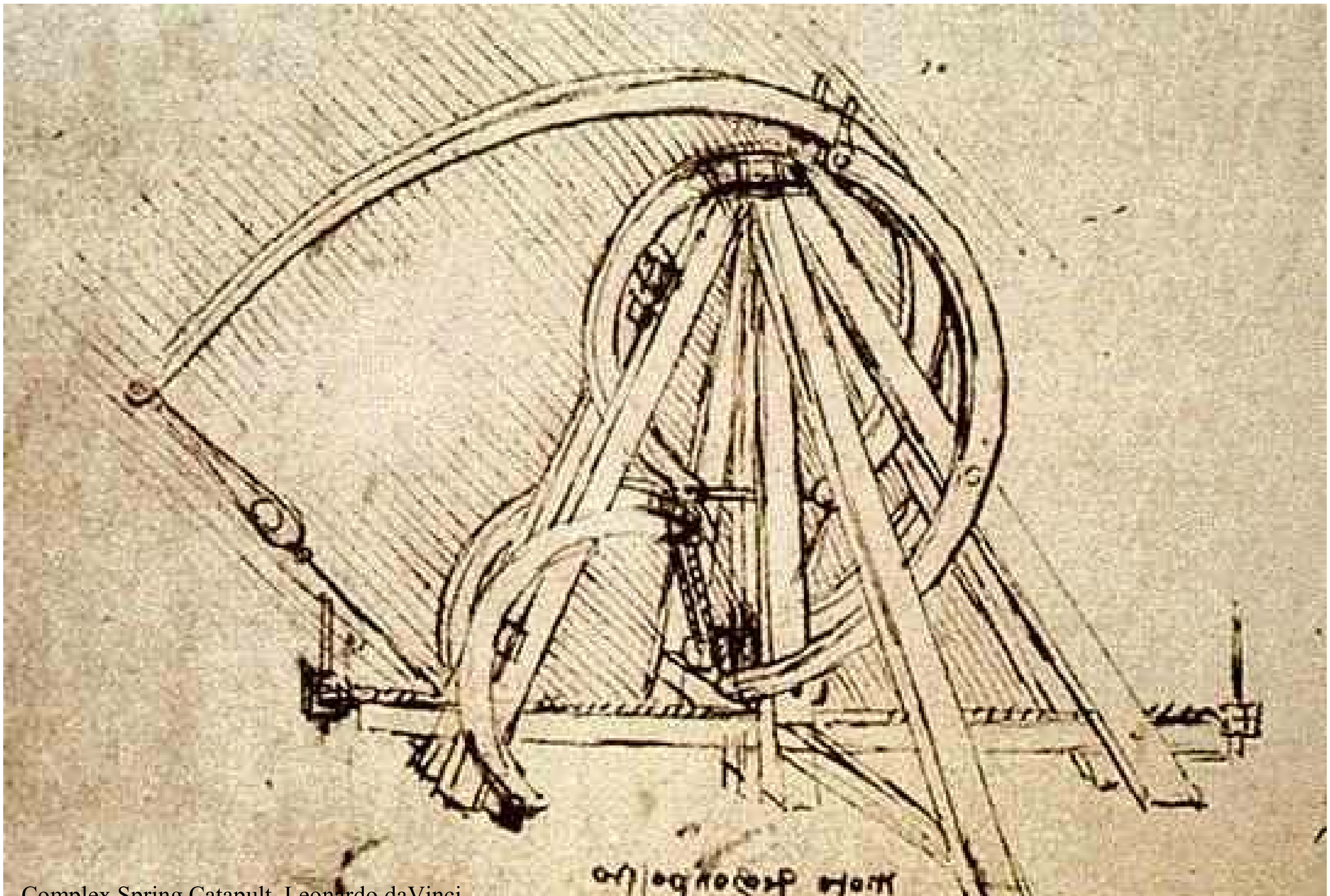
Hands-On in the

Inventor Center

The Catapult Forces Challenge

EDUCATOR'S GUIDE



Complex Spring Catapult, Leonardo daVinci
from *Leonardo's Catapults*, http://members.iinet.net.au/~rmine/Leonardo.html

WHAT'S INSIDE?

- Essential Questions
- Making the Most of Your Visit
- Correlations to Standards
- Facilitation
- Glossary
- Resources
- Activities (Coming Soon)

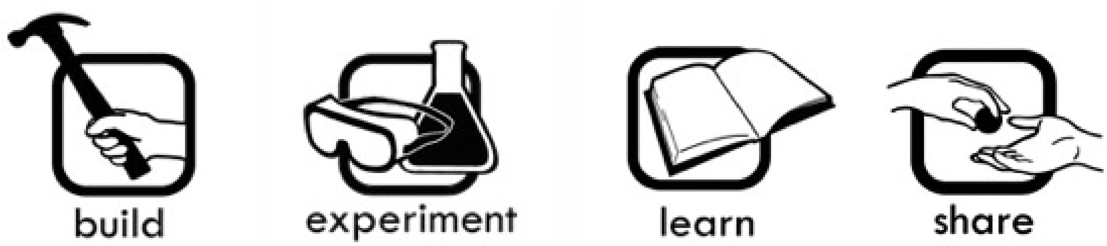
RMSC
Rochester Museum & Science Centre

ESSENTIAL **QUESTIONS**

During your facilitated hands-on experience in the *Inventor Center: Catapult Forces Challenge*, the facilitator will be posing essential questions to your students in two categories: The Inventive Process and the Science of Catapults and Trebuchets. These questions may also be useful for you as a teacher to gain background information as well as for facilitating higher order thinking during class discussions.

The Inventive Process

Inventor Center encourages students to explore the thrilling process of invention. The Inventor Center includes a series of participatory stations: build, experiment, learn and share. Students will define the problem, build a prototype, experiment with the prototype, learn how well the prototype works (solves the problem), and share their ideas or inventions with others.



Who is an inventor?

An inventor is someone who uses technology in a new way to solve a problem. An invention is a unique or novel device, method, or process. Inventions are different than discoveries because a discovery is detecting something that already exists. In the Inventor Center everyone is an inventor.

What is the inventive process?

There are many ways to invent. Most inventive processes consist of four main parts: learning, building, testing (or experimenting), and sharing. These four parts of the inventive process can happen in any order. See the Pre-Visit Activities for a close reading on the inventive process.

What do good experimental practices sound like and look like?

The first and most important thing to remember is to be safe. This means to conduct yourself in a responsible manner at all times while working with tools and equipment. In this challenge it is essential that students wear safety glasses and never launch a catapult or trebuchet anywhere except at the experiment station, which is equipped with a net to intercept stray balls.

It is also good practice to be clutter free. Leaving tables the way you found them and putting back any materials you use helps both avoid accidents and allows others to find materials if they want to use them.

Inventors discuss their ideas in quiet voices. When we speak of *scientific arguments based on evidence* we do not mean the kind of "argument" that involves raised voices or high emotions. Inventors respect each other's view points and explain their reasoning and their evidence calmly.

Last but not least is to record what you do. This is so that you can prove that you are the inventor of your design. Even more importantly, good records allow you and others to repeat what you have done. In ancient times, science was in its infancy and careful record keeping had not yet been established as important. In fact, the plans for many catapults were lost and people needed to start from zero each time. When science began to flourish during the Renaissance, Leonardo daVinci's drawings of inventions such as trebuchets were very detailed artistically but were still often hard to interpret scientifically. It is only in the last several hundred years that repeatability has become established as a fundamental rule of science.

The Catapult Forces Challenge

Students are presented with a problem: we (in our scenario, the English) need to take control of the RMSC castle away from the enemy (the Scots). To break the siege, we need students to work with each other and the laws of physics to design and build a catapult or trebuchet that can consistently launch projectiles into the castle. See the "Facilitation" section for details on how this will be presented to students.

Why were catapults and trebuchets invented?

Inventions usually start with a problem.

Human conflict has existed as far back as can be determined. Just as people invented better technology for constructive purposes such as travel, building shelter, and obtaining food, people also engaged in a continual arms race for better technology to attack others and to defend themselves.

A rock in a hand was replaced by a sling, which was replaced by a bow and arrow, which evolved into a crossbow. Defense technologies kept pace. Shields were supplemented with armor. By the Middle Ages, castles had become so strong that they could withstand long sieges. Sieges were expensive for everyone, including the attackers.

Catapults and trebuchets were invented to fill the need for a *way to transmit a lot of force from a safe distance.* A human arm could not throw a rock with enough force to knock down castle walls. In other words, mechanical advantage was needed.

Who invented catapults and trebuchets?

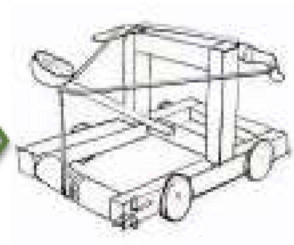
The history of catapults and trebuchets is a fascinating study of human ingenuity and the exchange of cultures that accompanied exploration, trade, and wars over two continents over thousands of years. For a short summary please see the Timeline in the Post-Visit Activities.

Rather than being a single invention, catapults and (later) trebuchets evolved over time by a series of modifications involving trial and error. This trial and error was in fact a form of the build-experiment-learn process. However, the sharing part of the process was often omitted.

The first written evidence of catapults being used in battle dates from about 400BC, in both China and simultaneously in Greece. The Chinese catapult was like a large crossbow, with the addition of a swinging arm. The Greek Dionysius the Elder, of Syracuse, is responsible for the invention of the Greek version. To make the crossbow more powerful it was made larger and set on a base. Two forms of catapults evolved from the Greek catapult: the double-armed catapult, called a ballista, which was used for shooting arrows, and a single-armed catapult designed for hurling stones. With many modifications, catapults remained a key weapon of warfare up through mediaeval times.

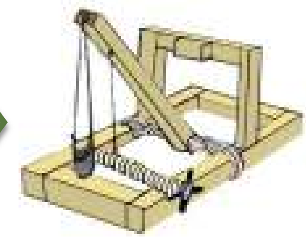
The force and distance with which catapults could launch projectiles was increased when torsion (twisted ropes) replaced tension (pulled ropes) but catapults always, by definition, involved the storage of potential energy as elastic stress. At first catapults were cocked by the use of muscles directly, but later gears were added.

Crossbow
(stretch and bend)



Chines Catapult 400 BC
(stretch and bend)

Greek Catapult 400 BC
(stretch and bend)



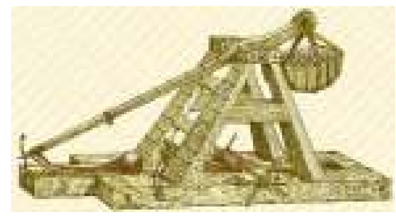
Later Torsion Catapult
(twist)

The trebuchet was invented in France and was first reported to be used in 1124AD in the siege of Tyre (in present-day Lebanon) during the Crusades. As it was much more powerful than a catapult, a trebuchet became the siege weapon of choice.

One of the largest and most famous trebuchets, called the Warwolf, was used by the English in 1304 to break the siege of Sterling Castle, in Scotland. See the Pre-visit Activities for a close reading about this historic event.

By the Renaissance, when the famous Italian painter, sculptor, draftsman, architect, engineer, and scientist. Leonardo daVinci (1452-1519), was designing trebuchets, the use of catapults and trebuchets had largely been replaced by cannons. DaVinci, although against war, designed intricate trebuchets, as well as many other ingenious devices.

Modern-day enthusiasts, such as those participating in the annual Punkin' Chunkin' Contest (http://punkinchunkin.com/) reconstruct mechanical throwing machines from ancient plans and vary the design to increase efficiency.



Trebuchet, *image from: http://medievallifestyle.com/siege-engines/trebuchet.html*

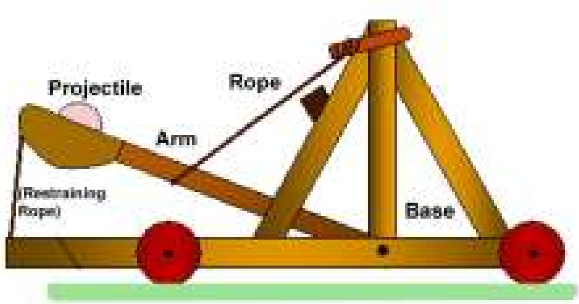
Leonardo daVinci, *self-portrait*

What are catapults and trebuchets?

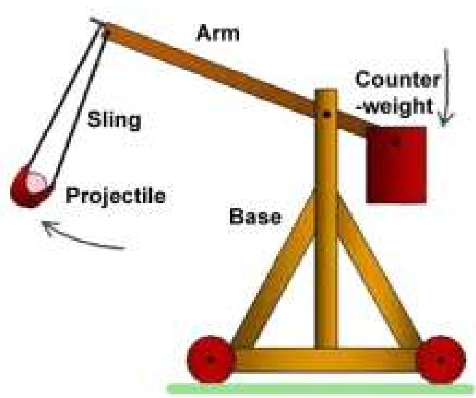
Many sources refer to catapults and trebuchets interchangeably, which can be confusing, but in the context of this Inventor Center Challenge we will use the commonly accepted scientific definitions:

Catapults and trebuchets are large-scale mechanical weapons that are used to throw objects, either defensively or offensively. They differ in their mechanics. Both catapults and trebuchets are made up of 3 essential parts:

1. a stable base
2. an arm
3. a structure that (slowly) stores potential energy until it can be released (quickly) as the kinetic energy of motion of the projectile.



Catapult



Trebuchet

The Base:
For a catapult or trebuchet to work efficiently it is important for the base to be stable so that when the stored potential energy is released, only the arm and the projectile move, not the base.

The Arm:
For a catapult the arm is a long straight part with an area at the free end to hold the object being thrown (projectile). For a trebuchet the arm rotates on a fulcrum so that it acts as a lever. The projectile is placed on one end (often in a sling) and a counterweight on the other.

The Structure for Storing Potential Energy:
The difference between a catapult and a trebuchet is how the potential energy is stored in the 3rd part.

How is Potential Energy stored in a Catapult vs. in a Trebuchet?

For a *catapult*, potential energy is stored as *elastic energy*. This energy results from the force put in as the muscular push or pull needed to stretch, bend, or twist some sort of elastic material that is attached to the throwing arm.

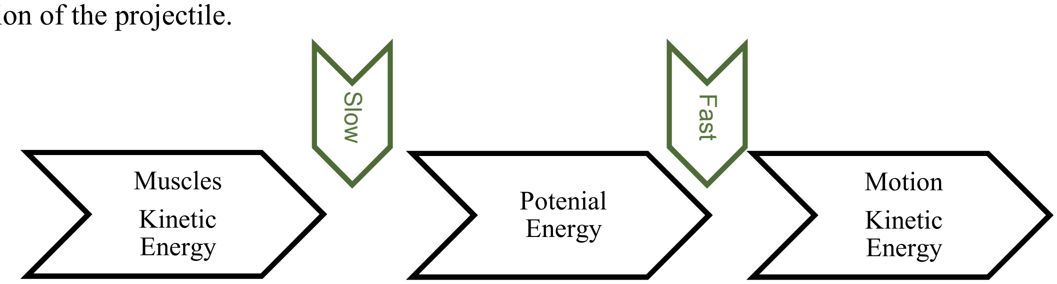
For a *trebuchet*, the potential energy is *gravitational*. This energy results from the force put in as the muscular push or pull needed to lift up the end of the lever with the heavy counter weight.

How is Energy Transformed in a Catapult and Trebuchet?

Energy is the ability to do work or cause a change. There are two types of energy: kinetic and potential. Kinetic energy is moving energy while potential energy is stored energy.

Energy also takes many forms: mechanical, electrical, chemical, magnetic, radiant (light), elastic, gravitational, thermal (heat), and even nuclear. Energy can change into a different form of energy; this is called energy transformation. The Law of Conservation of Energy states that energy cannot be created or destroyed, it can only change forms

During this Inventor Center Challenge we want to use the kinetic energy coming from our muscles to slowly build-up potential energy in the machine, and then release the energy very quickly in the form of the kinetic energy of motion of the projectile.



The chemical energy stored in food is transformed into chemical energy in the attacker's muscles, which is transformed into the kinetic energy to cock the siege machine. The energy in the cocked position has now been transformed into potential energy.

When the trigger is released, this potential energy is transformed suddenly as the kinetic energy of motion of the projectile. When the projectile hits the castle wall, the kinetic energy is used to do the work of crumbling the wall. Eventually all of this energy is dissipated as heat energy.

What forces do catapults and trebuchets use?

Force is a push or a pull. When force is applied over a distance, “work” is done. By “work” we mean the scientific definition of work, which is a form of energy. In the language of mathematics:

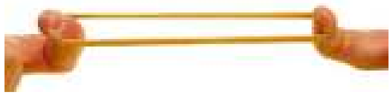
$$\text{work} = \text{force} \times \text{distance}$$
$$w = f \times d$$

Catapults:

Catapults take advantage of *elastic force*, involving stretched, compressed, bent, or twisted material. To prepare a catapult to launch a rock, it takes work to twist a rope (provide torsion), to stretch a rubber band (provide tension), or bend wood. The potential energy is stored as elastic energy of a stretch (tension), bend, or twist (torsion).

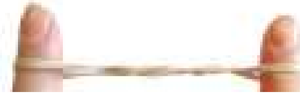
The material has to be elastic. Elastic materials are good at storing energy when they are reshaped, and releasing it when they return back to their natural shape. Think of stretching a rubber band. It gets long and skinny. Now let it go. It goes flying! Where did this kinetic energy of motion come from? It came originally from your muscles when you stretched it. Rubber, certain kinds of wood, steel, tendons, horns, and to some extent rope, are examples of elastic materials. Try bending a rock. If we apply enough force the rock will crack, not bend. Rock and glass are examples of non-elastic materials.

Stretch



Bend

Twist



Trebuchets:

Gravitational force is one kind of force that can be exerted even across empty space. Trebuchets take advantage of this kind of force. To prepare a trebuchet to launch a rock, it takes work to raise the arm with the massive counterweight against the acceleration of gravity. The force that we apply depends on the mass of the counterweight.

$$\text{force} = \text{mass} \times \text{acceleration}$$
$$f = m \times a \qquad (a = 9.8 \text{ meters / second}^2)$$

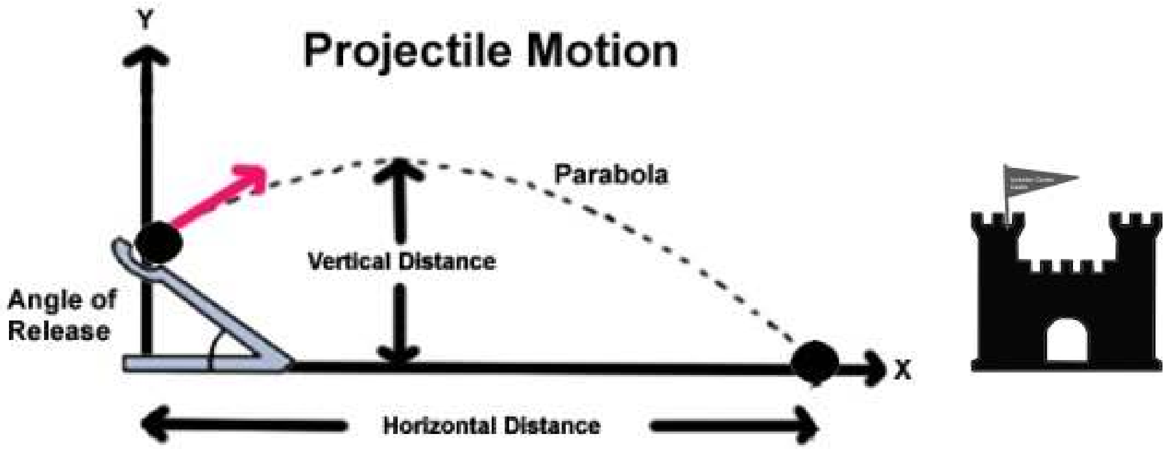
In either case, when the catapult or trebuchet is released, the potential energy is released as kinetic energy in the form of the motion of the rock. In this case the work that is performed is the crumbling of the castle wall. The more massive the rock and the faster it is moving, the more damage, or “work” is done on the wall.

What variables affect the trajectory of a projectile?

When designing a catapult or at trebuchet to throw an object, such as a large rock at a real castle wall or a small ball at our model castle in the Inventor Center, there are a lot of variables to consider.

Please see the Pre-Visit Activities for how to stimulate student thinking about what variables students should consider when building their catapults or trebuchets. See the Post-Visit Activities (for Grades 6-8 only) for a more complete exploration of projectile motion.

Let’s look at a typical trajectory of an object after it is thrown from a catapult or trebuchet with an initial velocity. Let’s suppose that it falls short of the target, the castle, as shown below:



This kind of motion is called projectile motion and follows some simple laws of physics, assuming no force other than gravity is acting on the object. (In other words, we assume that the air and the wind have no effect on the object.) The shape of the path, called a parabola, can be described with an equation. After the initial velocity has been applied, the object continues in motion by its own inertia. (Birds in flight do not follow the laws of projectile motion because birds are continually self-propelling themselves after take-off.)

What could we change about the catapult to make the object travel further? Variables are things that change. In an experiment (or in trying to get a projectile over a castle wall), an *independent variable* is the one which can be varied and controlled by the experimenter (attacker). The *dependent variable*, such as how far the object travels, depends on the independent variables.

In this case, independent variables include the amount of potential energy stored by the machine, the materials, the mass of the projectile, the angle of release, and (for a trebuchet) the relative distances of the counterweight and object from the fulcrum of the lever.

Potential energy

Storing more potential energy in the catapult will increase how far the projectile will travel. The higher the potential energy stored, the higher the kinetic energy of the projectile when released. How could we store more potential energy? There are many ways, such as winding a rubber band more tightly, or (for a trebuchet) increasing the mass of the counterweight.

Materials

Changing the materials that the catapult is made from will change how fast a projectile will be hurled through the air and therefor how far it will go.

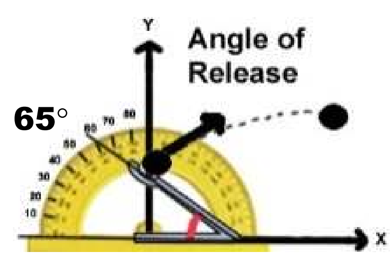
Mass of projectile

The mass of the projectile thrown by a catapult will change how far the projectile will be thrown before it falls to the ground. There is a trade-off between mass (m) and velocity (v) when a projectile is thrown by a catapult or trebuchet with a certain amount of kinetic energy (KE). The higher the mass of the projectile, the lower the velocity will be when it is released.

$$\text{Kinetic energy} = \tfrac{1}{2} \times \text{mass} \times \text{velocity}^2$$
$$KE = \tfrac{1}{2} \times m \times v^2$$

Angle of release

The angle that the projectile is launched at will change the trajectory and thus how far the projectile will travel. The angle of release can be measured by a protractor. An optimum angle is approximately 45 degrees.



Distance from fulcrum

For a trebuchet, the greater the distance of the projectile from the fulcrum, the higher the mechanical advantage will be, and the larger the distance the projectile will travel.

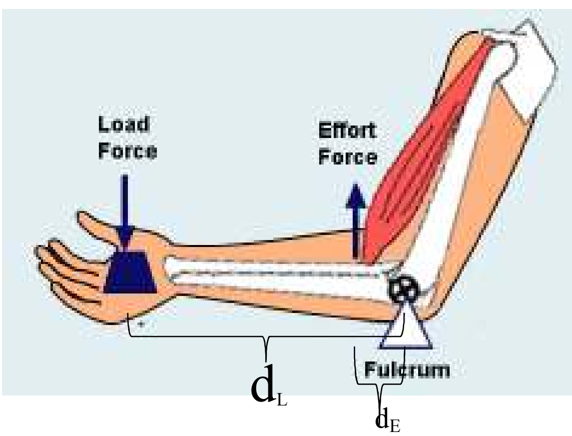
There are many other variables. Even less quantifiable factors such as skill can be considered variables.

Are trebuchets and catapults simple machines?

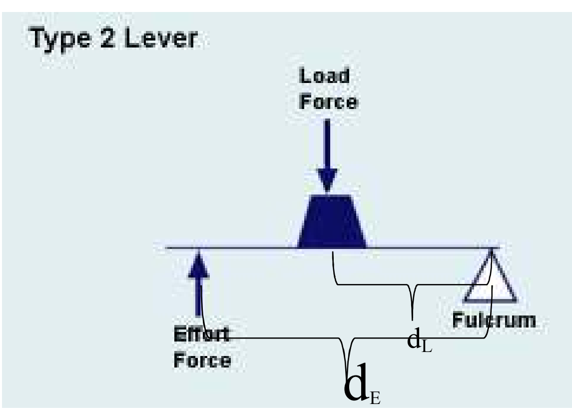
Some catapults and trebuchets, the ones that are very simple, are simple machines, devices that require the application of only one kind of force. Others, that contain more than one type of simple machine, are complex machines.

Catapults and trebuchets can be considered mechanical throwing arms. When we look carefully at a human arm we can see that it is an inverse Type 2 Lever, where the load and effort have been reversed. Likewise, an early trebuchet is an inverse Type 1 Lever, with the load and effort reversed.

Human Arm:
Inverse Type 2 Lever

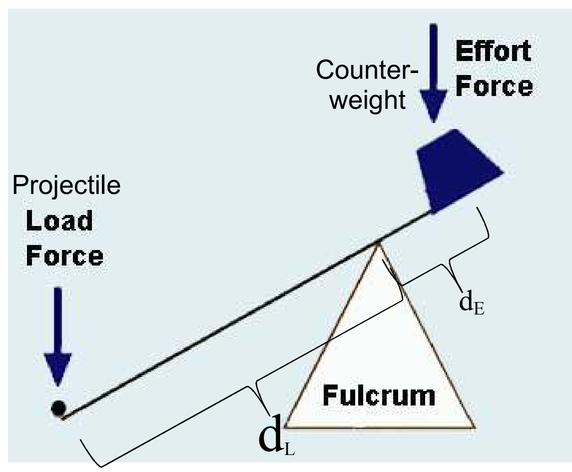


$$f_L \times d_L = f_E \times d_E$$

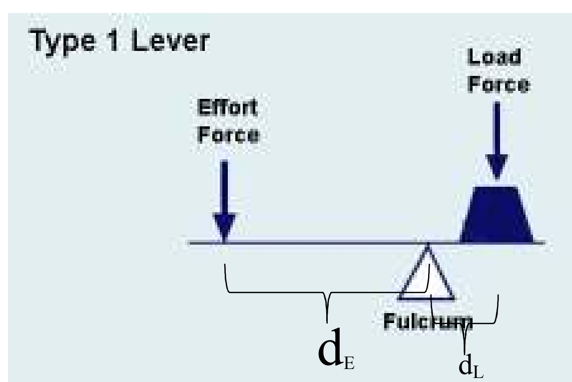


$$f_E \times d_E = f_L \times d_L$$

Simple Trebuchet:
Inverse Type 1 Lever



$$f_L \times d_L = f_E \times d_E$$



$$f_E \times d_E = f_L \times d_L$$

Work is equal to force times distance. The work put in on the effort side of the arm is always equal to the work done on the load side of the arm.

Effort (E)		Load (L)
work = force x distance		work = force x distance
w_E	=	w_L
f_E x d_E	=	f_L x d_L

Normally, our goal in using a lever is to decrease the amount of force that we need to apply on the effort side (f_E). We do this by increasing the distance that we apply this effort force (d_E) to, so that the product of (f_E x d_E) remains the same.

But in the case of a trebuchet, our goal is to increase the velocity of the object, or load, in other words to increase the distance (d_L) that the load will travel in a certain amount of time. In other words, the load must be placed on the long arm of the lever and the effort (the counterweight) on the short end, making the distance that the effort is applied (d_E) small. Therefore, the effort force (f_E) must be large so that the product (f_E x d_E) remains the same. In other words, an Inverse Type 1 Lever <u>increases</u> the force needed to do the work. But the sore muscles are worth it if the object is thrown faster.

The higher the ratio of the length of the projectile arm to the counterbalance arm, the greater the mechanical advantage and the faster the projectile will be thrown.

Most of the catapults and trebuchets over history were complex machines that became more and more complex over time. For example, wheels and axels were added to trebuchets so that when launched, the trebuchets could travel along a track rather than over-balancing themselves forward. Catapults often contained gears to apply maximum force to the elastic material attached to the arm.

MAKING THE MOST OF YOUR VISIT

Using This Guide

Before you visit, review the Essential Questions to see how the Inventor Center's educational themes connect with your curriculum. Identify what you would like your students to learn from the Inventor Center and how they could continue learning back in the classroom.

This Guide includes Activities for Before Your Visit, During Your Visit, and Back in the Classroom.