at various angles, inserting a stop of various thicknesses between the jaws of the binder clip, use a smaller or larger binder clip, etc.

4. What other variables may affect the distance the projectile travels?

   Answers may include how far back the lever arm is pulled, which end (narrow or wide) of the projectile is facing up in the cap, the size of the binder clip, wind (if launched outdoors), adding an extension to the lever arm, etc.

5. What do you need to know about the target in order to choose the best design solution?

   One needs to know the size and shape of the target, whether it is flat on the ground or an upright object, and how far away it is.

Sample Data for Design Challenge

Results are shown for a catapult modified by gluing the pairs of tongue depressors together to reduce vibrations. A triangular base made of tongue depressors was added for more stability. The challenge was to hit a 30-cm diameter target on the floor 5.5 meters away with 80% accuracy.

Before modifications

Projectile: Cork	**Lever arm: 12 cm**
Trial	**Distance (m)**
1	*5.10*
2	*4.60*
3	*5.20*
4	*4.96*
5	*4.47*
Avg.	*4.87*
St. Dev.	*0.32*

After modifications

Projectile: Cork	**Lever arm: 12 cm**	**Hit Target**
Trial	**Distance (m)**	**Yes or No**
1	*5.68*	*No, overshot*
2	*5.52*	*Yes*
3	*5.52*	*Yes*
4	*5.52*	*Yes*
5	*5.57*	*Yes*
Avg.	*5.56*	*Accuracy: 80%*
St. Dev.	*0.07*	

Answers to Post-Lab Questions *(Student answers will vary.)*

1. Consider the model catapult from Part 1.

   a. What acts as the fulcrum?

   The fulcrum is the corner of the binder clip that the metal arm presses upon.

   b. When the lever arm is released, what is the load that is being moved?

   The load is the projectile.

   c. When the lever arm is released, what provides the applied force that moves the load?

   The applied force is provided by the jaws of the binder clip closing. The stored potential energy in the open clip is converted to kinetic energy as the jaws snap shut.

2. How did the mass of the projectile affect the distance it traveled in Part IIA?

   The greater the mass, the less distance the projectile traveled. The rubber stopper, which had a mass 10 times greater than the cork, only averaged 2.78 m compared to an average of 4.92 m for the cork.

3. How did the length of the lever arm affect the distance the projectile traveled in Part IIB?

   The projectile traveled the farthest with the longest lever arm. However, the middle length lever arm was a very close second. This may have been, in part, a result of more experience in launching the projectile with greater consistency. The shortest lever arm resulted in the shortest average distance and less precision.

4. How does the relationship between the fulcrum and the load explain the results from Part IIB?

   When the projectile (load) is closer to the fulcrum, it does not move as far or as fast upon release of the lever arm as it does when the load is farther away from the fulcrum. Therefore, the initial launch speed of the projectile decreases as the distance to the fulcrum decreases, and the projectile does not travel as far.

5. List the modifications made to the catapult, in Part III and the reason for each.

   Student answers will very. See Sample Data for Design Challenge above for an example.

6. Explain why you chose the projectile used for the Design Challenge.

   Student answers will vary. Ex: The cork was chosen since the target was much farther than the stopper ever traveled in any of the original trials. The cork had a better chance of hitting the target if the improvements to the catapult achieved the desired results.

7. Which was more important in redesigning the model catapult—accuracy, precision, or both equally important?

   Student answers will very. In the example above, accuracy was more important. As long as the projectile hit the target, which had a leeway of 15 cm all around the center, the launch was considered successful. In the example above, the improved catapult was also more precise than the original model, as shown by the smaller standard deviation. An example where precision would be more important is a challenge to repeatedly hit the same place anywhere on a wall of given dimensions in order to simulate weakening a portion of the wall.

8. Did the redesigned catapult achieve the desired results? If not, what other improvements might be made?

   Student answers will vary.

The *Build a Model Catapult—Flinn STEM Design Challenge*™ is available from Flinn Scientific, Inc.

Catalog No.	Description
AP8054	Build a Model Catapult—Flinn STEM Design Challenge™
AP6021	Tape Measure, Wind-Up Type, Metric, 10 m
AP4412	Tongue Depressors, 500/pkg

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