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Ancient Catapults

Surviving Greek and Roman texts reveal the remarkable level of mathematical and engineering skill that went into the development of these early ballistic-missile launchers

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Web version made available with additional diagrams by: Darius Architectus (Kurt Suleski)

In 399 B.C. Dionysius the Elder, ruler of the Greek colony of Syracuse in Sicily, prepared his city for a long war with Carthage by undertaking search and development program. Utilizing such now familiar techniques as the assembly of large teams of specialists, the division of labor to break down the tasks into manageable units, and the provision of financial and psychological incentives. Dionysius clearly aimed from the outset at the production of novel weapons. Out of the program came quadriremes and possibly quinqueremes, ships with the equivalent of four or five banks of oars and so with more potential power behind their rams than the standard three bank triremes. Dionysius' engineers also devised the first catapults.

These early machines probably fired arrows from a bow not much stronger than one a man could draw. By mechanizing the drawing and releasing of the arrow, however, the catapult inventors made possible the construction of much more powerful bows. These devices appear to have been built of composite materials, with a wood core surmounted by a tension layer of animal sinew in the front and a compression layer of horn in the back. Eventually the flexible bow reached the limits of its design, and it was superceded by catapults based on the torsion principle. In this approach tightly stretched bundles of elastic fibers were further strained by a rigid bow limb as the weapon was brought to a full draw. Horsehair or human hair could be used for the ropes that made up these bundles, but for superior performance animal sinew was preferred.

To mechanize the archer's motions the catapult engineers incorporated a number of important design features. The basic piece in the catapult was the stock, a compound beam the formed the main axis of the weapon. Along the top of the stock was a dovetail groove, in which another beam, the slider, could move back and forth. The slider carried at its rear surface a claw-and-trigger arrangement for grasping and releasing the bowstring. In front of the claw on top of the slider was a trough in which it was the arrow lay and from which it was launched. In operation the slider was run forward until the claw could seize the bowstring. Then the slider was forced to the rear taking the string with it until the bow was fully drawn. In the earlier versions linear ratchets alongside the stock engaged pawls on the slider to resist the force of the bow. Later a circular ratchet at the rear of the stock was adopted. Forcing back the slider on the first catapults was probably done by hand, but before long the size and power of the machines called for a winch.

As soon as the catapult became too large to be fired from the shoulder it was placed on a pedestal. To facilitate aiming a special joint was devised to connect the stock with the pedestal. The solution to this problem anticipated the invention of the universal joint, which is usually attributed to either Girolamo Cardano or Robert Hooke, and hence to the 16th or the 17th century.

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Similarly, the sliding dovetail surfaces of the slider reappear everywhere in the construction of modern machine tools, and the use of a claw to replace the action of the human hand established a tradition of mechanical manipulation that has led to the robots under development today.
Most of this technological sophistication was passed over in silence by the more literary of the ancient Greeks and Romans. Even in more recent times classical scholars did not pay much attention to the surviving catapult texts. Not until the 20th century, when scholars who combined and engineering background with military experience began to decipher the ancient catapult treatises, was their importance made clear. The pioneering field studies of actual weapons constructed according to these texts shortly after the turn of the century by the German artillery officer Erwin Schramm stimulated a line of inquiry that has culminated in recent years with the definitive works of the British historian Eric William Marsden. This literature makes in plain that the Greeks were far from being as disdainful of close observation and exacting experiment as is usually supposed. Plato may have been contemptuous of the failure of objects in the real world to measure up to the ideal dimensions of geometry, and Aristotle may have based his biology in good measure on merely verbal description of species, but within the community of ancient mechanical engineers methods of assessing nature of considerably more importance for the future were being developed.

The replacement of the flexible bow by the torsion spring gave a great boost to catapult engineering. That advance was made roughly half a century after the invention of the catapult, and there is some evidence that Philip of Macedon, the father of Alexander the Great, was the ruler who subsidized this next phase of research and development. Certainly it was with the campaigns of Alexander that very powerful catapults first appeared. Indeed, there is reason to associate the rise of large empires with the advent of the catapult. The flexible-bow catapult had been limited to comparatively small arrows or stones, the stones requiring a bowstring with a pouch at its midpoint. The arrows might have been as large as a light javelin and the stones of a size small enough to be hurled overhand. When the torsion principle was perfected, it became possible to fire a stone weighting as much as 78 kilograms. Indeed, the Roman military engineer Vitruvius gives dimensions for catapults firing stones as heavy as 162 kilograms, although such giant machines may never have been actually constructed. More typical machines fired balls weighing from 13 to 26 kilograms. Arrow shooters firing shafts nearly four meters long now appeared. Even with catapult missiles of a more human scale the archer or slinger found himself completely outranged. The longest recorded range for a catapult firing an arrow of the ordinary size, about 70 centimeters, was about 640 meters, and there is some reason to believe the claim was not inflated. The maximum range for an archer was about 450 meters.

Catapults were able to fire such projectiles with considerable accuracy. Their fire could easily be concentrated on a single spot with repeated hits, knocking away the protecting battlements on top of a city wall or detaching the armor on a mobile siege tower. It was possible to aim catapults during the day, when the fall of the missiles could be observed, and then terrorize the enemy by firing at intervals into the same spot at night. At the siege of Avaricum in 52 B.C. Julius Caesar noted that his catapults had no trouble shooting down Gaulish warriors one after another as they stepped into a highly exposed position that was vital to the progress of the Roman attack. All of these details point to a high degree of intrinsic accuracy. (Indeed, when one of Schramm’s reconstructed catapults was test-fired in the presence of the Kaiser it reportedly split one of its arrows with a subsequent arrow, in the best Robin Hood style.)

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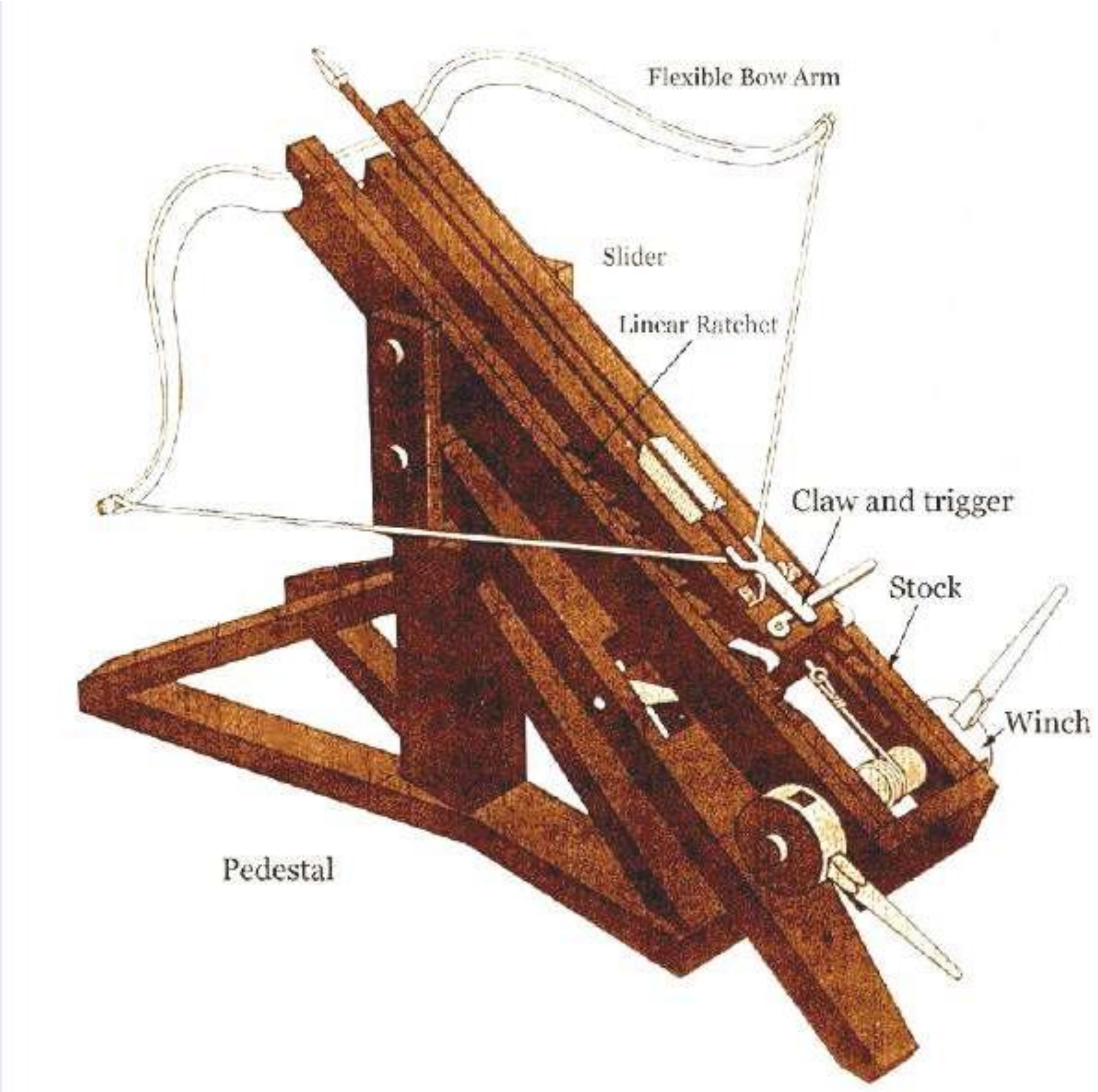
Clearly mechanization had far outstripped the capabilities of human archery. The result must have been dismaying for those who found themselves such machines.



Flexible bow was mounted at the end of a long wood framework enclosing a dovetail slider in this early arrow-firing catapult, based on a design originally devised technicians working for Dionysius the Elder of Syracuse in the fourth century B.C. The movable slider, carrying the bowstring with it by means of a claw-and-trigger arrangement, was held to the rear of the stock against the force of the bow by a linear ratchet after being pulled back with the aid of a circular winch. The piece connecting the catapult to its pedestal appears to have been an ancient version of the universal joint. The bow itself probably consisted of three different materials glued together: a wood core, a front layer of animal sinew and a back layer of horn. Since sinew is so strong in tension and horn in compression, such bows would have been much more powerful than the ordinary kind carved out a single piece of wood. The arrow is roughly two meters long.

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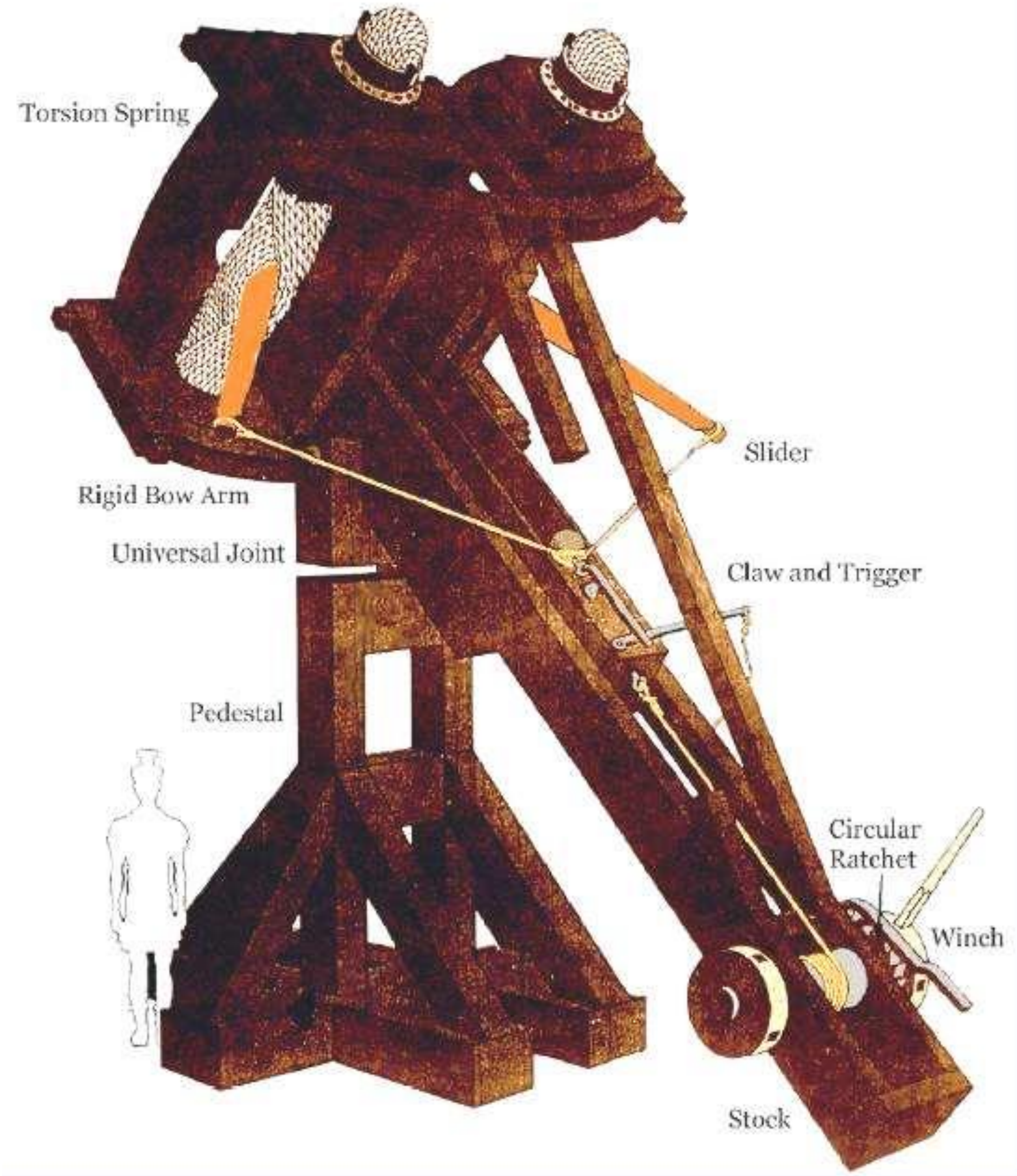

Torsion springs enabled the ancient catapult engineers to design much larger weapons, such as this Roman stone throwing version which launched a stone weighing one talent, or 26 kilograms. (A front view of a similar device appears on the cover.) A pouch woven into the center of the bowstring holds the stone, and a ring attached behind the pouch is grasped by the trigger claw. The washers at the ends of the torsion bundles in this particular model could be rotated and then pinned in place to adjust the tension before firing.

At the siege of Jerusalem in 63 B.C., Josephus, the commander of the Jewish forced defending the city, recorded that the head of a friend standing beside him on the wall was struck off completely by a Roman catapult ball. Even at ranges approaching 400 meters one of these balls could apparently smash through several ranks of soldiers before bouncing to a stop. At the same siege, according to Josephus, a pregnant woman was killed by a ball and the fetus was hurled 100 feet. The long, heavy arrows were equally effective. Advancing troops might literally be nailed to the ground by their descent. In fact, the word catapult is derived from the machine's penetrating power.

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Lightly armed Greek troops carried a shield called a pelte, and the prefix kata denotes downward motion. Thus a catapult is a device that can smash downward completely through a shield. At the siege of Gaza in 332 B.C. Alexander was wounded in the neck by a catapult arrow that had pierced both his shield and his breastplate. Archimedes' engines are known to have inspired terror during the siege of Syracuse by the Romans from 213 to 211 B.C. A typical reaction of the time was that of the Spartan general Archidamus, who watched a catapult being fired and then exclaimed prophetically "Oh Hercules, human martial valor is of no use any more!"

In sum, catapults significantly affected the direction of warfare and with it the equilibrium of politics and society. Broadly speaking, they shifting the advantage in the favor of the offense. Until the time of the catapult besiegers were almost always at a great disadvantage. The Trojan War supposedly lasted for 10 years, and the struggle between Athens and Sparta certainly lasted for a quarter century, notwithstanding the great superiority of the Spartan army. In those days, most cities that fell did so because of treachery. With the introduction of catapults, together with other was machines just coming into use in the West, sieges have become more effective. First Dionysius of Syracuse and then Philip and Alexander of Macedon employed tall, mobile siege towers that could overlook a city's walls and pour a withering fire down on the battlements, while enormous rams powered by as many as 1800 men, pounded the walls from below. Catapults could not compete with such rams in power, but they were able to knock down walls that were not properly constructed. Philo of Byzantium, in an artillery manual written in about 200 B.C., stated that a wall had to be at least 4.62 meters thick to withstand catapult stones and that it was a good idea to keep the stone throwers at least 150 meters distant by means of ditches and other obstacles. Even with proper walls the battlements projecting above them remained vulnerable. Because the battlements had to be kept thin to provide a good field of view it was easy to know them away with stone balls, leaving no shelter on the walls for the defenders. With the returning fire neutralized, the rams and crews undermining the walls could work with less interference. The catapult played a key role in making urban life in the fourth century B.C. significantly more precarious. During his first five years in power Alexander captured five major cities and many smaller ones. A passage in the Politics of Aristotle (Alexander's tutor) reflects the change. Rational town planning, with straight streets intersecting to form quadrilateral city blocks, had just been popularized in Greece by the architect Hippodamus. Aristotle objected that at least part of every city should preserve the haphazard arrangement of earlier times to make it more difficult for invaders to fight their way in. Moreover, he wrote, the design of walls and their careful maintenance was particularly important at that time, "when…catapults and other engines for the siege of cities [have] attained such a high degree of precision."

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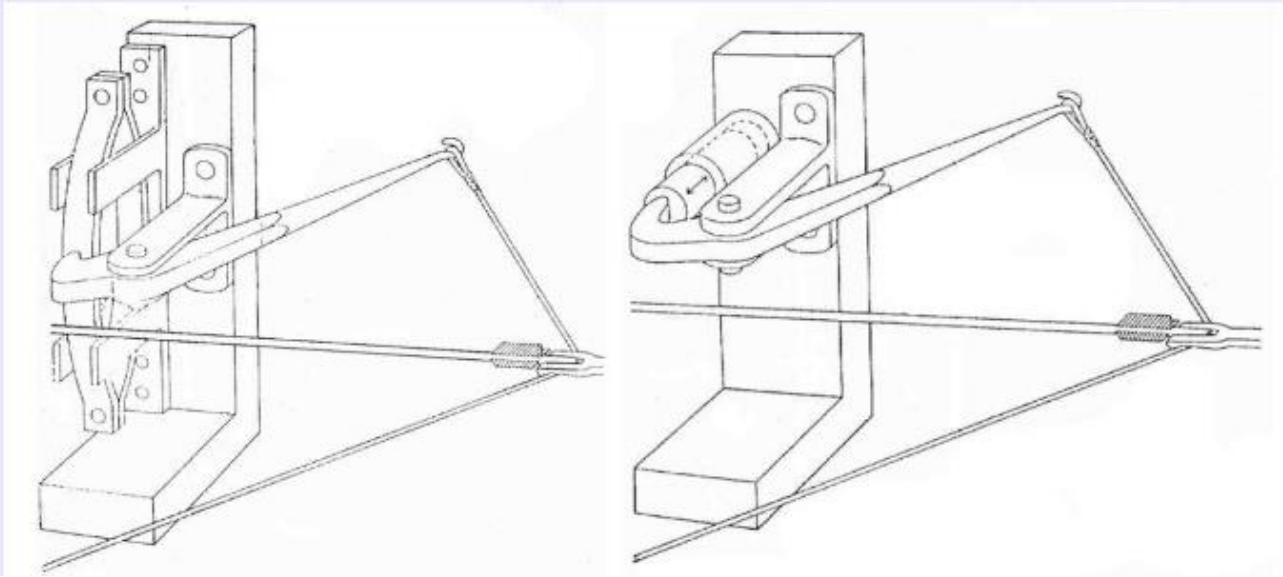

Two alternative for catapults were introduced by Ctesibius of Alexandria inthe middle of the third century B.C. toreplace the standard torsion spring device. Both approaches incorporated rigid bowarms pivoted close to the inner ends. When the bow was drawn, the inner ends of the arms bent in such a way that they pressed wither bronze springs (top) on pistons sliding in airtight cylinders (bottom). Neither scheme provided a force comparable to that of the torsion bow, however, and attempted improvements came to nothing.

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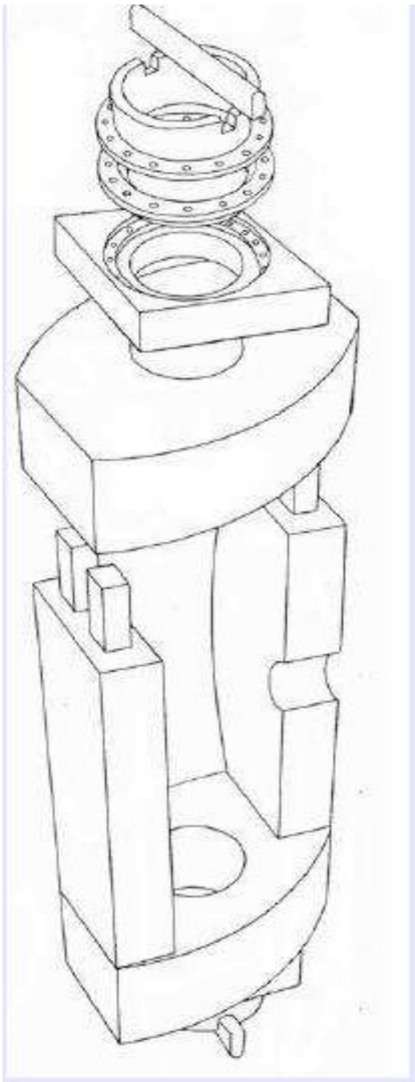

Dimensions of a board forming the top piece of one of the torsion-spring frames from a large stone throwing catapult were specified by the catapult designers in terms of the dimensions of the vertical sides of the frame, which in turn were determined by the diameter of the cord bundle forming the torsion spring.The thickness of the top board is not known for certain,but was probably equal to the diameter of the cord bundle. [Not entirely true, since Philon's tables of measurements and Vitruvius' text lists the thickness of the hole carrier as equal to the diameter of one cord bundle. – Darius Architectus] The catapult builders appear to have proceeded by first laying out a rectangle with one side equal to the depths of the vertical framepiece and the other side equal to twice this length. Theythen drew the diagonal on the rectangle, from A to G,and from D they drew a line parallel to the diagonal Line HG was next extended to intercept the parallel from D at E. The center point of the parallelogram ADEG was located and a circle was drawn around it equal to thesize of the cord bundle. (In the finished piece the circle actually defined a hole housing the cord bundle.) Thearcs DE and AG were then drawn, each with a radius equal to three times the diameter of the cord bundle.Finally the tenon holes were centered approximately inthe straight edges of the piece and sunk to about two-thirds of its thickness. Thus the catapult engineers had advanced their design procedures to the point where they incorporated automatic scaling methods in their instructions for catapult. Once the site and mission ofthe weapon had been selected the size of the projectile could be determined, and after that was specified the catapult formula would give the size of the torsionbundle that was needed. With the diameter of the bundle known, the construction manuals, incorporating decades of careful testing, would finally yield the sizes of the major parts of the machine as multiplies of the diameter of the cord bundle. In the actual construction critical parts of the wood frame would be reinforced with ironwork.

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Aristotle's counsel was not enough. The small democratic city-state was dying at the hands of the new technology. As its walls became vulnerable it was swallowed by large absolutist empires such as Alexander's. Democratic field warfare had stressed identically armed spearmen standing shoulder to shoulder in a line. Warriors had a standardized role, and one man could easily replace another in that role. This equality on the battlefield, together with the similar equality with the rowers in the battle fleet, had proved a strong prop of the democratic city system.

With the onset on specialized military engines the equality of arms was lost. Special mathematical and technical skills were necessary to build and maintain a catapult, and the risks involved in operating it were less than those of the rank and file. As a result hierarchies of specialists with particular functions and prerogatives began to appear. In time a political arrangement well suited to a level of technological development in which muscular force played a significant part was found wanting as individual citizen-soldiers began to yield their priority to machines.

In the new arrangements the ancient engineer tended to benefit. In earlier times his status had not been high. Of all the Olympian gods only Hephaestus, who labored at the forge and made cunning works of metal (including robots) was portrayed as being dirty, ugly and lame. The sculptor Phidias, who played a superintending role in the construction of the Acropolis under Pericles, was accused of sacrilege for daring to incorporate his own portrait in his work. Later, however, matters improved for such artisans. The names of Dionysius' inventors are not known, but from the court of Philip and Alexander three are recorded: Polydias, Diades and Charias. In the following century catapult designers broke into print, and the later names and works, at least in part, of Hero, Philo, Bito, Vitruvius, Ctesibius and others survive. The tradition culminates with Archimedes, whose great contemporary fame rested chiefly on his war machines, not his mathematics. Recent research by A. G. Drachmann of the University of Copenhagen and by Derek J. de Solla Price of Yale University makes it increasingly unlikely that Plutarch's report of Archimedes' disdain for engineering is an accurate one. In Roman times catapult expertise may even have enabled its possessor on occasion to survive political purges.

This rise in the status of the engineer rested on a strong demand for catapults. They became a part of every up-to-date fortress and siege train, and gradually they began to be deployed in the more mobile warfare of the battlefield. At sea they may have played a role in the naval arms race that led from the trireme, with its three banks of oars, to huge vessels with as many as 40 banks. Evidently the underlying assumption was that catapult fire could decimate the enemy boarding force while their ship was still too far away to grapple or ram. The larger the ship was, the more catapults it could carry and the more stable its firing platform was. This interpretation, then, sees the catapult superceding hand-to-hand warfare at sea as the cannon did 2000 years later. Eventually the advent of the new battle tactics, of armored ships called cataphracts and of Roman efforts to dominate the entire Mediterranean combined to reduce the size of warships once again. In a political parallel to land warfare, the influence of the citizen-rower was diminished in the process.

The effectiveness of the catapult led to efforts to improve its performance even beyond the introduction of the torsion bow. The engineer Ctesibius, for example, working in Alexandria in the middle of the third century B.C., attempted to supplant hair and sinew ropes, which were susceptible to breakage, rotting and changes in tension due to humidity or stretching.

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Both of his two alternative designs incorporated rigid arms pivoted close to their inner ends, which were bent in such a way that they pressed, when the bow was drawn, either on hammered bronze springs or pistons sliding in airtight cylinders [see illustrations]. Neither the compression of the bronze springs (which are of course inferior to steel springs for most purposes) nor the compression of the small amount of air the cylinders could contain, however, could provide a force comparable to that of a torsion bow. (In the process of researching his ideas Ctesibius discovered that “fire” would fly from the cylinder together with the piston he had forced into it with a hammer. The flame or smoke came perhaps from the ignition of the carpenter’s glue he used as a sealant. If the ignition was caused by the compression heating of the air, he can be viewed as the discoverer of the diesel effect.)
At about the same time Dionysius of Alexandria developed what was perhaps the most remarkable machine of its kind: a repeating catapult. [see illustration]. Arrows were loaded into it a vertical, gravity-fed magazine and then transferred one at a time into the firing groove by a rotating tray whose motion was controlled by a cam follower system actuated by the slider. In this system the follower reciprocated alongside the cam, which turned in response. No earlier instance of such a cam in known, and none as complex is known until the 16th century. A single windlass motion controlled the tray, the slider, the claw and the trigger, so that simply winding the windlass back and forth would automatically fire the machine until its magazine was empty. It is here that the flat-link chain, often attributed to Leonardo da Vinci, actually made its first appearance. The chain links presumably had extensions that meshed with an inverted gear: in other words, the teeth were internal, not external, much like those of a modern cam saw. (This interpretation rests in part on details in the surviving text and in part on the mechanical necessities of the situation.) The repeating catapult failed to replace the standard one. It paid for its ease and speed of operation by having too short a range. Furthermore, its accuracy paradoxically worked against it. The device concentrated its shots so closely at its maximum range (about 200 meters) that it did not pay to open fire on even a small group of troops at that distance. (It was a model of one of these repeaters that split an arrow in Schramm’s shooting exhibition for the Kaiser.) Commanders also feared that it would waste ammunition, a complaint that was raised again with the invention of repeating rifles two milleniums later. Another reason for the failure of these interesting variations can be seen in the sophistication of the engineering efforts applied in the meantime to the common catapult. Its success made it imperative to achieve ranges at least as long as those of the enemy. This made it necessary to adjust the quantity of elastic fiber to the weight of the missile. Probably the designers were pushed not to the point of attaining absolute maximum range but only to the point where escalating costs, declining convenience in handling or diminished accuracy due to downrange ballistic factors supervened. One of the crucial steps in designing the torsion springs was establishing a ratio between the diameter and the length of the cylindrical bundle of elastic cords. If the cords were too short, they would develop high internal friction and might not have allowable elastic elongation to avoid breaking when the arms were pulled all the way back. If they were too long, some of the elasticity would remain unused as the arms were pulled to the limits imposed by the framework. All the surviving catapult specifications imply that an optimum cylindrical configuration was indeed reached, and it could not be departed from except in special circumstances, such as the exclusively short range machines Archimedes built at Syracuse.

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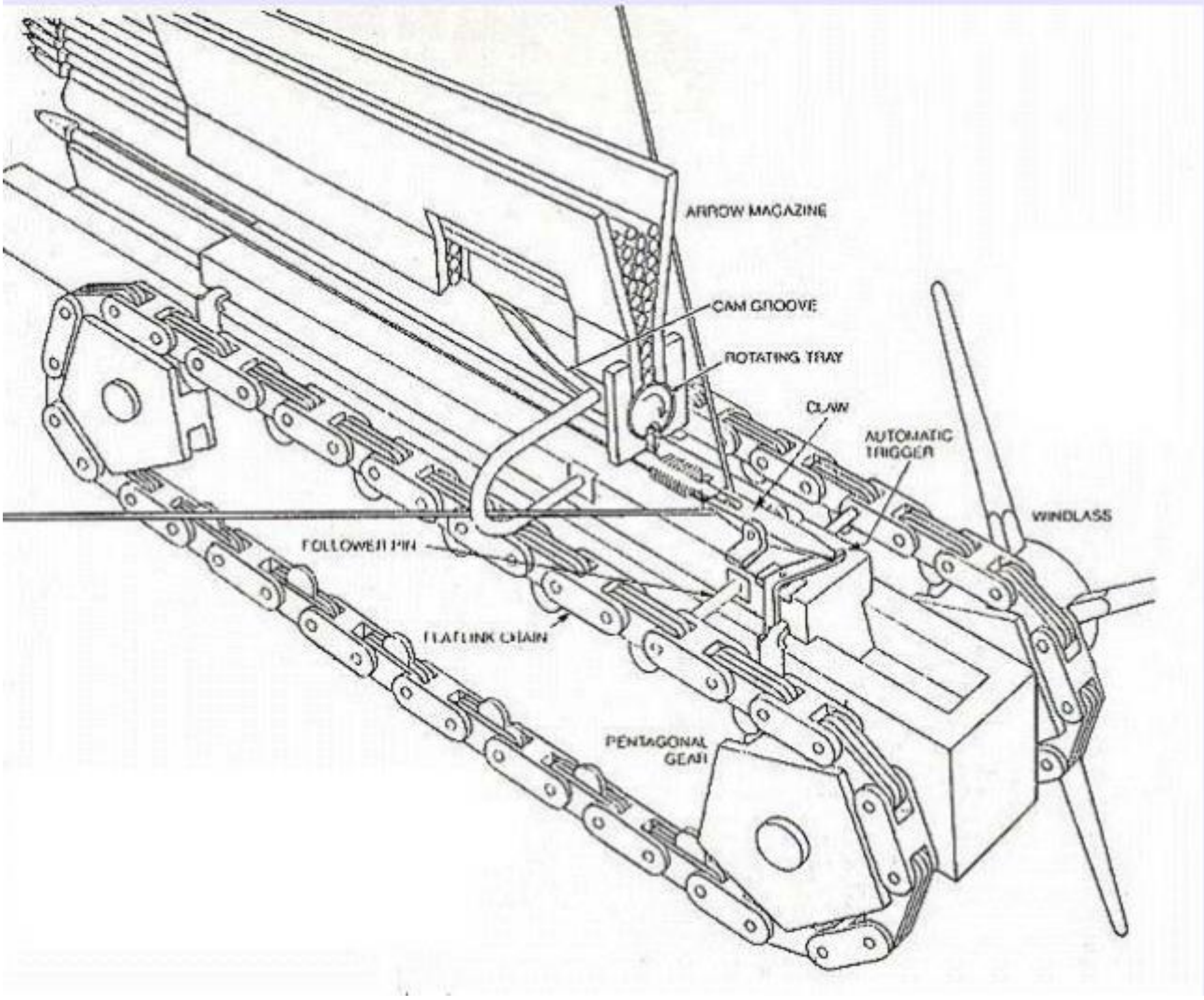

Dionysius Repeating Catapult. Most complex catapult invented in ancient times was a repeating weapon designed by Dioysius of Alexandria, who worked in the arsenal at Rhodes. As this detail drawing shows, arrows were fed by gravity from a magazine into the arrow trough by means of a revolving drum that was slotted to accept one shaft at a time. The revolution of the drum was controlled by a curved cam groove on its surface, which engaged a metal finger mounted on the slider. The motion of the slider was in turn produced by two flat-linked chains on each side to the machine. According to the surviving text describing the repeater, the chains ran over five-sided prisms at each end of their loop. In the author's view these prisms are assumed to have worked as inverted gears; in other words, the chain-link drive for the cocking and firing sequence relied on an engagement between the lugs on the chain links and a pentagonal gear for accepting the lugs. The rear prism was turned by a winch, and the bowstring claw was locked and unlocked at the appropriate times by pegs mounted in the stock of the weapon, past which the slider moved. Hence by reciprocating the winch the device could fire arrows automatically until the magazine was empty.

This optimization of the cord bundle was completed by roughly 270 B.C., perhaps by the group of Greek engineers working for the Ptolemaic dynasty in Egypt. There and at Rhodes the experiments of the catapult researchers were, according to Philo, "heavily subsidized because they had ambitious kings who fostered craftsmanship." This phase of the investigations culminated in quantified results of a distinctly modern kind. The results were summarized in two formulas. For the arrow shooter the diameter of the cord bundle was set simply as 1/9 of the arrow length.

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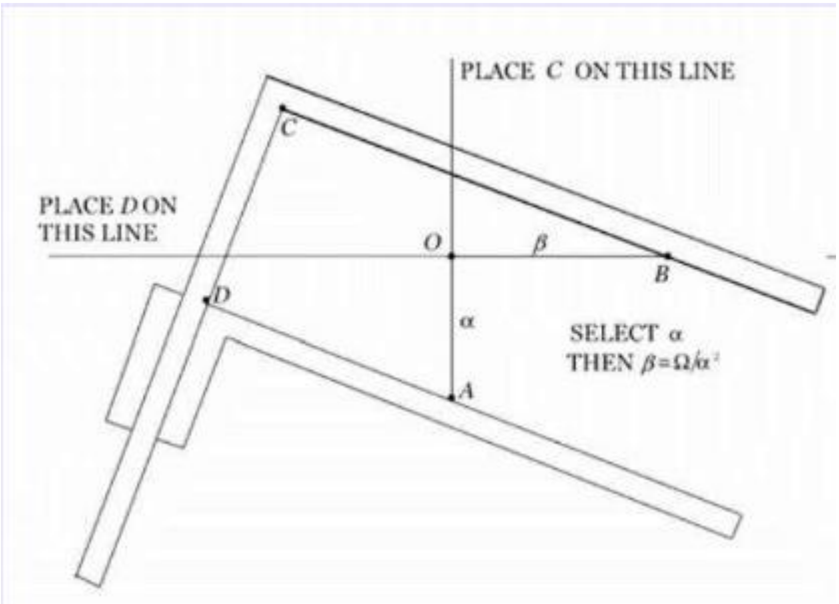
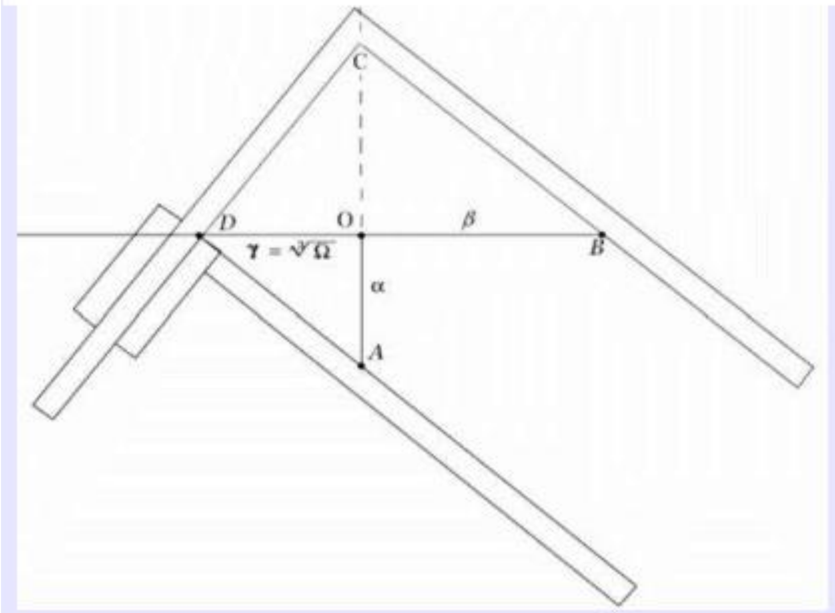
The more complex stone thrower formula stated, in modern terms, that the diameter of the cord bundle in dactyls (about 19.8 millimeters) is equal to 1.1 times the cube root of 100 times the weight of the ball in minas (about 437 grams). d = 1.13√100m The stone-thrower formula has two remarkable features. First, it gives a true and accurate solution for optimal design. To see why, first assume (as is indeed reasonable) that the catapult engineers wanted to maximize the performance of their machines. Accordingly they had to maximize the kinetic energy of their projectiles. To do this they had to maximize the potential energy stored in the torsion springs. Modern elasticity theory applied to the design of these springs tells us that the stored energy available will be proportional to the amount of initial tension give the bundle in string it through the frame, the additional tension caused by the pre-twisting of the bundle, the square of the angle indicating the amount of additional twisting by the pulling back of the bow arm, and the cube of the bundle's diameter. The cubing of the bundle's diameter means that to express the diameter in terms of the mass of the projectile one would have to extract a cube-root.





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Cube Root extractor, a simple mechanical contrivance invented by an unknown Greek geometer in the third or fourth century B.C., made it possible to deign a stone-throwing catapult to scale by solving a formula stating in effect that the diameter of the cord bundle in dactyls was equal to 1.1 times the cube-root of 100 times the weight of the stone in minas. In order to find the cube-root of some value W, for example, one first selected a line segment a and then obtained the value b such that Wa^2. The lines a and b were next plotted at right angles (left). By sliding the movable jaw of the device one was able to line it up so that point C would lie on the vertical extension of line a and point D would lie on the horizontal extension of line b (right). The solution was then give by g, a value equal to the distance OD. Suppose, for example, g equaled the cube root of 100. If one were to select a equal to 4, the b would be 100/16, or 6.25. The cube-root extractor, after proper alignment, would yield approximately correct result for g, namely 4.64.

Note that to arrive at this result one must employ the concepts of kinetic and potential energy, which were not brought into meaningful relation until the 18th century and the work of Leonhard Euler and Daniel Bernoulli. Also needed is elasticity theory, which had been begun by Hooke and Robert Boyle about a half a century earlier. Finally, one must employ the principles of ballistics, which were not clarified until the work of Francesco Cavalieri and Galileo Galilei in about 1630. That the ancient catapult engineers were able to arrive at a formula that stands up in the light of these much later developments is truly impressive.

It is the utilization of a cube-root extractor that constitutes the second remarkable feature of the stone-thrower formula, because it was written at a time when Greek mathematics was not yet capable of dealing fully with third-degree equations. In about 460 B.C. Hippocrates of Chios (not the famed physician) had stated that a cube might be accurately doubled in volume if two lines defining two mean proportionals between two given lines could be found. In the following century only a beginning had been mad toward solving the problem. Archytas of Tarentum anf Eudoxus of Cnidus had devised elegant theoretical solutions, but they were three-dimensional, very awkward physically and of no use in performing calculations. There the matter stood until the advent of the torsion bow.

Most of the next group of solvers of the cube-root problem had either a direct or an indirect connection with catapults. Menaechmus, according to tradition, was a tutor of Alexander the Great's, and therefore he as present at the time and place when the torsion bow first came into prominence. His solution involved intersecting conic sections, a concept he seems to have discovered. Unfortunately there in no evidence surviving on whether he was led to consider conic sections by the problem of extracting cube roots for the design of catapults.

The next solver of the cube-root problem was Eratosthenes, a friend of Archimedes' and a native of Alexandria, which was then a center of catapult research. Eratosthenes stated explicitly that the catapult was the chief practical reason for working on cube-root problems. We can assume he was interestd in engineering problems, since Archimedes dedicated his book On Method to him. In this work approximate solutions to mathematical problems are roughed out initially by a practical mechanical engineering approach. For example, sections of bodies are weighed to determine the ratios of their volumes. Eratosthenes' solution relied on a mathematical contrivance with sliding parts, somewhat similar to the one above on the previous page.

All of the next group of cube-root investigators, including Philo of Byzantium, Archimedes of Syracuse and Hero of Alexandria, were famous for their work on catapults. It is interesting to note that the largest stone-thrower on record, a three-talent (78 kilogram) machine, was built by Archimedes.

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A machine of this caliber would have required a cube-root extraction, because there are no natural roots in the quantities needed. Archimedes was also forced to depart from normal catapult proportions in building his short-range machines. Their effectiveness testifies to his skill as a mathematical engineer.

Taken as a group these early students of the cube-root problem stand apart from the mainstream of Greek mathematicians. Instead of limiting themselves to the straight edge and the compass, they devised simple mechanical contrivances that enabled them to generate conic sections and even curves of higher orders. Some aids, such as the simple “slide rule” shown in the illustration on page 11, anticipate the proportional compasses and gunner’ sectors of the late 16th century. The work of this group, however, was neglected until the Renaissance, when mathematical growth resumed at about the point where they had left off. Decartes’s La géométrie, for instance, begins with procedures and devices much like theirs.
It would appear, therefore, that the catapult engineers conducted experiments that forced them into a domain that traditional mathematical procedures had not yet penetrated. It is fairly easy even today to fit third-degree data to a second-degree curve if the data are bad or the investigator in unscrupulous. Hence one must feel a good deal of respect for these ancient investigators. They must have repeated their catapult-firing tests many times, kept very accurate records and interpreted their results with a high degree of precision. The introductory passages of Philo’s Belopoeica lay great stress on the experimental procedures and achievements of the early catapult engineers, and from the vantage of modern engineering theory the accuracy of this account seems to be fully borne out.

Having arrived at an optimal volume and configuration for the torsion-spring bundle, the catapult engineers continued their experiments until they had optimized the dimensions for the remaining pieces of the machine. If the arms were too short, the cocking force required would be excessive, the travel of the bowstring would be limited and its energy-transfer capabilities would be curtailed. If the bow arms were too long, they would retard the action of the springs by their increased mass or make the weapons too bulky. Once the length of the bow arms was determined, the length of the slider and the stock could be determined by the travel of the bowstring, and so on for the rest of the machine.

Eventually the catapult engineers wrote their text in such a way that the dimensions of the major parts were given as multiples of the diameter of the spring. Once this diameter had been calculated for the size of the projectile desired the rest of the machine was automatically brought to the proper scale. The surviving texts that contain this information testify to a level of engineering rationality that was not achieved again until the time of the Industrial Revolution.

The last major improvement in catapult design came in later Roman times, when the basic material of the frame was changed from wood to iron. This innovation made possible a reduction in size, an increase in stress levels and a greater freedom of travel for the bow arms. The new open frame also simplified aiming, which with the wood construction of the earlier machines had been limited, particularly for close moving targets.

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Late development in the history of catapult technology was the Roman cheiroballistra, a comparatively small wheeled machine dating from about the first century A.D. The weapon's iron frame gave it enough mobility for battlefield use, and its open structure made it easier to locate moving targets. The weapon was probably aimed by lining up the tip of the arrow with an appropriately elevated back sight mounted on the rear of the stock. The mathematical relations between the force of the bow, the displacement of the slider and the angle of elevation were such that by using a line of sight passing through the target, the arrow tip and the back sight, the shooter could automatically achieve the correct trajectory simply by estimating the distance and winching the slider backward for the appropriate number of ratchet clicks. The cheiroballistra was succeeded in turn by a simpler, one-armed stone thrower, called the onager.

The advanced catapult design came too late for the expansive period of the Roman civilization, but it played a role in stabilizing the boundaries of the Empire and in helping to prevent their erosion. As the decline of the Empire proceeded, however, the technical skills necessary to build and maintain such sophisticated machines appear to have become scarcer. A new, simpler machine called the onager, with only one spring and one arm, which terminated in a spoon and was used for throwing stones now came increasingly into prominence. [Actually, a spoon would rarely be used, since the use of a short sling at the end of the arm instead, as described by Ammianus Marcinellus, is far more efficient in hurling the stone and yields much greater force of impact. – Darius Architectus] It would be provide the heavy artillery of the Middle Ages until the appearance of the trebuchet, whose even simpler construction was gravity-powered. The scientific design of complex machines, with deliberate experimental adjustment of the dimensions of the components, did not appear again in Western civilization until the 18th century.

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During the ancient period the changes in which the catapult played a key part prefigured in striking ways issues that would appear again in the relations between science and technology on one hand and warfare and society on the other.

See also other Greek military Technology
- Ancient Greek Artillery Technology
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LINKS
http://news.nationalgeographic.com/news/2004/02/0205_040205_catapults.html
Roman Artillery
http://www.sciencemag.org/cgi/content/full/303/5659/771
Catapults (English and German)
ANCIENT ROMAN ARTILLERY
Reconstruction of the Cheiroballistra, Read also the translated Greek text of the Cheiroballistra
Another Version in Russian with more drawings!
Books
- The Art of the Catapult , Build Greek Ballistae, Roman Onagers, English Trebuchets, and More Ancient Artillery by William Gurstelle , Chicago Review Press (July 1, 2004) (for students with drawings and explanations)
- Greek and Roman Artillery 399 BC - 363 AD Duncan B. Campbell, Brian Delf (Illustrator) , Osprey Publishing (UK) (December 1, 2003)
- Greek and Roman Siege Machinery 399 BC - 363 AD Duncan B. Campbell, Brian. Delf (Illustrator), Osprey Publishing (UK) (June 1, 2003)