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The Water Lifting Devices and the Origin of Ancient Mechanics: *Shādūf* and Pulley

Summary

Scholars have not paid much attention to the *shādūf* and they often describe it without studying the historical developments of the mechanical principles upon which its functioning is based. However, this water lifting device plays a very important role in the emergence of some basic concepts of mechanics: equilibrium and the law of the lever. This paper looks at the history of these concepts in relation to the use of the *shādūf* and pulley. It allows us to identify a set of basic principles that we can find both in theoretical works (the oldest surviving text is the Pseudo-Aristotelian *Mechanical Problems* 300 BC) and in books more focused on the practical applications of such principles.

Keywords: mechanics; hydraulic machinery; simple machines; lever; pulley

Dem *shādūf* zollt die Forschung im Allgemeinen wenig Aufmerksamkeit, und wenn, werden oft historischer Kontext und mechanische Grundlagen dieser Technik vernachlässigt. Dabei spielt gerade diese Wasser-Hebevorrichtung eine herausragende Rolle bei der Entstehung wichtiger Grundbegriffe der Mechanik: dem Gleichgewicht und dem Gesetz des Hebels. Dieser Beitrag versucht, die Geschichte der beiden mechanischen Konzepte in Bezug auf die Verwendung des *shādūf* und des Flaschenzugs nach zu vollziehen. Dabei ist es möglich, eine Reihe von Grundkenntnissen zu identifizieren, die sich sowohl in theoretischen Werken wiederfinden (ältestes Beispiel ist ein Text über die Pseudo- Aristotelischen *Mechanischen Probleme*, um 300 v. Chr.), als auch in stärker praxis-bezogenen Büchern.

Keywords: Mechanik; hydraulischen Maschinen; einfache Maschinen; Hebel; Wellrad

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Most studies on ancient hydraulic machines treat the *shādūf* only very briefly (κηλώνειον in Greek, *tolleno* in Latin).[1] The reason may be the fact that this machine, which is thousands of years old, does not seem to have undergone any substantial changes up to our time. Therefore, it has almost always been groundlessly assumed that only one type of this machine existed, and it was described without studying the mechanical principle that it's based upon, a principle that began to be discussed in 300 BC in the Pseudo-Aristotelian *Mechanical Problems*.

I shall try here to show that the first assumption is misleading and that it is not possible to understand correctly the working of this machine without keeping in mind the developments of the theory of the simple machines. I will not use the method of research followed by many scholars, who have often neglected the idea of investigating this development in later periods (the Middle Ages and the Renaissance). Instead, I will make a wide ranging use of all of the documents available to me from these later periods. These are often directly connected with the ancient writings on the subject, and which are moreover of a great help for understanding the working and the construction of many mechanical devices, since they belong to a stage in the development of technology when the differences from the ancient practices were not so marked as later on.

The *shādūf* is a very simple machine made of two wooden beams, a weight, and a bucket for water that is tied to a rope or to a staff. The first beam is thrust straight into the ground, and works as a support for the other beam, which is placed crosswise along the upper part of the first beam and rotates around its support. This support is not placed under the middle point of the crosswise beam, but is placed at a point that divides the crosswise beam into two different parts, one of which is much longer than the other. The bucket hangs by the rope or by the staff from the end of the crosswise beam that is more distant from the support, whereas the weight is tied at the other end of this beam. This machine is placed near a river, a canal, or a well and is usually operated by a single man who draws the rope or the staff with the empty bucket downwards so that the bucket is lowered towards the surface of the water; once the bucket has been filled with water, the man lifts it with the help of the counterweight, and then he pours the water out.

I think that the first true depiction of the *shādūf* is found in the frescoes of the tomb of Apy at Thebes (tomb no. 217) (Figs. 1–2). In the past it was believed that the *shādūf* was represented on an Akkadian cylindrical seal, which is going back to the year 2300 BC, and in an Egyptian tomb discovered at el-Amarna (18th dynasty), but these identifications appear to be strained and hypothetical.[2] In the tomb of Apy (19th dynasty about 1300 to 1180 BC), on the other hand, we can see three complete representations of

1 Humphrey, Oleson, and Sherwood 1998, 309; Oleson 2000, 225–229; Wilson 2008, 350–351.

2 For a description of the seal, see Ward 1910, 146–147; Laessøe 1953, 12; Salonen 1965, 250–251; Bagg 2000, 76 and pl. 17b. For the Egyptian tomb at el Amarna, see Davies 1903, 41–42.

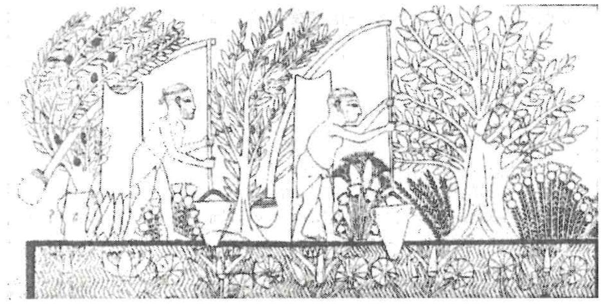

Fig. 1 Tomb of Apy at Thebes, left-hand side of the fresco.

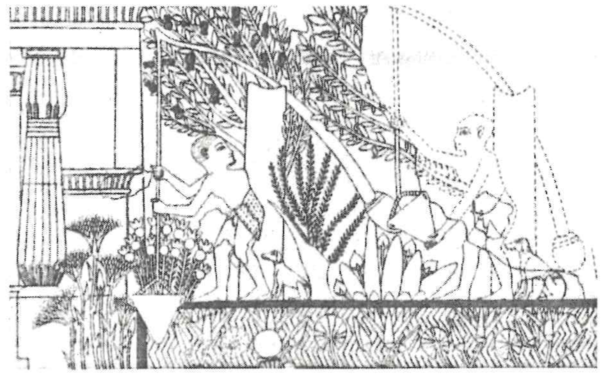

Fig. 2 Tomb of Apy at Thebes, right-hand side of the fresco.

the machine, together with the men who operate it.[3] The support, the crosswise beam, the counterweight, and the bucket are clearly depicted, and the men who are about to lower the buckets towards the water or to lift them from the water are shown at the beginning or at the end of their effort. A fragment behind the figure on the right shows a hand that is about to pour the water that had been picked up with another *shādūf* that is no longer visible.

Though these representations show the whole of the machine, not all of the questions concerning its means of operation are solved. On the contrary, from what can be seen in the frescoes and in the other representations on the tomb of Nefer-ḥotep (tomb no. 49, Fig. 3), the arrangement of the crosswise beam would turn out to be completely unfavorable for the proper working of the machine, since in all these representations the part of the beam between the support and the counterweight appears always to be longer then the part between the support and the rope or the staff attached to the bucket. In this arrangement the beam would turn out to be a lever with the moving power placed

3 For literary evidence of the existence of this water lifting device in old Babylonian period, see Laessøe 1953, 12–13.

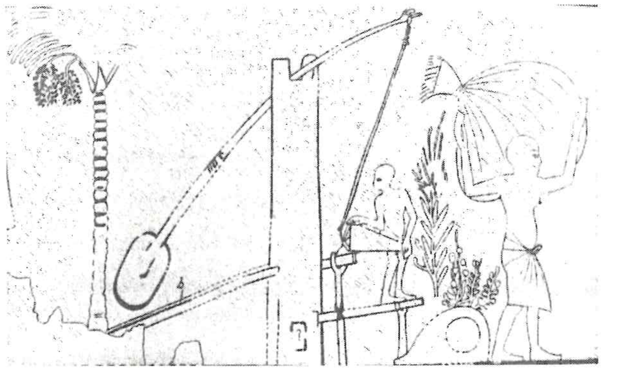

Fig. 3 Tomb of Nefer-ḥotep at Thebes.

near the fulcrum, and with the weight, which is to be movable, placed far away from the same fulcrum. This arrangement would make it difficult both to lower the bucket and to raise it, since the bucket would not be raised by a slow lowering of the counterweight, but the worker would have to apply a force in a direction contrary to that in which the force was applied for lowering the bucket.

We are here facing a real mechanical problem that should have immediately drawn the attention of those who have described and analyzed these representations, but such a problem does not appear to ever have been considered. A proper consideration of this problem was probably prevented both by the observation of the various *shādūf* that are still used along the Nile, and by the modern mechanical theory of the machine: these facts favored an interpretation of those representations that was distorted by ideas derived from more recent developments of technology; whereas it would have been more useful to explain those representations on the basis of the description of the object represented.

If we want to try to explain the way in which the machine is depicted in the representations I have described, without assuming that the Egyptian artists were not capable of correctly depicting the real machine used in their time, we must try to understand the reason for the particular arrangement of the parts of the machine. To do that, we must assume that the way in which it was operated was useful for raising the water without great effort. Now, in all these representations of the *shādūf*, no fixed connection between the vertical support and the horizontal beam is ever shown: this suggests the possibility that this beam was able to slide forwards and backwards (Figs. 1–2). The lack of the fixed point around which the beam could rotate, however, would seem to hamper the continuous operation of raising and lowering the bucket, unless the curved shape of the beam together with the width and the hollow shape of the top part of the vertical support could compensate for the unfavorable arrangement.

It is, therefore, possible that when the machine was operated, the crosswise beam

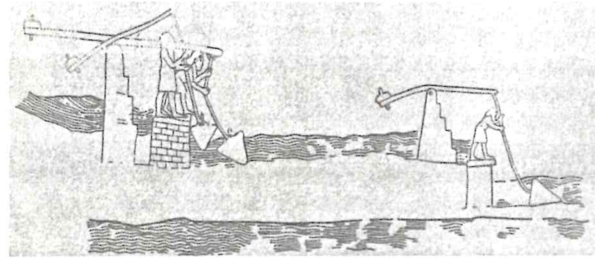

Fig. 4 Drawn from a bas-relief from the palace of Sennacherib at Niniveh.

was placed almost at an equilibrium on the support and then was made to oscillate on it; this movement being helped by its curved shape, which would have prevented the crosswise beam from sliding forwards, while the possible lateral shifting would have been avoided because of the curved shape of the top of the support. If this hypothesis is correct, then the man who was operating the machine would have first drawn the beam towards himself, so that the distance between the support and the rope or the staff which was holding the bucket would increase, after which, he would keep the beam in that position while the bucket was lowered and lifted. It would have been difficult for a single man to empty the bucket, though, because the beam would have had the propensity to slide back towards the side of the counterweight.

The lack of a fixed connection between the support and the crosswise beam would have made the working of the machine more complicated, slowing down operation, and, in the end, diminishing the quantity of water raised in a day. Perhaps the machines depicted in those ancient documents were not up to the task of supplying irrigation, which could mean that those unfavorable conditions were not considered very important.

All of these difficulties seem to disappear all together with the types of *shādūf* depicted in a bas-relief from the palace of Sennacherib at Niniveh, going back to the 7th century BC. Here, the machine is represented according to its classical form, with the crosswise beam almost always straight or slightly curved; with the weight attached to the end of the beam nearer the support; and with the bucket placed at the other end, more distant from the support. Even the connection between the vertical support and the horizontal beam seems clearly represented. This arrangement is not, to be true, visible in all the types of *shādūf* represented in the bas-relief, but it is clearly visible in one of them. The machine is arranged so that it can function with the greatest efficiency, and the workers engaged in raising the buckets could raise a great quantity of water from one level to other, so it could go to the places where it would later be distributed in smaller quantities (Fig. 4).

Let me summarize: the mural paintings of some tombs in Thebes show a device that is partially different from that which is portrayed in a bas-relief of Sennacherib's Palace

Fig. 5 Representation of a *shādūf* using a movable counterweight.

at Nineveh. As a matter of fact, the lack of a stable connection between the pivot and the transversal beam in the Egyptian reproductions, implies that the way in which the machine was operated was fundamentally different from how it worked later on, and raises many problems from a mechanical point of view. The effectiveness of the machine depends on the different ratio in the lever between the weight and the bucket, therefore, the more distant the weight is from the pivot, the more difficult it would be to operate the machine to lower the bucket.

The result obtained by using a fixed point of rotation offers a great advantage when one has to repeat the same operation, but the versatility of the use of the machine is lost. No wonder, then, that in the Greek-Roman world we find the *shādūf* with a crosswise beam that is not fixed. It is surprising, however, that a variation is introduced in the relation between the weight, the fulcrum, and the power by using a movable counterweight (Fig. 5). This arrangement appears reproduced on a vase that shows the description of a satyr and another man who operates the *shādūf*, waiting for two women near a well. Here, the smaller length of the crosswise beam on the side of the rope attached to the bucket makes up for the weight being nearer to the support. Another device is shown in a mosaic floor from a house at Oudna, now in the Museum of Bardo at Tunis (Fig. 6), where we can notice another beam that is similar to the support of the *shādūf*, but a bit shorter, to prevent the part of the crosswise beam with the counterweight from getting completely lowered down, making it easier to lift.

As I said, the working of this machine had been analyzed in the most ancient Greek treatise on mechanics that has survived, the Pseudo-Aristotelian *Mechanical Problems*. In it, the author tried for the first time to base the explanation of the workings of 'simple machines' (such as the lever, the windlass, the wedge, and the pulley) on a single mathematical principle, and to solve a series of questions that could be answered by referring

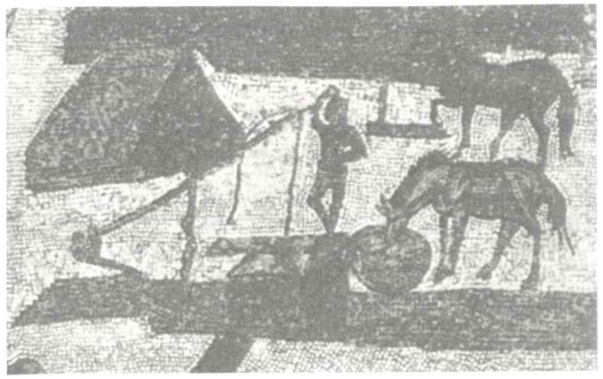

Fig. 6 Mosaic floor from a house at Oudna, now in the Museum of Bardo at Tunis.

to that same mathematical model. The starting point of the whole treatise was the astonishment roused by the operations carried out by means of a lever, such as the lifting of great masses that man was unable to move without that instrument. An even greater astonishment was roused by the fact that, by adding weight to weight, that is the weight of the lever to the weight that had to be lifted, the whole thing could be moved more easily.

> For it is strange that a great weight can be moved by a small force, and that, too, when a greater weight is involved. For the very same weight, which a man cannot move without a lever, he quickly moves by applying the weight of the lever.[4]

This fact upset the obvious relationship between the force needed to move a certain body and its weight; in fact the experience clearly shows that things 'weighing less' are easier to move than things 'weighing more.'

The author of the *Mechanical Problems* moved on to discover the principle that was able explain this remarkable fact: This principle was directly related to the movement of the lever, so that the working of the machines was reduced to the circle. He also considered it remarkable that the circle is an even more astonishing figure, since it is made up of opposites, a fact that becomes obvious when the circle is generated by a rotating line fixed at one end:

1. The generation of the circle is made by what is stationary, i.e. one end of the radius, and by what is moving, i.e. the other parts of the radius which move round and produce the surface of the circle.

4 Aristot. *mech.* 847b11–15.

2. The circle includes at the same time the concave, inside the circumference, and the convex, outside the circumference.

3. The rotating circle moves simultaneously in opposite directions, for it moves simultaneously forwards and backwards.

4. The circle is generated by the movement of one line drawn as a radius from the center, but no two points on that line travel at the same pace, but that which is further from the fixed center travels more rapidly.[5]

Having explained why the point more distant from the center travels more quickly than the point closer to it, though impelled by the same force, the author of *Mechanical Problems* moved on to explain in Question 3 why small forces can move great weights by means of a lever.[6]

The discussion of the lever, referring back to the paradox pointed out at the beginning of the treatise, not only explains the way this instrument works by relating it to the movement of different points of the radiuses of a different length than the lever, but tries at the same time to establish some sort of connection between the weight, the power needed to move it, and their relative distances from the fulcrum. This is an utterly new aspect of the problem that is not discussed in the later questions; certainly not in the case of the κηλώνειον-*shādūf* (Question 28), which could have been seen as a special form of lever. On the contrary, when this appliance is being discussed, the principle that explains how the different velocities of the points of the radius that generate the circle, is also totally ignored. Here, no reference of any sort is made to the theory of the lever, and the whole chapter is focused on the operation of drawing water, which is analyzed in the two essential movements of lowering the empty bucket (by raising the counterweight) and lifting the bucket full of water (by lowering the counterweight).

> Why do men make swing-beams at wells in the way they do? For they add the weight of the lead to the wooden beam, the bucket itself having weight whether empty or full. Is it because the machine functions in two stages (for it must be let down and drawn up again), and it can easily be let down whereas it is difficult to draw up? The disadvantage, then, of letting it down rather more slowly is balanced by the advantage of lightening the weight when drawing it up. The attachment of lead or a stone at the end of the swing-beam produces this result. For thus, when one lets down the bucket by a rope, the weight is greater than if one let the bucket down alone and empty; but when it is full, the lead draws it up, or whatever weight is attached to it. So that on the average the two processes are easier than they would be in the other case.[7]

5 Aristot. *mech.* 847b15–848a19.

6 Aristot. *mech.* 850a30–850b9.

The structure of the machine is assumed to be known to the reader, and so the author ignores a whole series of specific details that must be known to assure that the working of the appliance would be favorable for the man who has to draw the water. The relation of the distances and of the weights with the bucket full of water should produce a state of almost equilibrium, for if the counterweights weigh more heavily, the entire operation would be less easy. Those who were constructing such appliances, and probably some of those who were using them, must have somehow been aware of this fact, but it does not seem that this basic knowledge of mechanical principles resulted in pointing out the fundamental geometrical principle of the inverse proportion between the weights and the distances from the fulcrum.

Let us now analyze the mechanical operation accomplished by the *shādūf* and compare it with other operations generally employed for lifting weights, both with the help of machines and without them. The use of special technical devices for raising water from wells must have started very early in the history of mankind: the need of increasing the quantity of water drawn up was probably the cause of inventing such devices. The increased dimensions of the bucket involved an increased effort necessary to lift it, and this needed the employment of several workers, the use of animals, or the construction of specific contrivances for helping the men to bear more and more weight, and at the same time making it easier to lift that weight. The placement of those who had to perform this task was determinated by the operation that they had to execute, but required that they should be near the water. There was also a difference in respect to the lifting of solid weights: in our case it was impossible for one who was lifting the weight to put himself under it. The fact that the machines used for both operations showed aspects that were partly similar and partly dissimilar seems not to have ever been clearly pointed out.

Drawing water from above using only a bucket tied to a rope requires a remarkable effort, since during the lifting the entire weight of the bucket must be borne for a short time by one hand only. Drawing water from wells and rivers with the help of the *shādūf* was less difficult and required less effort. This was also true when one used the *trochlea*, a wheel placed above the well that could rotate about an axis, with a rope wound round its circumference and tied to the bucket. Instead of a wheel, any cylinder could be used with a rope wound around it several times.

On the contrary to what I pointed out for the *shādūf*, in the *Mechanical Problems*, the analysis of the workings of the *trochlea* (Question 9) is related both to the general

7 Aristot. *mech.* 857a34–857b8.

mechanical theory treated in that work, and to that which had been reported in the first Question concerning bigger and smaller weighing machines. Since the shape of a wheel is directly related to the circle, the wheels rotating around their pivot actually behave like balances; so, bigger wheels move and lift the weights with greater ease and more quickly than smaller wheels.

> Why is it that we can move more easily and quickly things raised and drawn by means of greater circles? For instance larger pulleys work better than smaller ones and so do large rollers. Surely it is because, the distance from the centre being larger, a greater space is covered in the same time, and this result will still take place if an equal weight is put upon it, just as we said that larger balances are more accurate than smaller ones. For the cord is the centre and the parts of the beam which are on either side of the cord are the radii of the circle.[8]

This way of explaining the working of a wheel was an immediate application of what had been said at the beginning of the *Mechanical Problems*: the reason for the presumed greater ease with which the bigger *trochleae* were operated was once more seen in the greater velocity of the points that were more distant from the center. In this case, the ease with which the weight was lifted was related to speed; this assumption was sharply criticized in the 16th century. In the Pseudo-Aristotelian treatise, the *trochea* was discussed from a general point of view, and was not in any way related to its possible use in lifting a bucket full of water from a well: this specific function was left to the κηλώνειον-*shādūf* alone. In the *Mechanical Problems*, neither the use of cranks attached to wheels nor the use of windlasses (Question 13 where their use is strictly related to the theory of the axle in the wheel) were treated in connection with our subject.

> Why are the larger handles more easy to move round a spindle than smaller ones, and in the same way less bulky windlasses are more easily moved than thicker ones by the application of the same force? Is it because the windlass and the spindle are the centre and the parts which stand away from them are the radii? Now the radii of greater circles move more quickly and a greater distance by the application of the same force than the radii of smaller circles; for by the application of the same force the extremity which is farther from the centre moves more. This is why they fit handles to the spindle with which they turn it more easily; in the case of light windlasses the part outside the centre travels further, and this is the radius of the circle.[9]

8 Aristot. *mech.* 852a14–22.

9 Aristot. *mech.* 852b11–21.

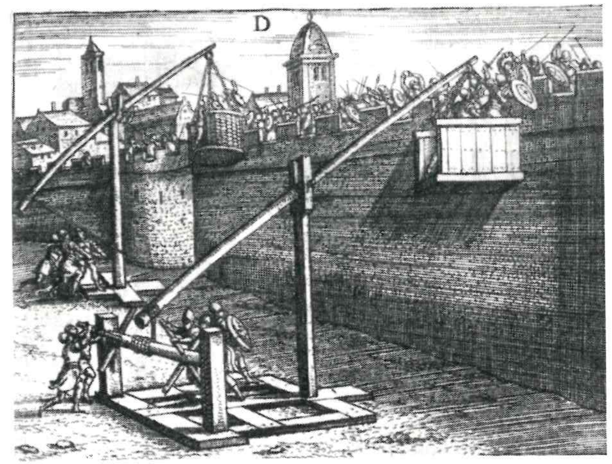

Fig. 7 Representation of a *tolleno*.

From Pliny's *Naturalis Historia*, we learn that in the Latin world the specific function of the *shādūf* seemed to be known: the *tolleno*, as well the *trochlea* and the pump, was used as a device to be placed near a well for the irrigation of the gardens of country houses.[10]

However, in late Antiquity the word *tolleno* was used to indicate a machine that worked like a normal lever; this lever, by having a very tall support, would have lifted the soldiers to the height of the walls of the city (Fig. 7).[11]

The *tolleno* had become an instrument in the hands of soldiers: without a counterweight, it seemed to have lost any connection with the κηλώνειον-*shādūf*, and with the original function of a machine for raising water. In this case also, things are not so simple as they look. In a painting of an Egyptian scene found during the excavation at Ercolano, a device for raising water from a cistern is represented that works in a way very similar to the *tolleno* used during a siege (Fig. 8).

The later works on theoretical and practical mechanics produced in the Greek-Roman world do not seem to have paid any attention to these two mechanical devices. We had to wait until the *Mechanical Problems* were rediscovered at the beginning of the 16th century and were later studied and commented upon for finding a renewed interest for the κηλώνειον-*shādūf*, together with attempts to integrate the Pseudo-Aristotelian text. Lacking a direct connection with the general mechanical principle of that work or with the treatment of the lever, the question concerning this machine seemed to be somehow incomplete to many authors who studied that book. Nicolò Leonico Tomeo (AD 1486–1531), the author of the Latin translation that most helped to make the work to be known for centuries, felt the need of adding an important specific commentary

10 Plin. *Nat.* XIX, 60.

11 Flavius Vegetius, 4th to 5th century AD, *Epitoma rei militaris* IV, 21.

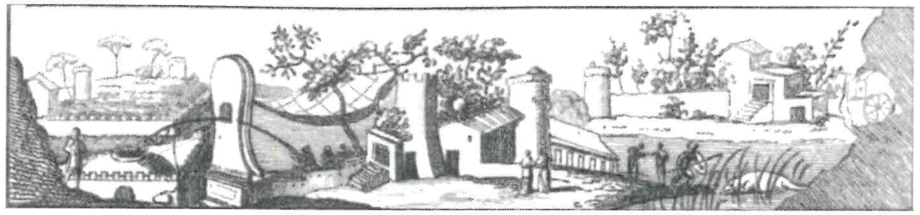

Fig. 8 Representation of a device for raising water found in Ercolano.

that actually related the device to the balance with the support placed underneath the pivot, a particular kind of balance discussed in the second mechanical problem.[12] This trend was followed decidedly by Alessandro Piccolomini (AD 1508–1578), the author of a *Paraphrase* of the Pseudo-Aristotelian work, in which for the first time, the mechanical reason for the advantage offered by the *shādūf* in the operation of raising water was pointed out and explained.[13] Finally, in the work *In Mechanica Aristotlis Problemata Exercitationes* (Mainz, AD 1621), written by Bernardino Baldi (AD 1553–1617), the mechanical operation performed by this machine was studied more deeply by pointing out the role played by the weight of the body of the person who was involved in the action of the lifting. He noticed in the first place, that in order to draw water by means of the κηλώνειον-*shādūf* one had to reverse the way in which the effort was normally applied with the use of only the hands. He wrote:

> Truly, with a hand, by means of a rope, the empty bucket can be easily lowered, but it is lifted with difficulty when it is full, whereas by using the κηλώνειον the things are reversed. The worker who lowers the bucket is helped by the weight of his body, while the one who lifts the bucket by means of a simple rope is hampered by the weight of his own body; certainly the help given by the weight of the body make it much easier to lift the bucket.[14]

This observation is very important, since it makes us better understand the dynamics of the various moments of the lifting of a weight, and it makes it possible to compare the operation made by hand, with that performed by means of the *trochlea*.

The use of a pulley has the advantage mentioned at the end of the passage I quoted: in this case, "the person who draws the water, by adding the weight of his own body to his forces, finds it easier to lift the bucket full of water".

All of these considerations make us reach a deep understanding of the working of this very ancient machine, which in its relative simplicity contained a complicated series

12 Aristot. *Quaestiones Mechanicae*, 51.
13 Piccolomini 1547, 60–61.
14 Baldi 2010, 331.

of applications of the law of the lever. It seemed that the working of the *shādūf* was at last recognized as different from that of the common lever, but the similarities were still considered very strong, even by Baldi. At the conclusion of his discussion of the problem, he did not hesitate to state: "the machine used in the war that is called *tolleno*, is not at all different from the κηλώνειον both for its form and for its way of operating".[15]

The discovery of all the documents concerning the ancient machines helped to attain a high level of theoretical investigation that took advantage of the recovery of Archimedes' work containing the law of the lever. What happened to the basic knowledge of mechanical theory during the previous centuries, though? The medieval works on the *scientia de ponderibus* are silent on this point, but that knowledge was not completely lost; something of it remained under the unexpected form of an esopic tale contained in the Roman de Renart.

This poem, written toward the end of the 12th century, was translated into many languages during the Middle Ages and has been very popular until our own time. In the fourth 'branch' or chapter (verses 151–364), it is told that a fox who had jumped into a bucket placed on top of a well, caused it to go down to the bottom of the well, raising at the same time the bucket tied to the other end of the rope. Not knowing how to get out of this situation, she managed to tell a wolf, who had just arrived near the well, that there was food at the bottom of the well. By persuading the wolf to jump into the bucket that was at the top of the well to go down to reach the food, the fox managed to raise the bucket that was at the bottom and therefore to save herself.[16] The basic idea of this tale seems to have very ancient origins, and is probably related to a traditional comment on some biblical passages of the Talmud.[17] Aside from the problem of the historical origin of the tale, its interesting point is the description of the use of the *trochlea*, or of a turning cylinder, which exploits the weight of the empty bucket that goes down, to make it easy to lift the full bucket. This trick reminds us of the function played by the counterweight in the *shādūf* and show us that the base knowledge of mechanics acquired in the second millenium BC was never lost, but was maintained in the popular memory through both the use of mechanical devices and moral tales, very different from the texts usually studied by historians of science.

15 Baldi 2010, 333.
16 See http://gallica.bnf.fr/ark:/12148/btv1b52505725s/f84.image (visited on 07/05/2018).
17 Varthy 2000, 245–248.

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Illustration credits

1 From Davies 1927, detail of pl. 28. 2 From Davies 1927, detail of pl. 28. 3 From Davies 1933, detail of pl. 46. 4 From Layard 1853, detail of pl. 15. 5 From Pfuhl 1923, fig. 276. 6 From Gauckler 1896, detail of pl. 22. 7 From Lipsius 1596, 34. 8 From Le Antichità Di Ercolano 1789, pl. 47.

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