

## DIY Science Catapult

How can making a catapult help you prove something that it took mankind millennia to work out? Look at the science behind siege engines in the DIY Catapult!

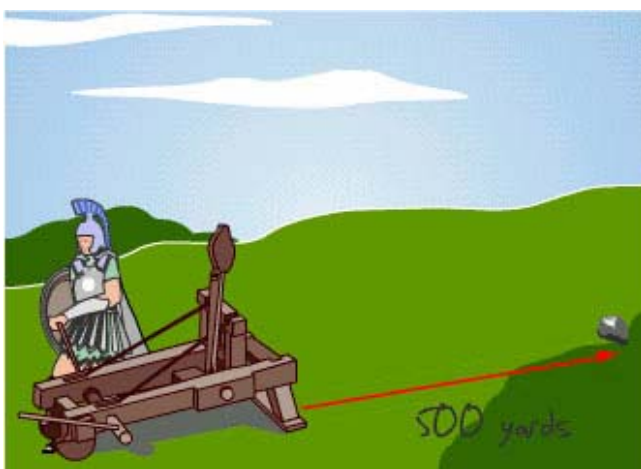
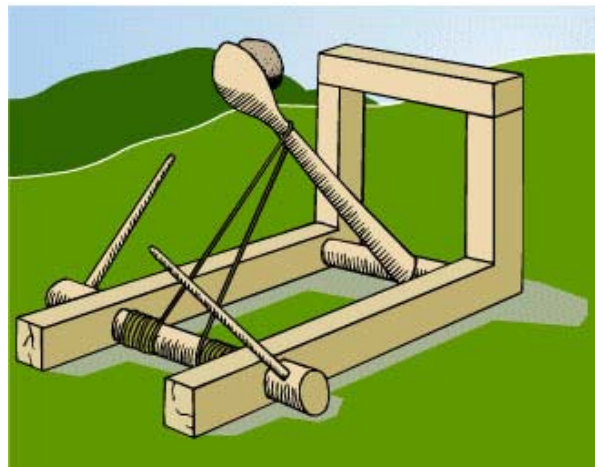
### Historical Overview On War Machines and Mangonels



One of the problems with warfare throughout history was that enemies had the annoying habit of hiding behind fortifications. The solution: to find a way of beating down, piercing or otherwise destroying part of the wall so as to gain entry. Alternatively, it was equally important to be able to keep others intent on destroying your walls at bay. Enter the one-armed throwing engine.

#### What's a Mangonel?

The Greeks c200 BC referred to these one-armed machines as among numerous devices that could be used by the defence against a besieger's machinery. People from the Mediterranean to the China Sea developed war machines that operated using the elasticity of various materials. The term **catapult** is used to describe all of the different types of throwing machines. What you and I know as a catapult is actually a **mangonel**, otherwise known as an **onager**. Onager was the slang term derived from the Greek name for 'wild donkey'. This referred to the way the machine 'kicks' when it's fired. The correct term for the machine is mangonel - derived from the ancient Greek term "manganon" meaning "engine of war".



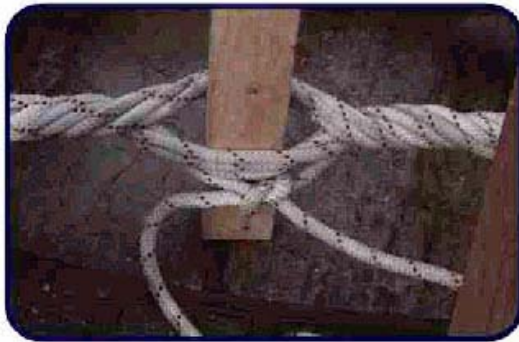
lighter version of the mangonel was thought to weigh about 1000 pounds and would have been able to hurl a 3-4 pound stone about 100 yards. Heavier machines would have been able to throw stones even

#### Historical Evidence

There is very little archaeological or historical evidence on the mangonel. However, the Roman, Ammianus, does describe one in his writings, but the proportions of the machine are unknown. There remain some medieval illustrations of the machines and some speculative drawings from the 18th and 19th centuries. However, it is believed that in late antiquity and the early Middle Ages the most commonly used stone-throwing engine was the heavy onager (mangonel). This war machine was thought to weigh approximately two tons and hurled an eight-pound stone some 500 yards. The

further, but were impractical as they were difficult to transport, and when used were assembled on the battlefield.

### How it Works

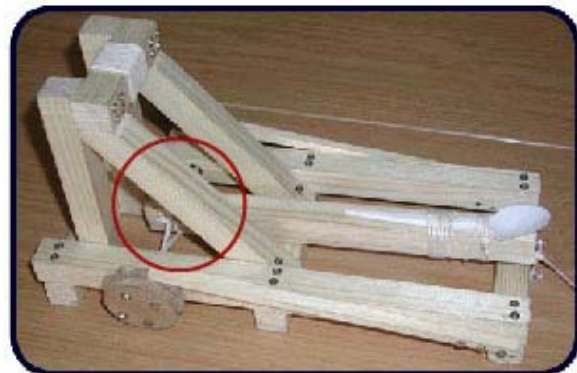


The mangonel uses a bundle of twisted ropes (known as the skein) to create torsion and is, therefore, known as a torsion engine. In antiquity these ropes would have been made from either horse hair or human hair, as they provide the best tensile strength in a fibre. The ropes are strung across a frame, and in the middle of the twisted cords the wooden throwing arm is inserted upright. In some versions, a sling is attached to the end of the arm. Many ancient drawings depict the mangonel as having a bucket or cup at the end

of the throwing arm, and this is the version most commonly depicted in Hollywood movies. This, however, is not the best way of throwing a rock - in fact, a sling is much more effective. This arm is lowered and secured, using the strength of between four and eight men, depending on the size of the machine. The missile could then be loaded into the sling.

### Fire!

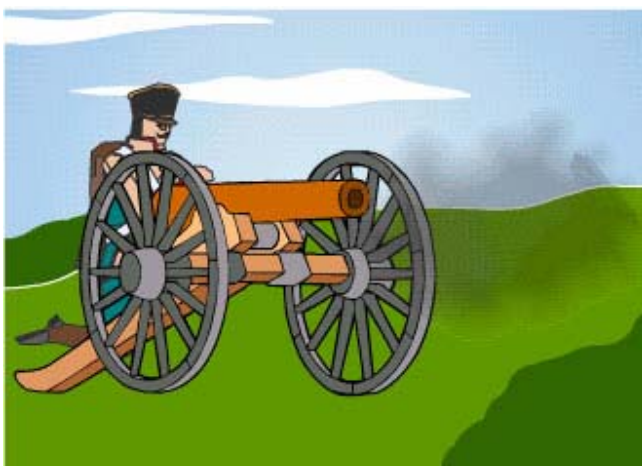
In lowering the arm, energy is stored in the rope, and when released, the arm is flung forwards. The force contained in the skein is at its greatest when the arm first starts to move, and at its least when it hits a padded buffer, which acts as a stopper. This allows the missile to leave the sling at maximum speed before halting. The sling detaches from its hook before the arm hits the stopper, at a point dependent on the length of the strings holding the sling. Adjusting the length of the string is how trajectory could be altered so accurately.



### Trébuchets

The period 1180-1220 saw further developments in one-armed throwing machines, with the development of machines that used fixed or mobile counterweights. These trabuceta (in French they are called trébuchets) were operated by 50 men, with up to a ten-ton counterweight and were capable of throwing a stone of 100-150kg about 150 metres. Even in the most favourable conditions a mangonel could only throw a stone of 20-30kg about 225 metres.

### An Age Ends



The age of the siege engine came to an end with the increasing use of explosives. Gunpowder was first developed in China, and migrated to Europe through the Muslim world. The first mention of the formula for gunpowder occurs in a Chinese work of 1044. In the West the first known recipe for gunpowder was that of Roger Bacon in 1267. From the middle of the 13th Century the Moors were known to use gunpowder in missiles thrown by catapults or trébuchets. The development of the cannon inevitably saw the end of the war machine, but trébuchets were still considered an essential part of siege

strategy well into the 15<sup>th</sup> Century.

## **LINKS**

<http://www.trebuchet.com/plans.html>

Projectile motion

<http://www.xs4all.nl/~mdgsoft/catapult/ballistics.html>

Make your own

<http://www.xs4all.nl/~mdgsoft/catapult/onager2.html>

Onager simulator

<http://www.xs4all.nl/~mdgsoft/catapult/sim/index.htm>

Medieval Mangonel

<http://members.iinet.net.au/~rmine/middel5.html#mangon>

How Stuff Works

<http://www.howstuffworks.com/question127.htm>

Trajectory

<http://id.mind.net/~zona/mstm/physics/mechanics/curvedMotion/projectileMotion/generalSolution/generalSolution.html>

The Virtual Trébuchet

<http://heim.ifi.uio.no/~oddharry/blide/vtreb.html>

## **OU COURSE LINKS**

S103 Discovering Science

[http://www3.open.ac.uk/courses/bin/p12.dll?C02S103\\_science](http://www3.open.ac.uk/courses/bin/p12.dll?C02S103_science)

S207 The Physical World

[http://www3.open.ac.uk/courses/bin/p12.dll?C02S207\\_science](http://www3.open.ac.uk/courses/bin/p12.dll?C02S207_science)

## How to make a Catapult



### Disclaimer - Please Read

A catapult/mangonel is a weapon. Please exercise caution when firing this model. This is a working scale model. To the extent permitted by law, the BBC, Open University and its employees or agents accept no liability or responsibility whatsoever for any loss, damage or injury arising from the use or misuse of the catapult/mangonel.

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### Parts list

Strip wood (approx. 2.08metres)	20mm x 20mm (2cm square) Lengths: 125mm x 4 150mm x 2 175mm x 2 300mm x 3
Strip wood	10mm x 10mm x 250mm long x 2
Plywood (or MDF)	50mm x 50mm x 6mm thick x 2
Plywood (or MDF)	40mm x 40mm x 6mm thick x 2
String	2.5mm diameter N.B. this must be non-elastic
Rounded Steel	3mm diameter Lengths: 18mm x 2
Screws	Wood screws, 3mm wide x 35mm long Chipboard Screws 3mm wide x 1.5mm long
Washers	2 x washers 17.5mm wide with an 8mm hole
Nails	A single oval nail about 20mm long N.B. the nail must not have a flat head

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### Tools required

General woodworking tools  
Electric drill (we used a 2mm drill bit)  
Jigsaw or coping saw  
10mm holesaw and drill fitting  
Work bench with vice  
G-clamps

Wood glue  
Breathing mask (if using MDF)

## Making the frame

1. Take two of the 20mm x 300mm pieces of strip wood and two 20mm x 125mm. Create a rectangular base. Check that the corners of the base are square (90 degrees). Put two 35mm wood screws and glue into each joint.
2. Fix the two 20mm x 150mm pieces of strip wood vertically inside one end of the rectangular base. Make sure the short 125mm pieces are at the bottom. Glue and screw, using 4 screws in each end of the upright.
3. Attach a 20mm x 125mm piece across the top of the uprights, on the side facing into the middle of the rectangle. Trim the ends.

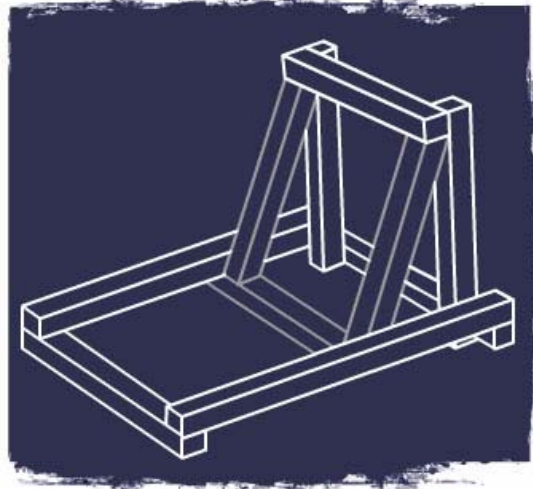


DIAGRAM 2

4. Measure 100mm down from the uprights, along the long edges of the rectangle. Fix the last 125mm piece of wood to the bottom of the rectangle at this point, making sure that it is parallel to the others.

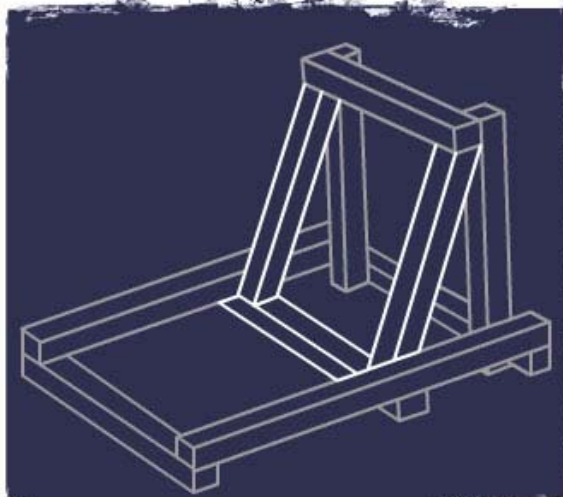


DIAGRAM 2

Measure and cut the two 20mm x 175mm pieces of strip wood so that they fit diagonally from the top of the uprights, as illustrated. Cut angles on the ends - don't worry if they don't fit perfectly.

## Making the ratchet

The ratchet mechanism can be made from 6mm plywood or MDF. Cutting MDF with a jigsaw produces toxic dust and should only be carried out in a well ventilated area and wearing a breathing mask.

1. Take one of the 50mm square pieces of 6mm thick plywood, draw a 50mm diameter circle. Using the same circle centre, mark on a 40mm diameter circle. Divide your circle up into eight pie sections by drawing 4 lines directly through the circle centre. Each line should be 45° from the next. Now draw smooth curves from the points where the straight lines meet the outer circle to the adjacent intersection on the inner circle (see *diagram 3*).
2. Carefully cut out the ratchet using a jigsaw (or coping saw) using a long wood blade.
3. Drill a hole through the centre of the ratchet using a 10mm holesaw.
4. Use the jigsaw to cut two small chunks of wood, 4mm deep and 4mm wide out of the centre of the

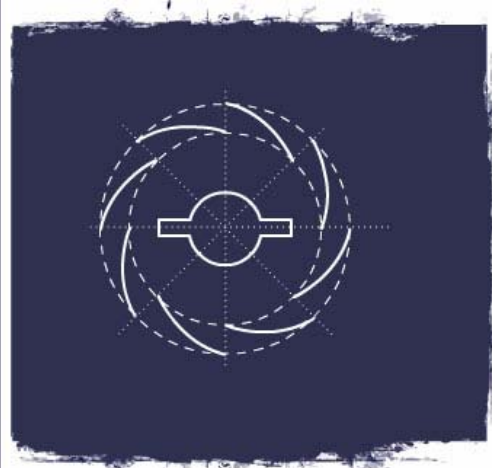


DIAGRAM 3

ratchet (see *diagram 3*). Make sure that the two chunks line up and are opposite each other.

5. Take one of the 40mm square pieces of 6mm thick plywood and mark onto it a 40mm diameter circle. Cut out the circle.

Repeat steps 1 to 5 to make a second ratchet.

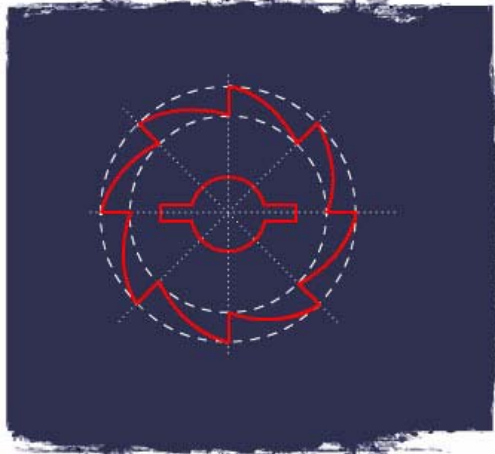


DIAGRAM 3

### Assembling the throwing arm

1. Make sure that the glue has properly dried on the catapult. Mark holes 28mm along the long arm of the base rectangle, measured from the inside edge of the uprights. To ensure correct positioning, put the remaining 300mm piece of strip wood vertically, inside the rectangle and touching the cross piece of

the two uprights. The holes should be in line with the centre of this vertical post (see *diagram 1*).

2. Use a 10mm holesaw to drill the holes. You may need to drill from both sides of the upright to cut all the way through the timber.
3. Take the string and feed it through the centre of a ratchet on one side, through one of the washers, through one of the holes in the frame, to one side of the loose, vertical throwing arm – and then through the hole on the other side of the frame, through one of the washers and through the centre of the second ratchet. Loop the string around one of the 18mm steel bars and then feed it all the way back to the other side of the frame, this time passing to the other side of the vertical piece of wood. Make sure you loop the string around the other short

metal bar. See *diagram 4* for correct positioning of the ratchet. Continue until you have a total of four strands on either side of the vertical post. Pull the string tight and tie off using a reef knot. Arrange the string so that the knot is inside the main frame, between the two ratchets.

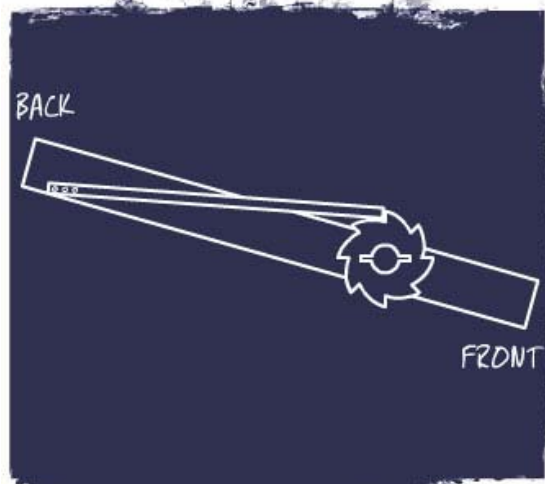


DIAGRAM 4

4. Fix a length of 10mm x 10mm x 250mm strip wood along the side of the main frame (see *diagram 1 and 4*). Only fix at the far end so that it can flex up and down as the ratchet turns. The end of the timber should lock into the ratchet and stop it moving backwards, but bends up when the ratchet turns forwards.
5. Use wood screws to fix the two 40mm diameter circles to the centres of the ratchets. This will completely cover up the ends of the rope and the short metal bars. Don't use glue, so you can adjust later.
6. Wrap string around the middle of the crossbar fixed to the vertical posts. This string will provide impact resistance to the throwing arm.
7. Adjust the throwing arm until it is in the middle of the crossbar, then twist each ratchet a couple of turns. This will twist the strands of string and hold the vertical post in place. Try to put the same amount of twist onto each side of the string.
8. Carefully pull the throwing arm back and down to the base. Mark where the throwing arm crosses the rear of the catapult base and cut the throwing arm to length.

### The firing mechanism and tensioning

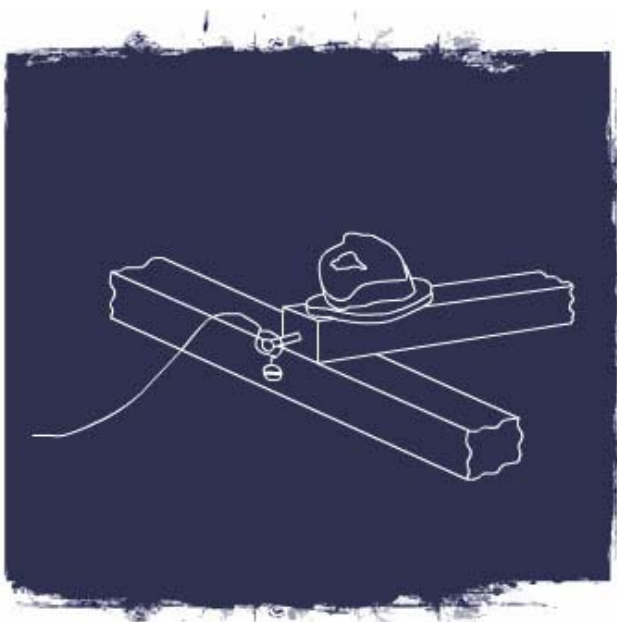


DIAGRAM 5

1. Hammer a single, oval headed nail into the end of the throwing arm. Leave 5mm protruding.
2. Below the nail, in the cross piece of the frame, put a screw.
3. Tie one end of the string to the screw and make a loop in the string about 5mm along from this end (see *diagram 5*)
4. You are now ready to tension the catapult and prepare for firing.

5. To tension the catapult - put a quarter turn into each ratchet - in turn.
6. Keep tensioning until it becomes hard to pull the throwing arm down to the catapult base.
7. Take the catapult to a wide open area and make sure that you can see all of the possible firing arc (180 degrees across and 5 metres long).
8. Pull the throwing arm back and hook the loop of string onto the oval nail.
9. Tug the string to fire. You will need to build a small launching platform onto the end of the firing arm, or alternatively tie a spoon on the end. The angle of the launch platform will determine the trajectory of the missile.

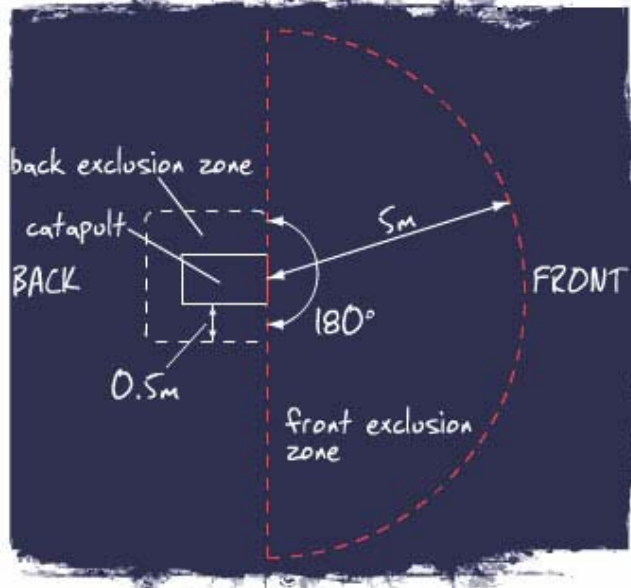


DIAGRAM 6

Have fun making the catapult and take care when firing it. May your aim be true...

### **Important Safety Advice**

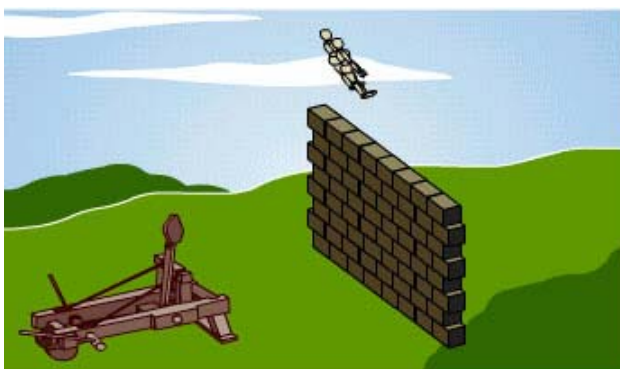
- Do not over tension the catapult. You should be able to move the throwing arm by hand. If you see any distortion of the frame slacken the string and strengthen the frame.
- Once the catapult's throwing arm is in the firing position beware – the weapon is cocked and ready to fire.

Once the catapult is loaded, keep half a metre clear of the back of the device and at least 5m clear of the front firing arc. Assume that the firing arc is 180 degrees across (see *diagram 6*).

## Science

### Men as Missiles

A catapult or mangonel is a weapon, and is quite dangerous. The science as described in this section is intended to be a theoretical introduction to the physics involved. Under no circumstances should anyone attempt to use a catapult to fly over a castle wall. Do not try it at home!



Would it be possible to fling two men over a castle wall using a mangonel? The first thing we should consider is historical accuracy. Very few pictures of mangonels exist, so even though we may build one that appears to work, there is no guarantee that it bears any resemblance to one used in antiquity. That said, let's take a look at the science - is it in the realm of possibility?

In order to minimise the risk to life and limb, rather than flinging ourselves out of a catapult, we'll look at the movie *Robin Hood*, starring Kevin Costner and Morgan Freeman, where the two protagonists appear to be successful in doing just this.

We need to calculate the *force* that the mangonel is exerting, to find out if the machine is capable of flinging two men over a castle wall. To do this we need to work out their *take-off speed*, so we can work out how fast the mangonel's arm *accelerates*, which, in turn, will allow us to calculate its force. At the beginning we can estimate that the two men weigh about 90 kg each, and we can see from the movie that the catapult's arm is about two metres long.

#### *Force*

The force of an object is determined by its mass multiplied by its acceleration. Force is measured in Newtons (N).

#### *Take-off speed*

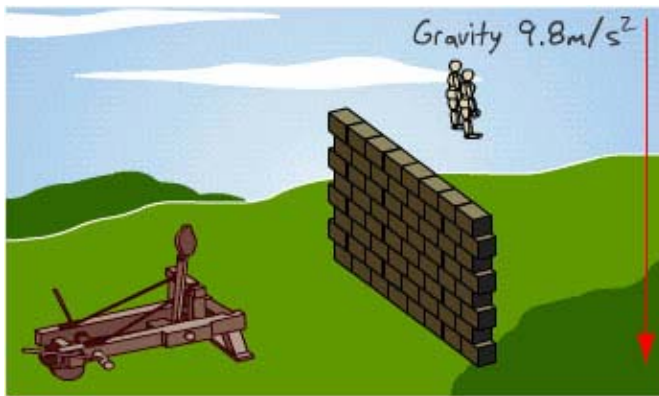
The velocity of an object is the measure of its speed, defined as the distance travelled over a set period of time. Velocity is measured in metres per second. (m/s). The difference between velocity and speed is that velocity can be expressed as a negative numerical value, whereas you can't get negative speed.

#### *Acceleration*

Acceleration of an object describes changes in its velocity. Acceleration is measured in metres per second (m/s).

The force comes from energy stored in the twisted rope, which is very strong and slightly elastic. When you twist it, it stretches. When you let it go it untwists again. The maximum force the twisted rope can exert is approximately the same as the maximum tensile force it can stand. Twist it any more and it would break. In reality the rope would need to be capable of forces greater than those calculated here, as we've made a few assumptions within the calculations that would lead to greater stress.

## Take-off Speed



In the movie the two protagonists fly upwards for 1.6 seconds. We know this, because we timed it from the movie, by counting the frames. This means that gravity takes 1.6 seconds to slow them from take-off speed to zero, which is when they drop back to Earth. Gravity will accelerate any object at a rate of 9.8 metres per second per second (also known as  $9.8 \text{ m/s}^2$ ). What this means is that if we fall for one second we'll reach a speed of 9.8 metres per second. After two seconds

we are travelling at 19.6 metres per second. So the further you fall, the more you speed up.

## Vertical Velocity

The first step in working out how fast the two men would be flying is to measure velocity in the vertical direction. To do this, we use this formula:

$$v_v = u_v + a_v t.$$

Roll over the equation to find out what the letters stand for.

$v_v$  is the final component of the velocity in the vertical direction, (which is zero at the point they stop rising).

$u_v$  is the initial component of the velocity in the vertical direction (what we want to find).

$a_v$  is the component of the acceleration in the vertical direction (-gravity).

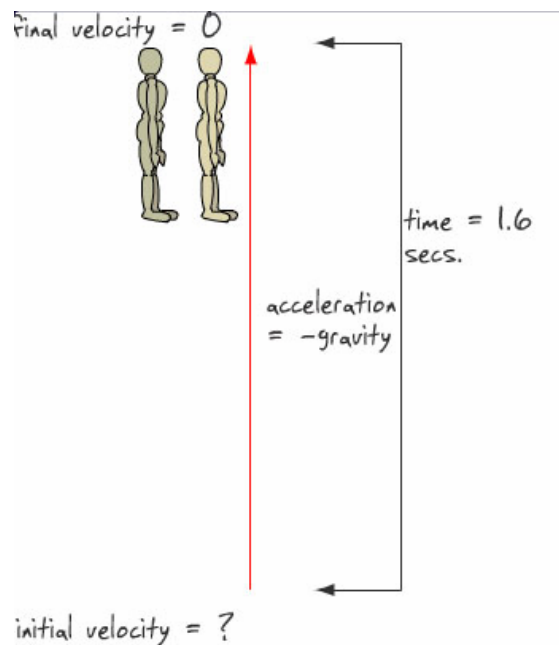
$t$  is the time taken.

$$0 = u_v + (9.8 \times 1.6)$$

therefore, by moving the  $u_v$  to the other side of the equals sign, we get:

$$u_v = 15.7 \text{ m/s}$$

So if the two men were just going up and down, they would take-off at just over 15 metres per second, which is about 35 miles per hour!



## Horizontal Velocity

However, the two protagonists do not just fly straight up and down. There is a component of the velocity,  $u_h$  in the *horizontal* direction. This is because they take off at an angle  $\theta$ , not vertically upwards.

Since  $u_v$  and  $u_h$  can be treated as vector quantities the velocity of take-off  $u$  can be calculated from trigonometry:

$$u = u_v / \sin \theta$$

Roll over the equation to find out what the letters stand for.

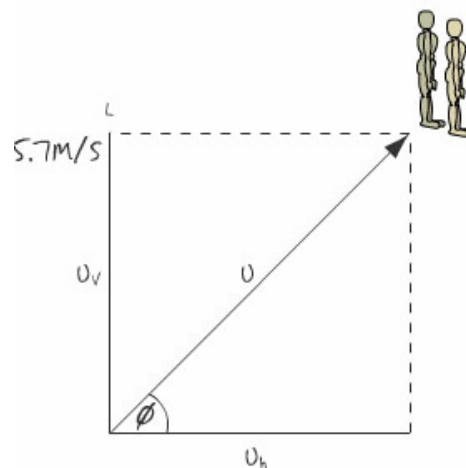
$u$  is velocity, which is what we want to find out.

It's also the hypotenuse of this triangle.

$u_v$  is the vertical velocity, and we just worked out that this is 15.7 m/s.

$\sin$  is the shortened version for 'sine' (pronounced like the word "sign"). It's a mathematician's shorthand meaning "the ratio of the height to the hypotenuse".

$\theta$  is the symbol we use to describe how big the angle is (in degrees) - we don't know what this is yet.

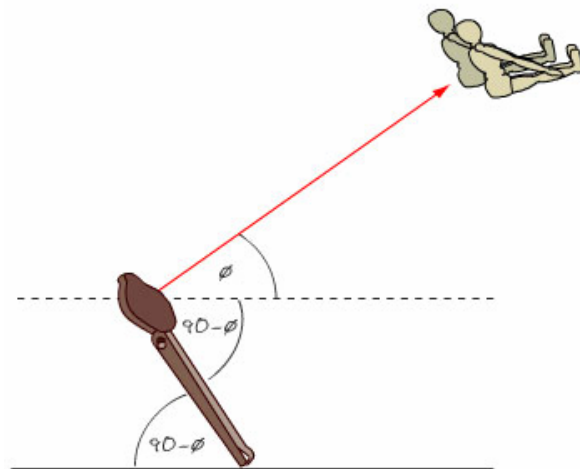


In order to work out this equation, we need to know what the angle is.

## How Far Does the Arm Move?

The distance they travel whilst being thrown by the mangonel depends upon which point they leave the seat.

If the angle of the trajectory is  $\theta$  to the horizontal then they travel  $90-\theta$  when being thrown. The circumference of a circle is  $2\pi r$  and in this case  $r$  is the length of the throwing arm, about 2m. So if they travelled a full circle ( $360^\circ$ ) they would move 12.6m ( $4\pi$ ), so travelling  $90-\theta$  means they move  $12.6(90-\theta)/360$ . So to find out the distance the catapult's arm is moving we now need to know what angle  $\theta$  is.



$2\pi r$  is the standard mathematical equation for finding out the circumference of a circle.

Pi  $\pi$  is 22/7.

$r$  is the radius of a circle, in this case this is made up by the throwing arm of the catapult, which we know is about 2m.

So to work out the circumference of a circle formed by the throwing arm of the mangonel:

$$2 \times 22/7 \times 2 = 12.6$$

## So What Was Their Velocity?

The angle of the trajectory depends upon how long the load is in contact with the arm.

Most mangonels show the arm stopping after it has travelled  $90^\circ$  so there should be no component of velocity in the vertical distance.

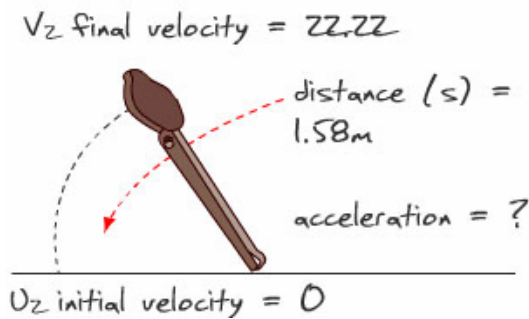
However, usually the load leaves the mangonel before the arm is completely upright (because the force of the arm drops off as it unwinds). This occurs at about  $70^\circ$  (this is a  $\theta$  value of  $20^\circ$ ). Hence the trajectory is pretty low.

However, the movie shows them going up and down pretty close to the vertical. For this the arm would only move a small distance, say  $20^\circ$ , before the load lost contact with the arm. In this case the arm would have travelled too small a distance to be able to get the velocity up to 15.7 m/s. So it seems that in the movie they cheated! The two men couldn't have passed over the wall at the angle shown.

So let's compromise with  $45^\circ$  which gives us a reasonable height and has the load in contact with the arm for a reasonable time.

So the velocity  $u = 15.7\sin(45)$   
 $= 22.2 \text{ m/s}$

**Acceleration**



We now need to know how much the mangonel's arm accelerates, so that we can use that to calculate the forces involved. To calculate acceleration we use the equation:

$$v^2 = u^2 + 2as$$

*v* is the final velocity, which we worked out earlier to be 22.2 m/s

*u* is the initial velocity, which we know is zero.

*a* stands for acceleration, which is what we want

to find out.

*s* stands for speed, assuming a constant acceleration over the distance moved. We worked out before that the distance the arm moves is  $12.6 \times 45/360 = 1.58\text{m}$ .

So  $s = 1.58\text{m}$ .

$$22.2^2 = 0 + 2 \times 1.58 \times a$$

we need to move **a** to the other side of the equal sign:

$$a = 22.2^2/3.16$$

$$a = 156 \text{ m/s}^2$$

**Force in the Catapult's Arm**

To work out the forces involved, we need to use Newton's First Law,

$$F = ma,$$

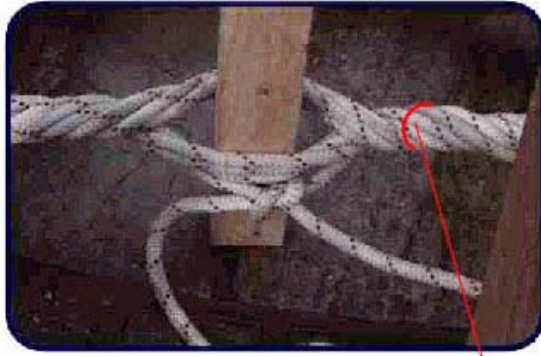
where **F** stands for net force, **m** is the mass of an object, and **a** is acceleration.

So if  $m = 180\text{kg}$  (the combined weight of the two men) and  $a = 156\text{m/s}^2$  then

$$F = 180\text{kg} \times 156\text{m/s}^2$$

$$= 28\,080 \text{ Newtons.}$$

This is equivalent to the downward force exerted by a mass of nearly 3 tonnes due to gravity.



radius = 0.2m

### Force Exerted in the Rope

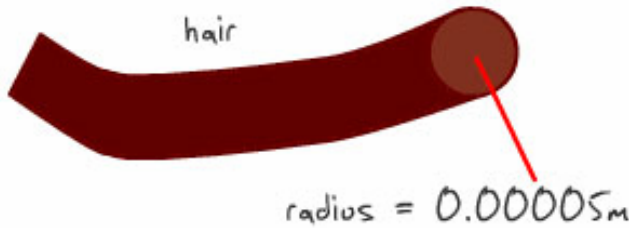
So we know that the force needed to throw the men is 28 080 Newtons. But how do we calculate how much force is actually exerted in the rope?

If we assume the tensioned rope at the centre has a radius of 0.2m, then the force to drive the throwing arm will be exerted along this radius. However, it is not evenly distributed because more rope is needed per unit radius as we move outwards, so the average point is actually two thirds of the radius, in this case  $0.2 \times 0.67 = 0.134\text{m}$ .

Assuming there is a force of 28 080 Newtons at the end of the throwing arm (2m) then the force needed at a point 0.134m from the centre is  $28\,080 \times 2/0.134 = 420\,000$  Newtons. This force (equivalent to the downward force exerted by a mass of nearly 14 tonnes due to gravity) must come from the coiled rope. The rope is already tensioned, and when the arm is pulled back the tension is increased. Thus the force exerted by the coiled rope must be greater than this.

### Would the rope be capable of that?

Would rope built in the year 1194 be that strong?



In 1194 rope was built of natural fibres - animal hair, sinew, hemp and even human hair. Human hair was used to make ropes when other resources were not available: the isolated Islanders of St Kitts used to make them to abseil down the cliffs to steal birds' eggs; Japanese

monks in the 13th Century made them over 10 inches in diameter to lift bells weighing more than 120 tons. Just for fun, we're going to test out human hair. We'll assume that the theoretical maximum force that the twisted rope could exert is comparable to its maximum tensile strength. So we need to know if a rope made of human hair is capable of exerting a force of 420 000 Newtons (or about 14 tonnes).

The average hair has a radius of 0.00005 m, then in a rope of radius 0.2m there will be:

$$0.79 \times \pi \times 0.2^2 / (\pi \times 0.00005^2)$$

$$= 12\,600\,000 \text{ hairs}$$

(the factor of 0.79 is because the hair has a circular cross section, thus cannot pack together completely.)



If there are 120 000 hairs on a human head this would require about 400-500 heads of hair for a four foot length. Assuming the force is felt equally across the rope, each hair feels a force of:

$$420\ 000/12\ 600\ 000 = 0.03 \text{ Newtons.}$$

This is equivalent to the downward force exerted by a mass of about 3 grams due to gravity.

So, we hung weights from a human hair to see if it could take a mass of 3g or greater and found it could hold 50g! More than enough to make the catapult fling!



Of course, there's dozens of things we haven't taken into account - like how would they make the rope, how long would it have to be, how friction affects the strength, whether stretching the hair affects its strength and even how elastic hair is...

## Try it!

Now that you've had to go at building your own catapult/mangonel, and you know a little more about the science behind it, here's your chance to prove your credentials. You may have noticed that in the Science section we did the calculations for two men being thrown over a castle wall. Strange how the mangonel we built was ever so much smaller!

## Experiment

Now if we were to throw a 2p coin that weighs 3.4 grams any distance with our model mangonel, what would be the required force generated in the string? Assume that we are using the proportions as outlined in the "How to make a Catapult" section.

## Equation Toolkit

(for explanations of these equations please look at "Men as Missiles")

Vertical Velocity

$$v_v = u_v + a_v t$$

Horizontal Velocity

$$u = u_v / \sin \theta$$

Circumference of a circle

$$2\pi r$$

Acceleration

$$v^2 = u^2 + 2as$$

Force

$$F = ma$$

Average point of rope's radius

$$2/3r$$

## Variables (What you need to know)

- How long does it take the coin to fly through the air and hit the ground? You'll need to halve this to get the time to the top of the parabola (where it stops rising and starts to come down again).
- Gravity is  $9.8 \text{ m/s}^2$ .

- Once we'd trimmed the throwing arm, it measured 250mm, although yours may be longer.
- What is the angle at which the coin leaves the catapult's arm (from the horizontal)? This will need to be an educated guess from your own observations (and it's a really good excuse to fire your catapult a few times!). If you haven't built your own catapult/mangonel, then you will have to estimate this angle.

How did you do? Join our forum at <http://www.open2.net/forum/forum.jsp?forum=14> and let us know whether you've cracked it.

Now here's another one for you. If we didn't know what gravity is - how would we find out? It's a question that took man thousands of years to discover, but using your catapult and what you've learnt here, you should be able to find out! Join the debate! Visit the forum and let us know how you've done, go to: <http://www.open2.net/forum/forum.jsp?forum=14>

