The Engineering Beauty of the Trebuchet
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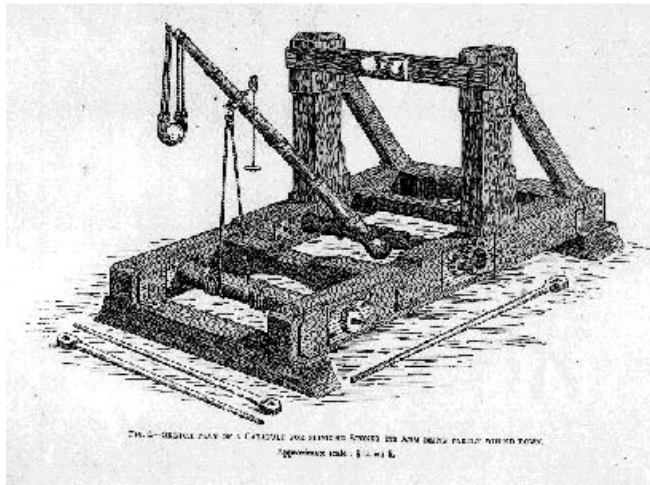
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Introduction

The word "trebuchet" sounds like something you would find on a menu in a fancy French restaurant. But this medieval weapon of mass destruction was certainly not edible. Trebuchets were used to break through castle walls from about 850-1350 C.E. Dead livestock or giant rocks were the usual ammunition, but sometimes prisoners of war or especially annoying people were added to the flying debris. Other launching devices similar to the trebuchet include the catapult and the ballista.

The catapult rolled into battle before the trebuchet was even invented, with reports that the Greeks and Romans used it around 350 C.E. The catapult had an arm with a large cup attached to the far end, where "missiles" were loaded and flung over the castle walls. However, the most successful catapults had slings attached to their throwing arms, which allowed the catapult to throw even farther.
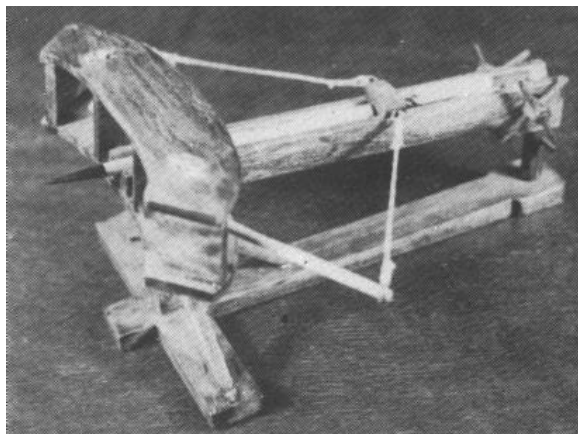

The catapult with a sling

Catapult without a sling

The ballista was akin to a very large crossbow and was used in warfare for shooting arrows and stones. The projectiles would be placed in a groove, and a windlass was turned until the string the arrow or stone was attached to stretched back. The workers could then release the projectile at any moment and watch as if flew hundreds of feet into an enemy's ranks.
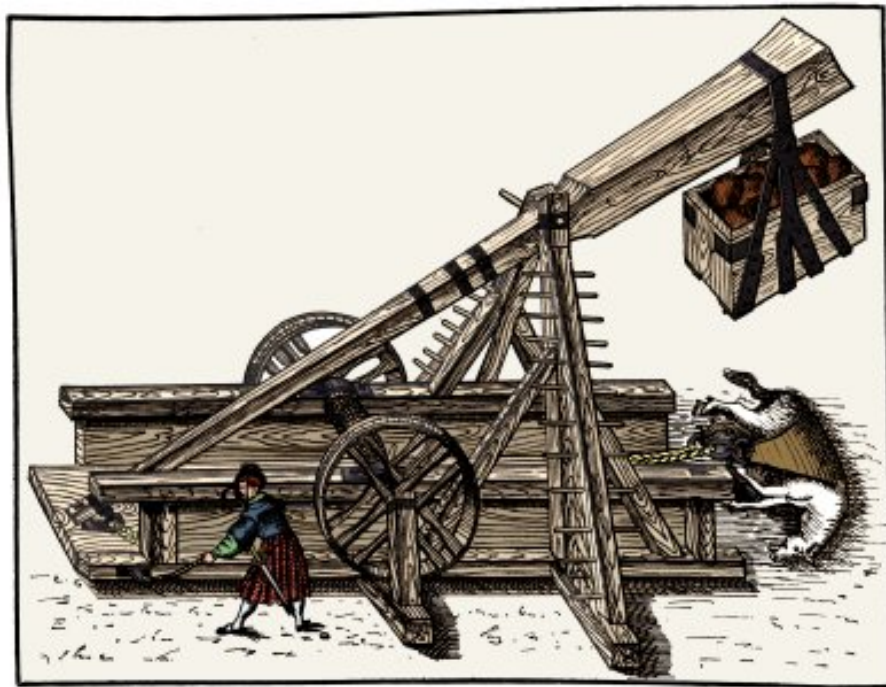

A loaded ballista

The Trebuchet

The trebuchet was the last of these ancient heavy artillery weapons to be introduced onto the battlegrounds in Medieval Europe. A trebuchet must be made with a sling; otherwise the object being launched would probably fall out and only

roll about two feet before stopping. The way the arm swings is the biggest

difference between the trebuchet and its relatives, the ballista and the catapult.

The wider end of the arm has a counterweight on in that when released causes the

tapered end to fly into the air dragging the sling behind it. The sling releases the

projectile into the air and the object flies away. Trebuchets are also most powerful

of the three launching machines.

The Trebuchet about to throw a dead horse

The trebuchet that our Honors Physics class has built has a 16-foot throwing

arm and is designed to accept up to 500 pounds in its counterweight. One of our

greatest concerns is that there will be torque pressure on the rotating axle, which

could snap it in half. Fortunately, we've a 65 pound steel axle that should be able

to stand this torque.

Of course, there's always the fact that working with 500 pounds of counterweight can always conjure up problems of its own.

Catapults come in a wide range of strengths and sizes, varying from a small slingshot with a rubber band, to a 300-foot long aircraft launcher. During the medieval ages, the catapult was used to attack fortresses and cities. Due to its capability of launching a projectile such a long distance, it was also a very effective defensive device. The three most common types of catapults that were used during the medieval ages were the ballista, mangonel, and the trebuchet.

The ballista and the mangonel launch their projectiles from the torsion that is created by twisting ropes. The design of the crossbow is very similar to that of the ballista. The Roman mangonel design uses twisted ropes stretched horizontally. A lever arm with a scoop at the end is inserted into the center of the ropes. The projectile object is placed inside of the scoop while the lever arm is pulled back against the force of the ropes. As the arm is released, it flings forward and hits a wooden barrier thus causing the projectile to fly forward at the enemy. It was a very effective design, capable of launching 50-60 pound stones and destroying towers and castle walls. A particular flaw in the design of the mangonel was that it wasted a large amount of energy upon impact with the wooden barrier.

The French eventually introduced the near flawless design of the trebuchet in the twelfth century. Unlike the previous catapults, the trebuchet relies on the terrestrial gravitation from the counterweight to provide the force rather than using torsion obtained from twisted cordage. The counterweight hangs at one end

of the beam, opposite of the sling. The sling is pulled towards the ground while

the counterweight is raised at the opposite end of the beam. As the sling is

released, the counterweight quickly falls towards the ground, flinging the

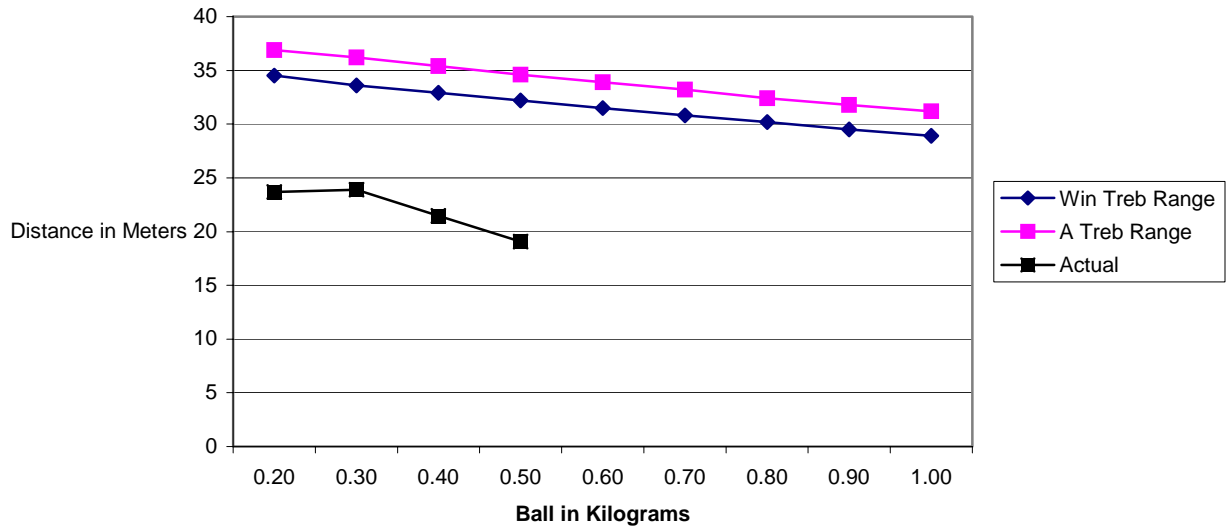projectile and wasting much less energy than the designs of earlier catapults.

The trebuchet superseded the previous siege engines for many reasons. It

was far more efficient than any other design of its time and wasted very little

energy. The problem with earlier catapults was the difficulty that the operators

faced when the situation called for accuracy. The trebuchet was consistent and

easier to customize because the distance that the projectile would be thrown

depended on the weight of the counterpoise. The Roman mangonel could throw

50-60 pound stones but a large trebuchet was capable of throwing a 300 pound

projectile over 300 yards. During the years of the plague, armies would use the

trebuchet to launch diseased bodies over the enemy's castle walls. People would

often dig large ditches around their castles to prevent besiegers from scaling

ladders to the walls. Besiegers would solve this problem by launching barrels

filled with dirt to fill the ditches, allowing them to pass over the ditch and access

the castle.
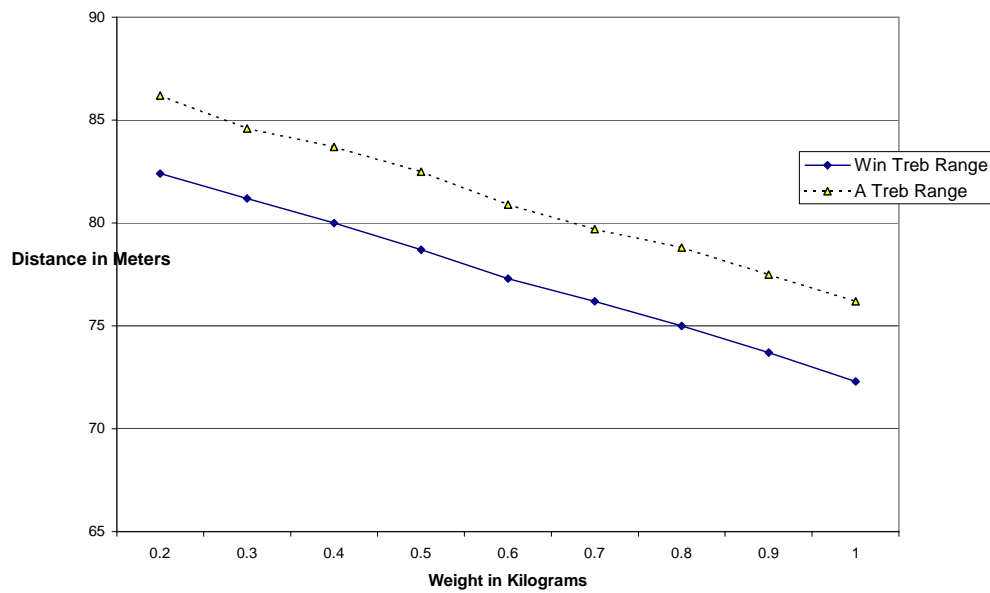
Math Simulations and Actual Data Collection

We have collected data from two mathematical trebuchet simulators, A Treb

and Win Treb. While the results from the two simulations are different from each

other most of the time they are consistent and proportional with each other. (We

will finishing the testing the trebuchet and compare all of its results to that of the

simulations as of April 15, 2004. The following charts reflect the partially
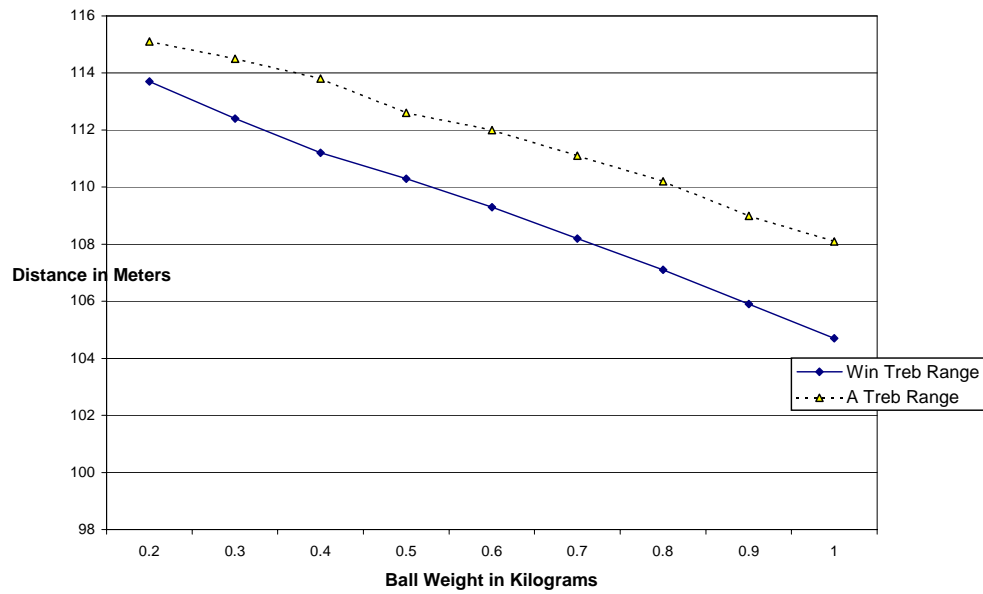
completed testing.)

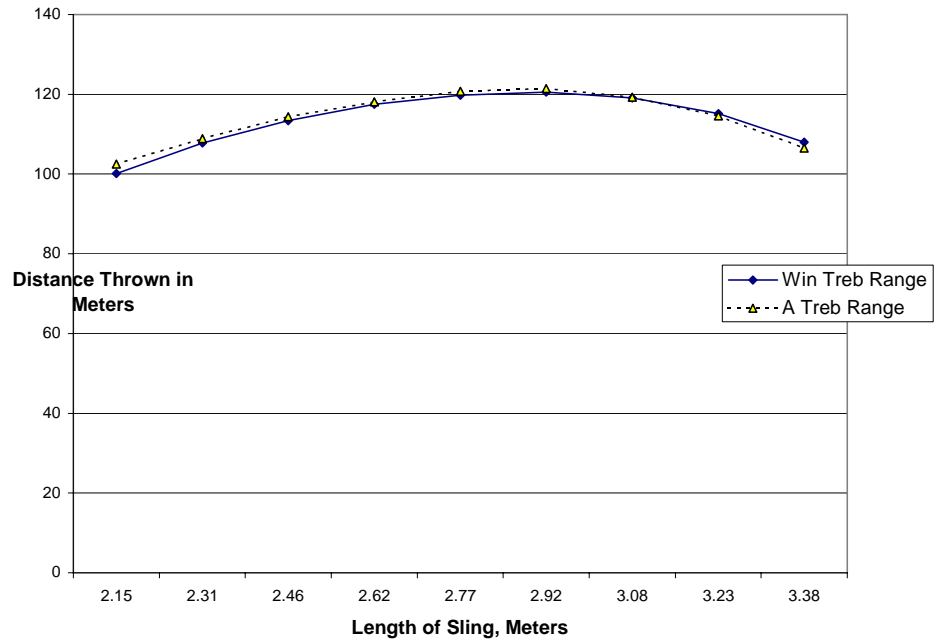**Math Models Versus Actual Distance Thrown, 77.3 Kilogram Counterweight**

Range and Altitude Thrown as Ball Weight Increases, 152.7 Kilogram Counterweight

Range and Altitude Thrown as Ball Weight Increases, 228.2 Kilogram Counterweight

Range and Altitude Thrown, 228.2 Kilogram Counterweight and 0.25 Kilogram Ball

A number of simulations were done with the following variables and produced elegant curves or straight lines in the resulting charts.

Length of the short side of the throwing arm

Length of the long side of the throwing arm

Length of the sling for throwing a water balloon

Height of the support columns

Distance from the throwing arm to the counterweight

Weight of the counterweight

Weight of the balloon being thrown

Both the Win Treb and A Treb simulations showed that the length of the sling was a major variable that we could manipulate during construction of the trebuchet. The A Treb simulation separately identified the angle of the release pin as being a significant variable.

Construction of the Trebuchet

We started our construction with making the "throwing arm." This is by far the most critical part of the trebuchet, because it is the piece that holds the concrete, and is thus burdened with the most weight. Seeing as how it is the most crucial part it is also the part that takes the longest to build. It was decided that we would use three 2 by 9 beams that were sixteen feet long, to create one big beam. In order to keep these from coming apart, we used seven 9-½, and as a backup, we used gorilla glue.

We used the same method of bolts and glue for the ten-foot side supports. Our research told us that the perfect throwing arm would weigh nothing, but that seemed impossible to us. We decided that like 60% of America, our beam needed to loose weight, although the Atkins diet wouldn't work for this particular cut back. So, we decided to pull out the saw and cut off two sections on each side of the beam. This resulted in the loss of 60 pounds. Not only does a lighter beam have increased efficiency, but it's a lot easier to carry as well.

After we finished with the beam, we began work on the box that would have the job of holding 1,200 pounds of concrete. In my opinion this would be the worst of the jobs to have. When building, we used 24-inch 2 by 4's, and then covered the bottom of the box with a square piece of plywood. This would hold the 50-pound square blocks of cement that were stacked inside of the box to give us the total weight of 1,000 pounds. We figured that this would be the precise weight that we would need to through the seventh out of the school.

Next the box was attached to the throwing arm with a 2 by 36 inch metal pipe. This pipe runs through a hole at the end of the throwing arm, and is glued in place. To connect it to the box, we used pipe sleeves that could slide on and off

the pipe. Through these pipe sleeves we ran ½ inch cables that were then tied around the box. This design is much related to a harness that you might put on a dog.

For the base of the trebuchet we used sixteen 2 by 4's that were eight feet long, and made two boxes that would then be able to fit together to make 16 feet. We decided that the width of the base would be 30 inches, because this would be wide enough to support the beam. After the base was constructed, the top was covered with plywood so that our sling would be able to slide off of it during launches.

While constructing our fabulous marvel of technology, there were a few things that we had to keep in mind. Altogether, our wondrous piece of work weighs about 1,700 pounds, so it would be preposterous to dream of trying to have seven teenagers lift it by themselves. The trebuchet had to be able to break down into separate pieces so that each lighter section could be carted to different places, and then reconstructed at its destination. Also, the trebuchet would be holding 1,000 pounds of weight, so the supports and beams had to be extremely strong. With these ideas in mind, many of our designs had to change. For example, we constructed the base so that it could break into two pieces. The throwing arm is able to slide on and off the axle, both side supports can be moved separately, and the bucket can slide off the axle that it's on. This will be crucial in the process of moving it.

The most precarious part of the trebuchet was the pivoting axle of the arm. This runs through both side supports and the throwing arm. When designing, we

were trying to figure out what size axle would be big enough and strong enough to hold 1,300 pounds. It was thought that a 2-inch thick pipe would be able to hold the weight. However, after we ran some calculations, we discovered that the weight immobile would weigh about 1,300 pounds; but that same weight in movement would create about 3 tons of weight. This led us to one conclusion: "we're going to need a thicker pipe." Little did we know the pipe that our teacher ordered was 4 inches thick and weighed about 100 pounds. So once again our previous ideas were forced to change.

We slid the axle through two holes that were cut into the side supports, and, because we knew that the trebuchet would be more efficient if the axle stayed still, we wanted to glued one end of it into one of the support beams, but for the sake of the poor people who would have to carry it we didn't glue it in place. Next, we made a metal sleeve that fit perfectly over the axle, allowing both sleeve and throwing arm to rotate around the axle during launch. When we used the trebuchet we put grease around the axle to minimize friction.

When you have a structure that is close to 25 ft tall it is pretty hard to take just one step back to look at the bigger picture so, we looked at a miniature model of our trebuchet; we noticed that it swayed from side to side a lot. Because of this, we decided to add side braces that resemble the flying buttresses in older buildings. Along with the side braces, there are diagonal braces running from the vertical support to the base. They are critical in making sure that the swinging weight doesn't make the vertical supports fall over.

Many trebuchets at the end of the throwing arm have one release pin, which is straight out, however our research told us that it is good to have more than one pin, all at different angles. The way that the release pin works is when the arm begins to swing the sling is beginning to be thrown, however once it the end of the arm reaches a certain point the inertia pulls the loop off the pin. With different angled pins the release point will change. So one pin will make it fire more vertical than horizontal, whereas the other one will do the opposite.

Using one of our simulation programs we determined that the perfect launch item would weigh 2 pounds. Unfortunately it is very hard to find a 2-pound metal ball, so we have decided to improvise. The only thing we could find where we could change the weight freely was a water balloon. The problem with water balloons is that they change shape as they are being flung. This makes them much less aerodynamic, so we decided to freeze them so that they would keep their shape. While we were thinking about the freeze processes, we decided that it would be helpful if we could somehow get the balloon to leave a trail in the air. The solution that we came up will was liquid nitrogen. If we dipped the balloons in the nitrogen right before we shot them, they should hypothetically leave a trail.

Two Construction Flaws

The trebuchet was built in modular sections. The base was built as one module and the support columns built as a second module. The throwing arm was built as a third module while the counterweight box was built as a forth module. A major construction flow resulted in the third and fourth modules.

The support axle was built to have a minimum length in order to reduce the amount of stress on placed on it from the throwing arm and counterweight.

The concern was that the axle could bend under the combined weight if it was very long. The axle had an overall length of 24 inches after construction and an effective gap of 15 inches after being placed on the two support columns.

The box for the concrete blocks was constructed to be 24 inches on a side in order to hold 40 pound concrete blocks that measured 12 inches by 12 inches on a side. The concrete blocks then were to be placed in two parallel rows and easily added or removed. It was only when the modules were being assembled that we realized that the 24 inch wide box would not be able to swing freely between the 15 inch gap of the two support columns.

The two support columns therefore were modified to spread on diagonals rather than remain vertical. The box was rebuilt of steel with three high density concrete blocks used for the counterweights. Each high density concrete block weighs 166 pounds and requires two people to lift into position—difficult but possible. The result was a box that was 13 inches on a side and gap of 24 inches at the base of the support columns.

The second flaw occurred with the throwing arm. The throwing arm had been tapered in order to reduce its weight. However the taper (see drawing page 10) introduced a failure point at the angle of the taper. Although we modified the taper to reduce the possibility of failure at this point, we were not successful. The tapered throwing arm broke catastrophically on the second throw of a frozen water balloon and when the counterweight had a weight of only 350 pounds.

A replacement throwing arm therefore has been built without a taper in it. This new throwing arm has worked successfully for the initial test throws.

However the arm now weighs 136 pounds. A significant amount of weight in the counterweight now must be used to overcome the weight of the arm rather than contributing energy to the water balloon being thrown.

Results

A functional trebuchet has now been made with significant engineering lessons in the construction of a massive machine. A careful set of complete drawings should have been used instead of proceeding with separate modules. However only experience could tell us if the tapered beam would withstand the anticipated load.

The initial actual data for thrown water balloons shows that both the A Treb and Win Treb math simulations significantly over estimate how far a water balloon may be thrown. This may be due to the following factors. The axle turns inside a circular sleeve. This sleeve has not yet been greased and so a significant amount friction may be created while the throwing arm is moving. A part of the energy from the counterweight therefore may be lost to friction.

Second, the release pin presently is set at 0 degrees to the horizontal. The documentation for the A Treb math simulation model states the angle of the pin will have a major impact on the distance thrown. A downward angle of about 50 degrees may result in a significant increase in the distance thrown horizontally. The water balloons presently are being thrown in a high parabolic curve. A changed pin angle may result a shallower curve but with greater distance.

Trebuchet Mathematics

Newton's second law of motion states that force equals mass times acceleration. For the trebuchet, because the forces operate on curves, the equation is a little different. The equation for the acceleration is: $F * r = Ia$ and the acceleration is actually angular acceleration, to account for the curves. The I in the equation is the moment of inertia or. $I=\sum mr^2$. The moment of inertia is conceptually found by cutting the acceleration of the mass into all of its infinite moments or points and find the mass of each point times the distance from the center squared then add each of the infinite accelerations to find the inertia, hence $I=\sum *m*r^2$.

The basic motions and forces of the trebuchet are divided into three parts: the thrown weight, the throwing arm, and the counterweight. Due to these three basic components, the calculations for the inertia of the trebuchet can be significantly simplified and broken up into component equations. The throwing arm is a beam with a set mass per meter *m* and a certain length *l*. The pivot too is a factor and is calculated in terms of its distance in meters *h* from the center of gravity of the throwing arm. Assuming that both the counterweight and the projectile weight are both focused at exact points at the end of the arm on each of their respective sides, the equation for the inertia for the arm with the mentioned variables is:

$$I=ml^2/12+mh^2$$

The simple equation for the inertia of the projectile is:

$$I_{projectile}=m*l\text{\textasciicircum}2$$

Where I is the overall inertia of the projectile, m is the mass of the projectile, and l is the length of the projectile arm. Or stated more simply, the inertia of the projectile as an isolated system is equal to the mass of the projectile multiplied by the length of the projectile arm or that section of the throwing arm which is directly applying force to the projectile.

The equation for the inertia of the counterweight is as follows:

$$I_{counterweight}=m*l\text{\textasciicircum}2$$

As can be seen, the equation for the inertia of the counterweight as an isolated system is almost exactly the same as the earlier equation through which the inertia of the projectile may be found. The sole difference being that it is in terms of the counterweight and not the projectile.

Finally, in order to calculate the inertia of he entire trebuchet, and thus be able to use the principle of motion, $F*R=Ia$, the three inertias are combined. All forces acting on the trebuchet are pulling down. Trebuchets are engines of war that utilize gravity as their power. Though all forces acting on the trebuchet, assuming the trebuchet is an isolated system as a whole, are pulling downward, the forces can be divided into roughly two categories, the forces that are perpendicular to the throwing arm and those forces that are parallel to the throwing arm. For the purposes of this essay, we are assuming that friction has no effect. Only the perpendicular forces have a readily noticeable effect, as they are the ones that pull on the counterweight arm and force it downward in a circle. The

parallel forces are attempting to push the trebuchet over lengthwise, and as such, are not of any use in throwing the projectile. The fulcrum of the trebuchet serves to transmit all of these forces throughout the trebuchet, countering the parallel forces and transferring the perpendicular forces, rather like a force filter.

The equation for the perpendicular force is:

$$F\perp = F\sin\theta$$

Where angle θ is the angle of the fulcrum to the counterweight arm.

The strength of the perpendicular force depends on the distance from the point of application to the center of the fulcrum, or the radius of the circle described by the trebuchet arm. Thus, the perpendicular force utilizes torque to multiply the force of the counterweight.

In the original acceleration equation, *F*R* may now be replaced by *F*r*sinθ* or *F⊥*r*. Thus the acceleration of the trebuchet is directly related to not only the mass of the counterweight and the projectile, but also to the angle of the throwing arm in terms of the fulcrum. Once the angle gets to 90, the force peaks and all angles there after have increasingly less force, because at 90 degrees the counterweight is exactly perpendicular with the ground and gravity will no longer be supplying the force at any larger angle. This is because at 90 degrees the counterweight is as close to the ground as it is going to get or as close as gravity is trying to make it.

The final and much simpler equation for acceleration is:

$$F*r = F*r*sin\theta$$

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