The Trebuchet

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Recent reconstructions and computer simulations reveal the operating principles of the most powerful weapon of its time

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Centuries before the development of effective cannons, huge artillery pieces were demolishing castle walls with projectiles the weight of an upright piano. The trebuchet, invented in China between the fifth and third centuries B.C.E., reached the Mediterranean by the sixth century C.E. It displaced other forms of artillery and held its own until well after the coming of gunpowder. The trebuchet was instrumental in the rapid expansion of both the Islamic and the Mongol empires. It also played a part in the transmission of the Black Death, the epidemic of plague that swept Eurasia and North Africa during the 14th century. Along the way it seems to have influenced both the development of clockwork and theoretical analyses of motion.

The trebuchet succeeded the catapult, which in turn was a mechanization of the bow [see "Ancient Catapults," by Werner Soedel and Vernard Foley; SCIENTIFIC AMERICAN, March 1979]. Catapults drew their energy from the elastic deformation of twisted ropes or sinews, whereas trebuchets relied on gravity or direct human power, which proved vastly more effective.

Recovering Lost Knowledge

The average catapult launched a missile weighing between 13 and 18 kilograms, and the most commonly used heavy catapults had a capacity of 27 kilograms. According to Philo of Byzantium, however, even these machines could not inflict much damage on walls at a distance of 160 meters. The most powerful trebuchets, in contrast, could launch missiles weighing a ton or more. Furthermore, their maximum range could exceed that of ancient artillery.

We have only recently begun to reconstruct the history and operating principles of the trebuchet. Scholars as yet have made no comprehensive effort to examine all the available evidence. In particular, Islamic technical literature has been neglected. The most important surviving technical treatise on these machines is Kitab aniq fi al-manajaniq (An Elegant Book on Trebuchets), written in 1462 C.E. by Yusuf ibn Urunbugha al-Zaradkash. One of the most profusely illustrated Arabic manuscripts ever produced, it provides detailed construction and operating information. These writings are particularly significant because they offer a unique insight into the applied mechanics of premodern societies.

We have made scale models and computer simulations that have taught us a great deal about the trebuchet's operation. As a result, we believe we have uncovered design principles essentially lost since the Middle Ages. In addition, we have found historical materials that push back the date of the trebuchet's spread and reveal its crucial role in medieval warfare.

Historians had previously assumed that the diffusion of trebuchets westward from China occurred too late to affect the initial phase of the Islamic conquests, from 624 to 656. Recent work by one of us (Chevedden), however, shows that trebuchets reached the eastern Mediterranean by the late 500s, were known in Arabia and were used with great effect by Islamic armies. The technological sophistication for which Islam later became known was already manifest.

The Mongol conquests, the largest in human history, also owed something to this weapon. As a cavalry nation, the Mongols employed Chinese and Muslim engineers to build and operate trebuchets for their sieges. At the investment of Kaffa in the Crimea in 1345–46, the trebuchet's contribution to biological warfare had perhaps its most devastating impact. As Mongol forces besieged this Genoese outpost on the Crimean peninsula, the Black Death swept through their ranks. Diseased corpses were then hurled into the city, and from Kaffa the Black Death spread to the Mediterranean ports of Europe via Genoese merchants.

The trebuchet came to shape defensive as well as offensive tactics. Engineers thickened walls to withstand the new artillery and redesigned fortifications to employ trebuchets against attackers. Architects working under al-Adil (1196–1218), Saladin's brother and successor, introduced a defensive system that used gravity-powered trebuchets mounted on the platforms of towers to prevent enemy artillery from coming within effective range. These towers, designed primarily as artillery emplacements, took on enormous proportions to accommodate the larger trebuchets, and castles were transformed from walled enclosures with a few small towers into clusters of large towers joined by short stretches of curtain walls. The towers on the citadels of Damascus, Cairo and Bosra are massive structures, as large as 30 meters square.

Simple but Devastating

The principle of the trebuchet was straightforward. The weapon consisted of a beam that pivoted around an axle that divided the beam into a long

During their heyday, trebuchets received much attention from engineers—indeed, the very word "engineering" is intimately related to them. In Latin and the European vernaculars, a common term for trebuchet was "engine" (from ingenium,"an ingenious contrivance"), and those who designed, made and used them were called ingeniators.

and short arm. The longer arm terminated in a cup or sling for hurling the missile, and the shorter one in an attachment for pulling ropes or a counterweight. When the device was positioned for launch, the short arm was aloft; when the beam was released, the long end swung upward, hurling the missile from the sling.

Three major forms developed: traction machines, powered by crews pulling on ropes; counterweight machines, activated by the fall of large masses; and hybrid forms that employed both gravity and human power. When traction machines first appeared in the Mediterranean world at the end of the sixth century, their capabilities were so far superior to those of earlier artillery that they were said to hurl "mountains and hills." The most powerful hybrid machines could launch shot about three to six times as heavy as that of the most commonly used large catapults. In addition, they could discharge significantly more missiles in a given time.

Counterweight machines went much further. The box for the weight might be the size of a peasant's hut and contain tens of thousands of kilograms. The projectile on the other end of the arm might weigh between 200 and 300 kilograms, and a few trebuchets reportedly threw stones weighing between 900 and 1,360 kilograms. With such increased capability, even dead horses or bundled humans could be flung. A modern reconstruction made in England has tossed a compact car (476 kilograms without its engine) 80 meters using a 30-ton counterweight.

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Engineers modified the early designs to increase range by extracting the most possible energy from the falling counterweight and to increase accuracy by minimizing recoil. The first difference between counterweight machines and their traction forebears is that the sling on the end of the arm is much longer. This change affects performance dramatically by increasing the effective length of the throwing arm. It also opens the way for a series of additional improvements by making the angle at which the missile is released largely independent of the angle of the arm. By varying the length of the sling ropes, engineers could ensure that shot left the machine at an angle of about 45 degrees to the vertical, which produces the longest trajectory.

At the same time, so that more of the weight's potential energy converts to motion, the sling should open only when the arm has reached an approximately vertical position (with the counterweight near the bottom of its travel). Observations of the trebuchet may have aided the emergence of important medieval insights into the forces associated with moving bodies.

Swinging Free

The next crucial innovation was the development of the hinged counterweight. During the cocking process, the boxes of hinged counterweight machines hang directly below the hinge, at an angle to the arm; when the arm of the trebuchet is released, the hinge straightens out. As a result of this motion, the counterweight's distance from the pivot point, and thus its mechanical advantage, varies throughout the cycle.

The hinge significantly increases the amount of energy that can be delivered through the beam to the projectile. Medieval engineers observed that hinged counterweight machines, all else being equal, would throw their projectiles farther than would fixed-weight ones. Our computer simulations indicate that hinged counterweight machines delivered about 70 percent of their energy to the projectile. They lose some energy after the hinge has opened fully, when the beam begins to pull the counterweight sideways.

Although it exacts a small cost, this swinging of the counterweight has a significant braking effect on the rotating beam. Together with the transfer of energy to the sling as it lifts off and turns about the beam, the braking can bring the beam nearly to a stop as it comes upright. The deceleration eases the strain on the machine's framework just as the missile departs. As a result, the frame is less likely to slide or bounce. Some pieces of classical-era artillery, such as the onager, were notorious for bucking and had to be mounted on special compressible platforms. The much gentler release of the trebuchet meant that engineers did not have to reposition the frame between shots and so could shoot more rapidly and accurately. A machine of medium size built by the Museum of Falsters Minder in Denmark has proved capable of grouping its shots, at a range of 180 meters, within a six-meter square.

Capturing the Trebuchet's Lessons

Later engineers attempted to capture the great power that trebuchets represented. Some of these efforts are made visible in historical records by the proliferation of counterweight boxes in the form of the mathematical curve called the saltcellar, or salinon. The counterweight boxes of the more elaborate trebuchets took this shape because it concentrated the mass at the farthest distance from the hinge and also reduced the clearance necessary between the counterweight and the frame. The same form reappeared on later machines that incorporated pendulums, such as pendulum-driven saws and other tools.

Most attempts to extend the trebuchet's principles failed because the counterweight's power could not be harnessed efficiently. Success came only in timekeeping, where it was not the trebuchet's great force but rather its regular motion that engineers sought. Pendulums were a dramatic step forward in accuracy from earlier controller mechanisms.

Although the pendulum is usually associated with the time of Galileo and Christiaan Huygens, evidence for pendulum controllers can be traced back to a family of Italian clockmakers to whom Leonardo da Vinci was close. Indeed, da Vinci explicitly says some of his designs can be used for telling time. His drawings include a hinge between the pendulum shaft and bob, just as advanced trebuchets hinged their counterweights, and show notable formal resemblances to fixed counterweight machines as well. In the case of earlier clockwork, there is a marked similarity both in form and in motion between the saltcellar counterweight and a speed controller called the strob. The strob oscillates about its shaft just as the counterweight does before quieting down at the end of a launch.

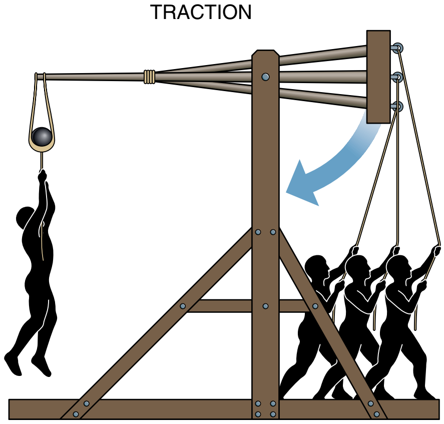
Trebuchets also appear to have played a role in the greatest single medieval advance in physical science, the innovations in theoretical mechanics associated with Jordanus of Nemore. The key to Jordanus's contribution is his concept of positional gravity, a revival in the Middle Ages of the idea of a motion vector, or the directedness of a force. Jordanus held that for equal distances traveled, a weight was "heavier," or more capable of doing work, when its line of descent was vertical rather than oblique. In particular, he compared cases in which the descents were linear with those that followed arcs. Eventually this understanding led to the notion that work is proportional to weight and vertical distance of descent, no matter what path is taken.

The connection is clear. Engineers knew that machines with hinged coun-

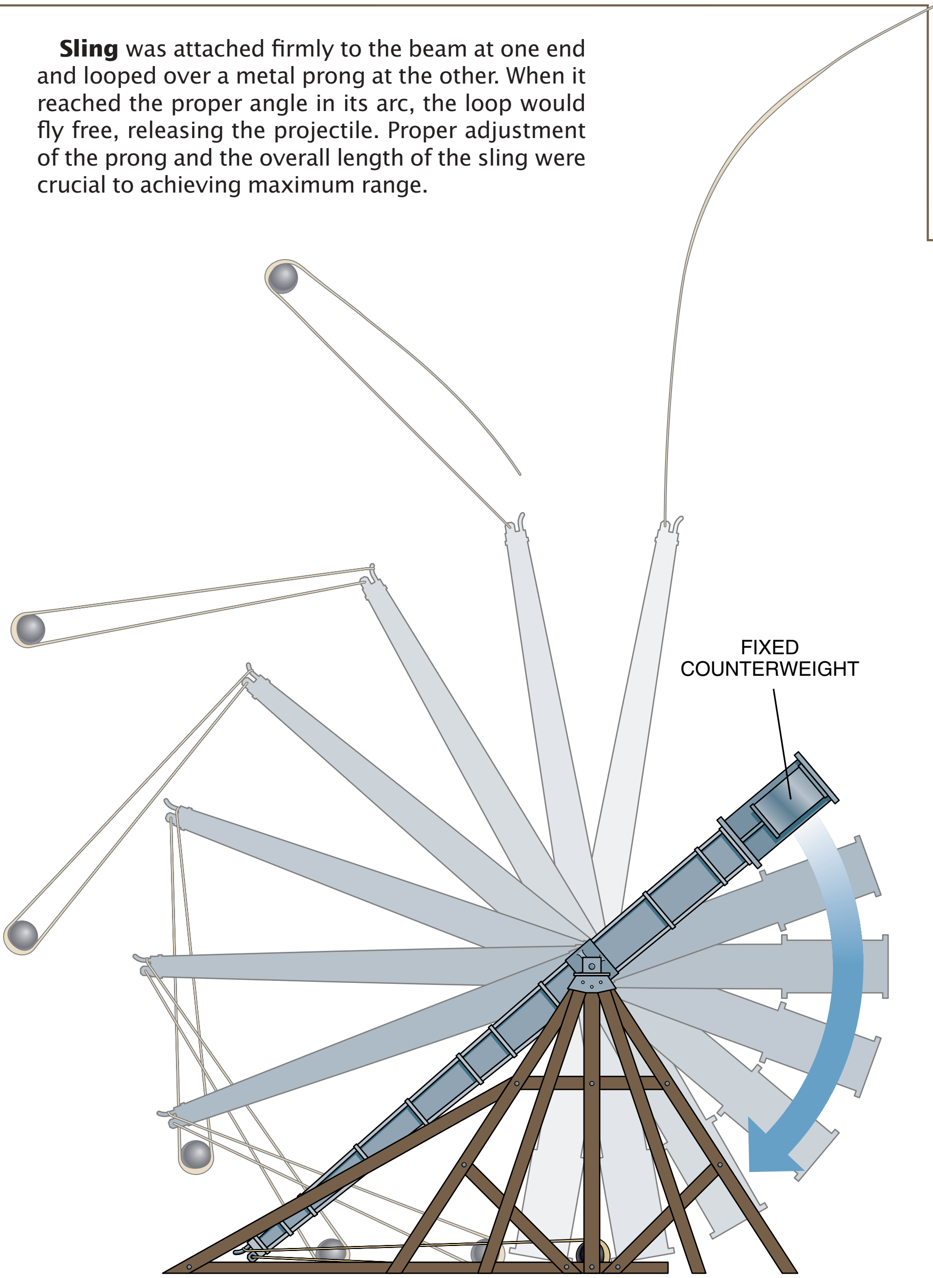
The Physics of the Trebuchet

The motion of the trebuchet is simple enough in its essentials to have inspired medieval studies of motion, but its details are subtle and require computer simulations to interpret accurately. Only recently have we come to understand how the rotation of the counterweight plays a crucial role in transferring energy to the beam and thence to the sling and projectile.

Sling was attached firmly to the beam at one end and looped over a metal prong at the other. When it reached the proper angle in its arc, the loop would fly free, releasing the projectile. Proper adjustment of the prong and the overall length of the sling were crucial to achieving maximum range.



Earliest trebuchets were powered by crews pulling on ropes rather than by counterweights. Crews of as many as 250 men pulled to send projectiles 100 meters or more. In this example of a small traction machine, the sling-holder's weight flexed the beam and increased the range.

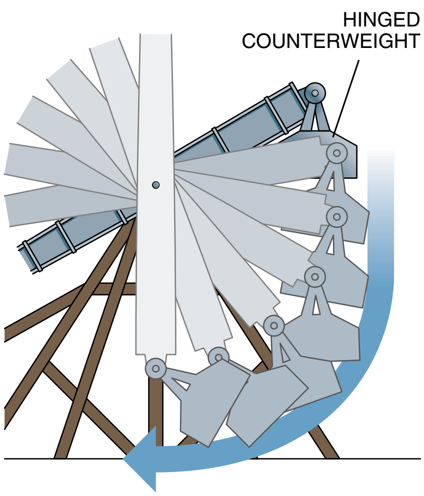


Addition of counterweights increased the power of the trebuchet. The elimination of the pulling ropes made possible another innovation: by placing a trough under the trebuchet beam to hold the projectile, engineers could lengthen the sling and increase the range even further. The sling rotates faster after the shot is airborne, so its length controls the launch angle.

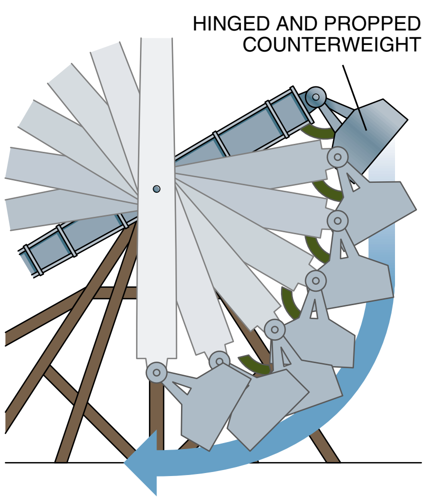
terweights, in which the weight descends essentially straight down during the first, crucial part of the launch cycle, would throw stones farther than would their fixed counterweight equivalents, in which the mass travels in a curve.

Other aspects of Jordanus's work may show military connections as well. The suspension of the hinged counterweight, with the constantly changing leverage of its arm, may have spurred Jordanus's related attempts to analyze the equilibrium of bent levers and to emphasize that it was the horizontal distance between the mass on a lever arm and its fulcrum that determined the work it could do. Observations of the differing distances to which fixed and hinged counterweight machines could throw their stones may have helped Jordanus in his pioneering efforts to define the concept of work, or force times distance. Jordanus's observations are usually studied as an example of pure physics, based on the teachings of earlier natural philosophers, such as Archimedes. The closeness of his mechanics to trebuchet function, however, suggests that engineering practice may have stimulated theory. Closing the circle, Galileo later incorporated such Jordanian ideas as virtual displacement, virtual work and the analysis of inclined planes to support such newer mechanics as his famous analysis of the trajectory of cannon shot.

Galileo's theoretical innovations came only after the replacement of trebuchets by cannon, a process that took nearly two centuries and was not fully accomplished until metallic shot replaced stones. The last instance of trebuchet use comes from the New World, at the siege of Tenochtitlán (Mexico City) in 1521. As ammunition was running critically low, Cortés eagerly accepted a proposal to build a trebuchet. The machine took several days to build, and at the first launch the stone went straight up, only to return and smash it. In view of the tremendous power of these devices, and the finesse required to make them function properly, would-be replicators should take careful note.



Hinged counterweight machines added yet another increment to the range by improving the efficiency with which the trebuchet converted gravitational energy to projectile motion. The center of gravity of the weight fell straight down during the first phase of acceleration; as the hinge straightened, the rotation of the weight around its center of gravity added to the energy transferred. Continued rotation helped to slow the beam as the projectile was released, reducing strain on the mechanism. The smoothness of the trebuchet's action meant it did not have to be repositioned after each shot and so could discharge more missiles in a given time.



Propped counterweights allowed engineers to squeeze even more energy out of the counterweight. By propping up the counterweight at an angle before firing, they gave it slightly farther to fall. This innovation also increased the distance between the center of gravity of the counterweight and the pivot around which the trebuchet beam rotated.

—Vernard Foley

JARED SCHNEIDMAN DESIGN

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Further Reading

TREBUCHETS. Donald R. Hill in Viator, Vol. 4, pages 99–115; 1973.

CHINA'S TREBUCHETS, MANNED AND COUNTERWEIGHTED. Joseph Needham in On Pre-Modern Technology and Science: Studies in Honor of Lynn White, Jr. Edited by Bert S. Hall and Delno C. West. Undena Publications, 1976.

BESSON, DA VINCI, AND THE EVOLUTION OF THE PENDULUM: SOME FIND-INGS AND OBSERVATIONS. Vernard Foley, Darlene Sedlock, Carole Widule and David Ellis in History and Technology, Vol. 6, No. 1, pages 1–43; 1988.

ARTILLERY IN LATE ANTIQUITY: PRELUDE TO THE MIDDLE AGES. Paul E. Chevedden in The Medieval City under Siege. Edited by Ivy Corfis and Michael Wolfe. Boydell & Brewer, 1995.

SCIENCE AND CIVILIZATION IN CHINA, Vol. 5: CHEMISTRY AND CHEMICAL TECHNOLOGY, Part 6: MILITARY TECHNOLOGY: MISSILES AND SIEGES. Joseph Needham and Robin D. S. Yates. Cambridge University Press, 1995.