# THE ARCHIMEDEAN SCREW-PUMP: A NOTE ON ITS INVENTION AND THE DEVELOPMENT OF THE THEORY

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ABSTRACT: Following Drachmann and others the authors argue that it is reasonable to assume that Archimedes invented both the infinite screw and the screw-pump. They argue that these inventions can be related to Archimedes' interest in the problem of the quadrature of the circle. Moreover, they discuss aspects of the development of the theory of the screw-pump.

KEYWORDS: screw pump, Archimedes, Galilei, Daniel Bernoulli, Hachette, Weisbach

## INTRODUCTION

Some authors attribute the invention of the screw-pump to Archimedes; others believe that the screw-pump was invented earlier and only attributed to Archimedes because of his reputation.

Oleson [23] has given a survey of the data with respect to the origin of the screw-pump. There are several texts from Antiquity in which the screw-pump is attributed to Archimedes.[1] As for Archimedes' involvement with screws there is, next to these texts, another remark by Moschion, that is relevant. Moschion states that Archimedes launched a ship "by means of a screw, which was an invention of his own" ([7], p. 279). This seems to refer to an endless screw. Oleson describes the archeological evidence as well. The earliest representation of a water-screw is on a fresco from the Casa di P.

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[1] The earliest evidence is a text by Moschion (after 241 B. C.) concerning the "Great Ship of Hieron of Syracuse". The text says: "And the bilge, although of a remarkable depth, was pumped out by a single man operating a water screw, an invention by Archimedes" ([23], p. 60). Then there is a statement from Agatharchides (floruit 180-116 B. C.) about the Nile delta: "the inhabitants easily irrigate the whole region by means of a certain device which Archimedes, the Syracusan, invented, called the 'screw' on account of its design" ([23], pp. 22-23) Then we have a text from Posidonius of Apamea (floruit ca 135-51 B. C.). The text describes the use of the water-screw in a series for mine drainage: "At a depth they [the miners] sometimes break in on rivers flowing beneath the earth, the strength of which they overcome by diverting their welling tributaries off to the side in channels [...] they draw off the streams of water with the so-called Egyptian screw, which Archimedes invented when he visited Egypt" ([23], pp. 92-93)

Cornelius Teges in Pompeii, obviously dating from before 79 A. D.[2] On the fresco an individual is moving a cylinder with his feet in a landscape that is allegedly Egyptian. Because water comes out of the cylinder it is generally assumed it must be a water-screw. From the imperial period we have two other Egyptian representations (in the British Museum and the Archeological Museum Cairo, respectively) and an Egyptian model of a water-screw (in the Hilton-Price collection). Moreover, remains of water-screws dating from the imperial period have been found in mines in Spain. None of these representations or remains of water-screws dates from before the time of Archimedes.

There is a very limited number of books on technical mechanics from Antiquity. For our purposes Vitruvius' book on Architecture [14] is important. It contains the oldest known description of a water-screw. The book dates from about 25 B. C.[3]

In this paper we will phrase a hypothesis with respect to the way in which Archimedes possibly invented the screw and the screw-pump. Moreover, we will discuss the way in which Cardano, Galilei, Daniel Bernoulli, Hachette and Weisbach studied the screw-pump.[4] The theoretical considerations concerning the screw-pump reflect the history of the theory of machines. Galilei was the first to give a complete and correct theory of the five simple machines (Cf. [21]). He was also the first to correctly explain the functioning of the screw-pump. In the course of the 17th and 18th century Newtonian mechanics and the calculus were the major new developments. The application of these new theories to machines was fragmentary and led to isolated results. Daniel Bernoulli's treatment of the screw-pump reflects this. Finally the treatment of Hachette and Weisbach of the screw-pump is characteristic of the 19th century approach to machines: geometric and graphical methods combined (in the case of Weisbach) with calculations. Judging on the basis of Rorres' remarks about the Archimedean Screw Pump Handbook ([22]) it seems that in 1968 the theory had not yet developed above the level reached by Weisbach and in practice Archimedean screw-pumps were built on the bases of rules of thumb ([26], p. 73). Rorres' treatment ([26]), that we will not discuss, represents the modern approach: he wrote a MathLab computer programme.

## DRACHMANN'S RECONSTRUCTION

Dijksterhuis [10], Kellermann & Treue [18], Krause (in his contribution in [30]) prefer to assume that the screw-pump was invented before Archimedes and that Archimedes probably merely applied it or studied it theoretically. Others, like Drachmann ([7] and [8]), Oleson [23] and Rybczynski [27], argue that the available evidence, although rather limited, points clearly at Archimedes and that there is no evidence pointing elsewhere. The same argument applies to the endless screw. As for Archimedes and the

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[2] [30] contains a complete reproduction of the (erotic) fresco.

[3] Also Heron's works on practical mechanics are important, in particular his textbook on Mechanics which has come to us in an Arabic translation only. Heron's books, written after 62 A. D. are by far the best source on ancient mechanical technology. Also Pappos wrote on mechanics; his work contains many fragments of earlier authors. Pappos lived at the time of Diocletian (285-305 A. D.). These books were all written more than about a century after Archimedes' death. Vitruvius describes the screw-pump without reference to Archimedes. Heron and Pappos describe other applications of the screw, but shed no direct light on Archimedes' role in this respect.

[4] The first sections of this paper are based on [20].

screw, we follow Drachmann and Oleson. Drachmann has argued ([8], p. 153) that Archimedes invented the screw-pump after having seen in Egypt the operation of a water-drum or tympanum (a water-lifting wheel with a body consisting of eight compartments, see Figure 1a). While the tympanum rotates, water enters a compartment through a hole close to the periphery of the drum, and after half a turn the water leaves the compartment again through a hole close to the axis. Oleson, who sympathises with Drachmann's reconstruction, described the moment of Archimedes' breakthrough as follows "if the tympanum were to be drawn slowly along the axis of its rotation as it turned, its compartment walls would describe the spirals of just such a screw" ([23], p. 298). Each of the eight compartments of the tympanum then generates one of eight spiral-shaped channels that together fill a cylinder (Figure 1b).

ANOTHER SOLUTION

If Drachmann is right, Archimedes must have seen a tympanum as described by Vitruvius in action and as a result of that imagined the screw-pump as described by Vitruvius. However, the insight that water can be lifted with the resulting object is far from immediate.

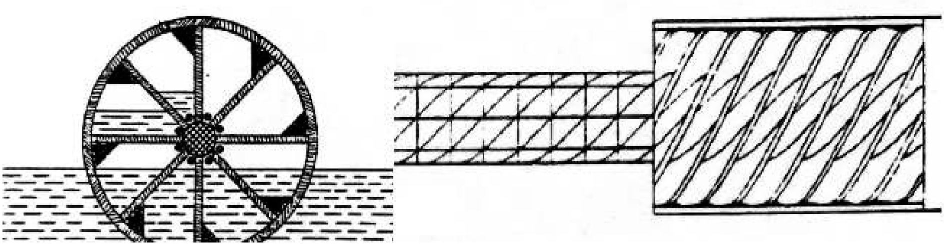

Fig. 1a Roman tympanum. Fig. 1b Screw-pump.

In Drachmann's reconstruction Archimedes invented the screw-pump of Fig. 1b when he watched the tympanum of Fig. 1a in action (Illustrations taken from [8], p. 150 and 153)

If a tympanum in action is tilted and imagined to be moved during its rotation along its axis it seems natural that this movement will be upward, away from the water. If the thought-experiment is executed in this way the resulting screw-pump will only lift water if the direction of the rotation that generates the pump in the thought-experiment is *reversed*![5]

We would like to suggest another scenario. The Chinese are famous for their inventions. Yet they did not invent the screw. This suggests that something was missing in China which was present in the West. Greek mathematics was missing in China. My

[5] In order to execute the thought-experiment in such a way that a working screw pump is obtained without having to reverse the direction of the rotation it is necessary that in the though-experiment the tympanum is "screwed" downwards, into the water. This seems hardly a natural thing to imagine.

reconstruction of the invention starts with the problem in pure Greek mathematics of the quadrature of the circle, which led to the study of different kinds of spirals, among them the cylindrical helix. We will show that the cylindrical helix can be used to execute the quadrature of the circle, a construction that is immediately related to the fact that the helix can be obtained by wrapping a triangle around a cylinder. We are arguing that at this point Archimedes will have related pure mathematics to mechanics and Heron of Alexandria tells us how. In Heron's *Mechanics*, Book 2, this particular relation of cylindrical helix and rectangular triangle is not only used to design a screw, but Heron also explains the functioning of the screw as follows ([8], p. 76):

> "Now we must take the screw to be just a twisted wedge, for the triangle from which we draw the screw line is really a wedge, and ist head is the side which is equal to the height of the screw turn [...]. And so the screw becomes a turned, twisted wedge, which is worked not by a blow, but by turning, and its turning here replaces the blows on the wedge; and so it lifts the weight [...]".[6]

The wedge is a very old piece of equipment, dating from long before Archimedes. The first somewhat unsatisfactory theoretical remarks that we know of are in *Mechanical Problems* from say 280 B. C., attributed to the peripathetic school ([8], p. 12). It is inevitable that Archimedes studied the wedge. My hypothesis is that the revolutionary idea that we can wrap a wedge around a cylinder and get a screw, comes from Archimedes. His work on the quadrature of the circle combined with his vivid interest in applied mechanics made him see all of a sudden the relation between the wedge and the cylindrical helix and at that moment he realised that also the screw could be used to exert power. The first application will have been very simple: a spiral groove in a wooden cylinder will have been used to move a piece of wood that was forced to remain in the groove (See footnote 6). All other applications came later. Pondering on how water could be lifted by a screw, wondering how water could "stay securely and solidly in its place by a power which is in itself", to use Heron's words, he discovered the screw-pump. Gravity would hold the water in its place!

## FROM THE QUADRATURE OF THE CIRCLE TO THE CYLINDRICAL HELIX

One of the famous problems that mathematicians in Antiquity struggled with was the problem of the quadrature of the circle: given an arbitrary circle, construct by means of compass and ruler a square with an area equal to the area of the circle. The circle quadrature is equivalent to the production of a straight line segment that is equal to the circumference of the circle. Circle quadrature and circle rectification are equivalent problems. The Greek mathematicians did not succeed in solving the problem of the quadrature or the rectification of the circle by means of compass and ruler.[7] For a

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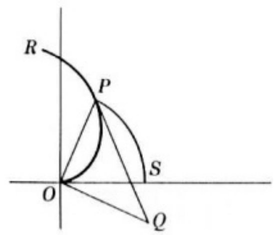
[6] The use of the screw (not the screw-pump) is actually described by Heron as well. Heron writes (in Drachmann's translation): "When the screw is turned, it moves the piece of wood that is called tulus, as I have said already, and it lifts the weight in a straight line; and this tulus must, when the screw is not moved, stay securely and solidly in its place by a power which is in itself, and it must not be so that, when the screw is at rest from turning, the weight overcomes it, I mean that when this block is fitted into the screw furrow and is like a support for it, then it does not slip out of the screw furrow, because if it does slip out, the whole weight will go down to the place from which it was lifted."([8], pp. 97-80).

[7] In the nineteenth century it became clear that the problem in this form is in fact insoluble.

rectification we need more than merely the use of compass and ruler. For example, in a famous treatise, *Spiral Lines*, Archimedes shows how any circle can be rectified provided one particular curve, a planar spiral is given and a tangent can be drawn to the spiral. Although Archimedes' argument is quite complicated, the result boils down to the situation of Figure 2. If PQ is the tangent to the spiral and OQ ⊥ OP, we have OQ=Circular arc PS.

Fig. 2 Rectification of a circle by means of a planar spiral




Archimedes undoubtedly knew the cylindrical helix and its properties.[8] It can be generated easily in a way analogous to the generation of the planar spiral by means of a superposition of a uniform rotation and a uniform translation: a segment of fixed length rotates uniformly in a plane about one of its endpoints, while at the same time this plane is moved uniformly in a direction perpendicular to the plane. The cylindrical helix can also be used to rectify a circle. Pointing out the analogy with the rectification by means of the planar spiral, Heath described the rectification as follows:

> "if a plane be drawn at right angles to the axis of the cylinder through the initial position of the moving radius which describes the helix, and if we project on this plane the portion of the tangent at any point of the helix intercepted between the point and the plane, the projection is equal to an arc of the circular section of the cylinder subtended by an angle at the centre equal to the angle through which the plane through the axis and the moving radius has turned from its original position." ([16], Vol.I, p. 232)[9]

This rectification of the circle by means of the cylindrical helix boils down to unwrapping a rectangular triangle from a cylinder, precisely the reverse of Heron's above-mentioned construction of the cylindrical helix.

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[8] A contemporary mathematician, Apollonius (c.262-c.190), is known to have written a treatise on the Cochlias, i. e. the cylindrical helix.

[9] In an interesting reconstruction Knorr ([19], 1986, pp. 166-167) argues that the rectification as described by Heath actually led Archimedes on a heuristic level to the rectification by means of the planar spiral.

THE SCREW-PUMP IN THE RENAISSANCE

The water screws from Antiquity that we know of are all based on one or more helical blades fitted inside a cylinder.[10] After Antiquity for many centuries there is no theoretical interest whatsoever in screw-pumps. Only at the end of the Middle Ages the interest returns. The first illustration after Antiquity is in Konrad Kyeser's *Bellifortis*, an early 15th century manuscript. It is obviously a pump with one or more helicoids inside (Figure 3a). [11]

Fig. 3a Screw-pump in Kyeser's *Bellifortis*[12]

In Da Vinci's *Codice Atlantico* we find a screw-pump consisting of a helical tube wound around a central drum (Figure 3b), as well as a pump made by winding a tube around a central core with a triangular intersection. According to Da Vinci the triangular pump can lift much more water, but is less easily turned around.

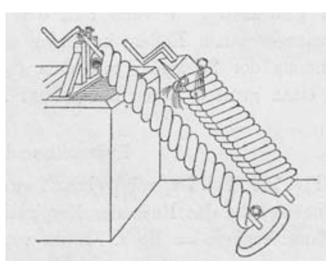

Fig. 3b Screw-pumps in Da Vinci's *Codice Atlantico*[13]

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[10] In the Spanish copper-mines of the imperial period pumps with one helicoid were found ([18], p. 23).

[11] For technical reasons the illustrations 3a, 3b and 4a are taken from secondary sources.

[12] Illustration taken from [13], p. 64

[13] Illustration taken from [3], p. 468. Described by Cardano in[5].

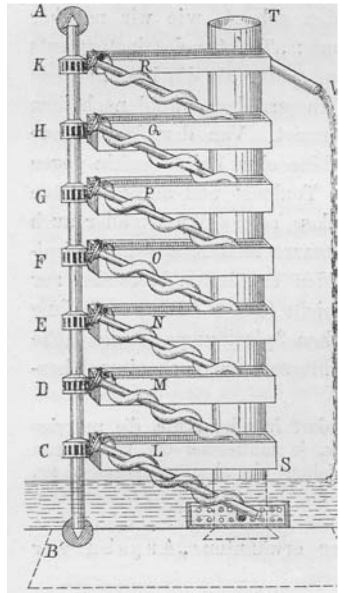



Fig. 4a The Augsburg Machine[14]

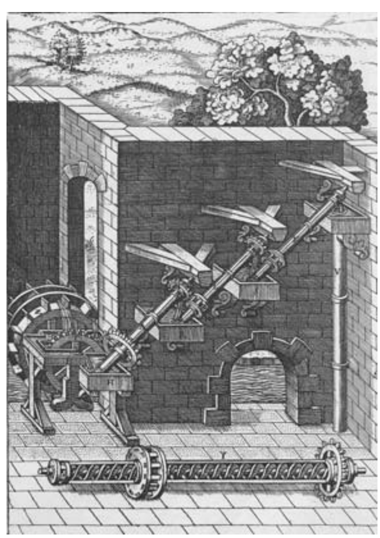


Fig. 4b Plate 64 from Ramelli [25]

[14] Illustration taken from [3], p. 180

Other 16th century authors in whose work we find the screw-pump are Cardano and Ramelli. In Cardano's work we have the Augsburg Machine (Fig. 4a), that actually existed. The pumps are based on helical tubes. In Ramelli's 1588 drawing (Fig. 4b) the pumps are based on two helical blades.

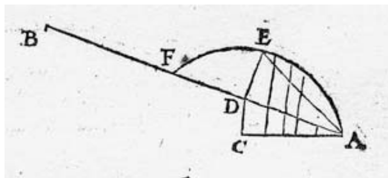



Fig. 5 From Cardano, [5], p. 19

it and so did Galilei. The first explanation of the functioning of the screw was given by Cardano. With respect to Figure 5 (in which AB is the axis of the pump, DC represents its elevation, and the curved segment AE represents the tube wound around the core of the pump). Cardano's argument is essentially this: He replaces the curved segment by the cord AE. He assumes that DE is longer than DC. Then, when E rotates around A, in its opposite position E will be under C, and a weight in A will fall towards E. Clearly this will also be the case when we consider the motion along the curved segment when it is in its lowest position. The fact that a weight continues to fall from E to F when the pump is rotated is explained by Cardano by the impetus the weight has in E and the fact that the situation repeats itself. Cardano in this context seems not to relate the cylindrical helix to a triangle wound around a core. It means that he understood how the screw pump works, but could not really make his insight precise. That is where Galilei came in in the 90s of the 16th century. Galilei wrote about the screw-pump "it is not only marvellous, but it is miraculous" (non solo è meravigliosa, ma è miracolosa – [12], p. 183), because in the srew-pump the water ascends by continually descending.

Galilei considered the cylinder MJKH with the winding line JLOPQRSH round it (Figure 6) The winding line is considered as a channel in which the water rises by descending. The winding line is generated by means of triangle ABC (drawn on the right side very small in Figure 6 just above the horizontal line), which means that the elevation of the channel is determined by angle CAB. Galilei now argues as follows.

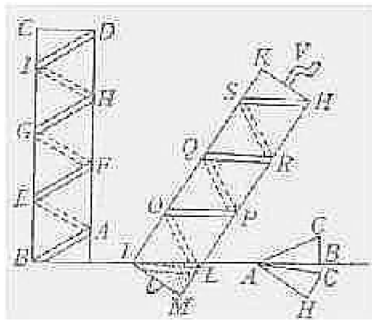
> "Now it is clear that the rise of this channel will be taken away if the point C is dropped to B, for then the channel will have no elevation at all, and dropping the point C a little below B, the water would naturally run out downward through the channel AC from the point A to the point C."

Galilei then assumes that angle A is one third of a right angle and he continues (Figure 3).

> "These things understood, let us turn the triangle round the column, and let us make screw BAEFGHJD. If placed upward at right angles with the extremity B in water, this would not upon being turned draw up the water […]"

However, if we tilt the column through one third of a right angle "the water will move downward from the point J to the point L. And turning the screw round, its various parts successively displace one another and present themselves to the water in the same position as the part JL."[15]

Figure 6 From Galilei's *Mecchanice,*[12]




Galilei concludes: the water raising screw must be tilted a little more than the angle of the triangle that generates the screw. This is fundamental and Galilei seesm to have been the first to prove it and write it down.

THE CALCULATIONS OF DANIEL BERNOULLI

The Archimedean screw raises discrete scoops of water. Daniel Bernoulli (1700-1782), who studied the screw pump in his *Hydrodynamics* (1738),[16] seems to have been the first to study the size of the pockets that contain the water. He considered a tube of infinitely small diameter shaped as a cylindrical helix, generated by wrapping a triangle around a cylinder. The triangle is in Fig. 7b[17] under the horizontal line; in the upper part we have in fact an orthogonal projection of the tilted cylinder on a vertical plane. The projection of the cylindrical helix is a tilted sinusoidal curve. Bernoulli applied the differential- and integral- calculus (at the time less than half a century old). He first determined the height above the horizontal plane H(X) of a point P of the cylindrical helix on the tilted cylinder as a function of X, the angle of rotation during the generation of the helix. The radius of the cylinder is taken equal to 1 and then X equals the arc.

It is not difficult to check that

$$H(X) = X.\tan\psi\ \cos\varphi + \sin\varphi(1 + \cos X)$$

Here $\psi$ is the angle that the pump makes with the horizontal and $\varphi$ is the inclination of the cylindrical helix. It is clear from figure 7a that the pocket that can contain water has a deepest point corresponding to a minumum of H(X) and that one of its endpoints corresponds to a maximum of H(X) Putting the derivative of H(X) equal to zero yields

$$\mathrm{Sin}X = \tan\psi/\tan\varphi$$

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[15] The translation is Stillman Drake's ([9])

[16] For an English translation see [4] and for an annotated German translation see [11].

[17] Fig. 7b is our drawing, suggested by the drawings in the annotation by Flierl ([11])

On the interval $0 < X < \pi$ corresponding to the first section of the cylindrical helix we have no extrema when $\psi > \varphi$; the helix is then an ascending curve and water does not enter the tube. This is in fact Galilei's result, derived differently. However when $\psi < \varphi$ the equation has two solutions. There is a maximum corresponding to point o and a minimum corresponding to point p. Bernoulli remarked that in this case the quantity of water in one pocket is determined by the section opq of the helix; q being on the same level as o. He wrote that the length of this scoop cannot be determined algebraically, but can be approximated in every specific case.
It is interesting that Bernoulli also calculates the force needed to operate the pump. He imagined a weightless helix in which a masspoint is rolling without friction.

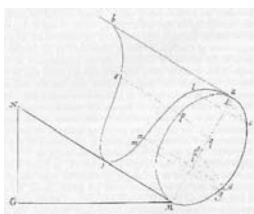


Fig.7a Bernoulli's drawing

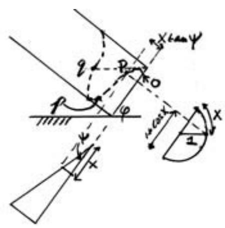


Fig. 7b

Gravity pulls the mass point down and makes the helix turn. He imagined the masspoint at point p, corresponding to the above determined minimum, the lowest point of the pocket. The component of the weight directed along the axis of the cylinder does not have any effect, but the other component makes the cylinder turn. One can easily verify that if the weight is p, the moment about the axis equals

$$p.\tan\psi.\cos\varphi.$$

In the case in which we are not dealing with one pointmass positioned at the lowest point, but in which the whole pocket opq is filled with water Bernoulli determines the moment that the weight of the water exerts about the axis of the cylindrical helix by means of an integration. The conclusion that he reaches is that the same formula applies: if the total weight of the water is p, the moment equals

$$p.\tan\psi.\cos\varphi.$$

and we have the same formula as above.
In or some time before 1755 Leonhard Euler formulated fourteen mathematical problems (*Quaestiones Mathematicae*), that were read in 1757 to the members of the Petersburg Academy. The first problem concerned the need for a theory of the screw-pump. Although the pump was widely and successfully applied still Euler felt the need for a theory, he wrote. As far as we know Euler himself never developed such a theory.

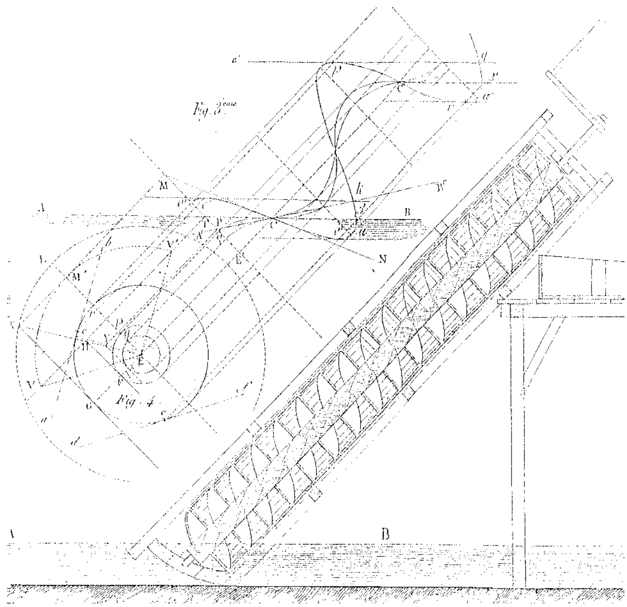
## HACHETTE'S APPROACH

One of the reasons why Gaspard Monge is famous, is the fact that he defined and developed the subject called "descriptive geometry". When the *Ecole Polytechnique* was founded in Paris in 1794, a course in descriptive geometry became obligatory for all students. Part of the course was devoted to (elements of) machines. This part was taught by Jean-Nicolas-Pierre Hachette (1769-1834), who later published the notes in the form of his *Traité des machines*. The goal of descriptive geometry is to make drawings of three-dimensional objects that are such that from the drawing, shape and relative positions of parts of the object can be deduced geometrically. The method boils down to the following. In space two perpendicular planes are chosen, $\Pi_1$ and $\Pi_2$. The 3-dimensional object is projected on both planes and in order to get a 2-dimensional picture $\Pi_2$ is rotated 90 degrees about the line of intersection of the two planes until it coincides with $\Pi_1$. Usually the projection on $\Pi_1$ is in the upper part of the drawing and the projection on $\Pi_2$ is in the lower part. Although the drawings in Hachette's *Traité élémentaire des machines* are all very well made, the use of descriptive geometry is limited, because most of the mechanisms are planar. In important exception is, however, Hachette's treatment of Archimedes' screw pump. Hachette's treatment of the screw is entirely based on descriptive geometry. The pump consists of a cylindrical core and a barrel with a helical blade between them. The blade can be generated by means of a straight line segment with its points describing cylindrical helixes. Hachette considers a case in which the angle between the tangents to the inner helix (described on the core) and the axis of the pump is 45 degrees. Fig. 8 shows the pump and above it the two projections. The projection in $\Pi_1$ is *Fig. 3* in Hachette's numbering and the projection in $\Pi_2$ is *Fig. 4* The sinusoidal projections of the inner and outer helixes are constructed in *Fig. 3* on the basis of Hachette's *Fig. 4* by constructing some discrete points and connecting them by means of a smooth curved line.

Suppose that G (*Fig.4*) and C (*Fig.3*) are the projections of a point on the inside of the barrel for which the tangent to the helix is parallel to the plane $\Pi_1$. GK (*Fig. 3*) and CM (*Fig.4*) are the projections of this tangent. When the pump is working this tangent is rotated about the axis of the pump and describes a hyperboloid of revolution. The question is whether there are positions of the tangent that are such that it points downwards, so that water present at point C would "fall" upwards in the pump. In order to treat this question Hachette considers an arbitrary point on the axis of the pump and considers the cone with this point as center consisting of all lines parallel to positions of the tangent during its rotation about the axis. If the horizontal plane through the center of this cone has two lines of intersection with this cone, the pump will raise water; if there is one or there are no lines of intersection, the pump will not raise water. The border case in which we have precisely one line of intersection leads Hachette to a problem in descriptive geometry: given a cylindrical helix and a plane, construct a tangent to the helix parallel to the plane. Hachette had already discussed this problem in his *Traité de géométrie descriptive* ([15], pp. 142-153).

Hachette points out that the cylindrical helixes that are generated by points on the generating segment closer to the axis are steeper. If the outer helix is such that water can be raised with it, the inner one may be too steep. In fact Hachettte proposes to define the optimal inclination as the one in which the cone corresponding to the inner helix is tangent to the horizontal plane ([16], p. 183).

Fig. 8 From Hachette's *Traité élémentaire des machines*



WEISBACH'S CONTRIBUTION

As far as we know the most complete 19th century treatement of the problem was given by Julius Weisbach ([29], 1851-1860, pp. 811-828). Figure 9 illustrates his approach. The central problem is the volume of water that can be lifted in one pocket. The integral involved cannot be calculated analytically (Cf. [26], p. 80). Weisbach determines the intersection of the water in one pocket with a number of cylinders, in fact slicing up the volume in curved slices, starting from the core of the pump and finishing with the inner cylinder of the outer barrel. He takes the average value of the areas of the slices, and he multiplies it with the distance between the core cylinder and the outer cylinder of the pump. This gives him a good approxiamtion of the volume.

He determines the areas of the curved slices as follows. On the left side of Fig. 9 we have a drawing of the pump in a vertical position in accordance with the rules of descriptive geometry. BFA is the projection on the horizontal plane of half of the core; $B_1F_1A_1$ is the projection of the outer cylinder. The area QSUT in Fig 9 is the intersection of the inner cylinder with the pocket of water. The surface of the inner cylinder is flattened and the intersection of the horizontal surface of the water with the cylinder becomes a sinusoidal curve QTRS. When the cylinder is flattened the cylindrical helix becomes a straight line: QS. Because Weisbach studies a pump with two helicoids, the water is trapped between them. TU in Figure 9 corresponds to the cylindrical helix of the second helicoid. The area of QSUT is determined with Simpson's rule

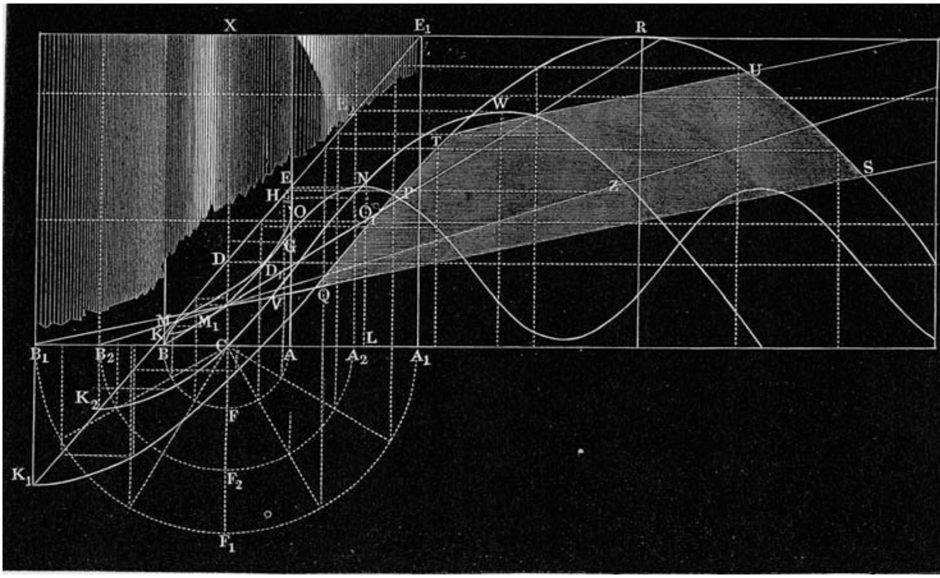



Figure 9 From Weisbach ([29])

## CONCLUSION

In this paper we have concentrated on the theoretical considerations concerning the screw-pump. We have seen that the treatment of the screw in each of the cases we discussed reflected the state of the art in the theory of machines. For a modern treatment we refer to ([26], 2000)..

Inherently the determination of the volume of water that a screw pump can lift is a difficult problem that cannot be solved analytically. Understandably, because of the theoretical difficulties, the pump was also studied by means of experiments. Hachette reports about experiments by Touroude from 1766 ([16], p. 186-187). In the twentieth century experiments were executed by Addison ([1]). Addison concluded that the discharge at a given speed falls off rapidly as the inclination of the axis increases. Because the screw-pump was so popular, undoubtedly more experiments have been done. It seems that still in 1968 in practice rules of thumb determined the design of screw pumps.

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