The water pump

Al-Jazarî's water pump

Arabic mechanics and technology

Three principles dominate mechanics in Arabic tradition : theoretical or static mechanics, the study of hydrostatics and specific gravity, the science of machines, which is a discipline dedicated to the description of machines and the study of how they work. Called in Arabic *'ilm al-hiyal*, which signifies "the science of engineering processes", the science of machine constitutes the forerunner of engineering sciences. It understands the construction and description of machines and the explanation of their applications in different practical tasks: lifting heavy objects, to pump water from rivers and wells, to construct and make work clocks, automations and other ingenious engines.
Some works have been made reference to:
— the *Kitâb al-hiyal (The book of engineering processes)* of Banũ Mũsâ (IXth century) gives the description of a hundred machines of which the majority are sophisticated mechanisms to serve liquids and drinks;

— the *Kitâb al-asrâr fi natâ'ij al-afkâr (the book of secrets about the results of ideas)* of al-Murâdî (IXth century) consists of descriptions of water watches and automations;

— the *Kitâb 'ilm al-sâ'ât wa l-'amal bihâ (book of the science of watches and their use)* of Ibn Ridhwân as-Sâ'âtî (XII century);

— *l'Al-Jâmi'bayna al-'ilm wa l-'amal al nâfi'fi sinâ't al-hiyal (Compendium of the theory and practice in the construction of machines)* of al-Jazarî (XIIth – XIII th century);

— *l'Al-Turuq al-saniya fi'l-âlât al-rũhâniya (methods for pneumatic machines)* of Taqî al-Dîn ibn Ma'rũf (XVI century).

Al-Jazarî : an innovative engineer

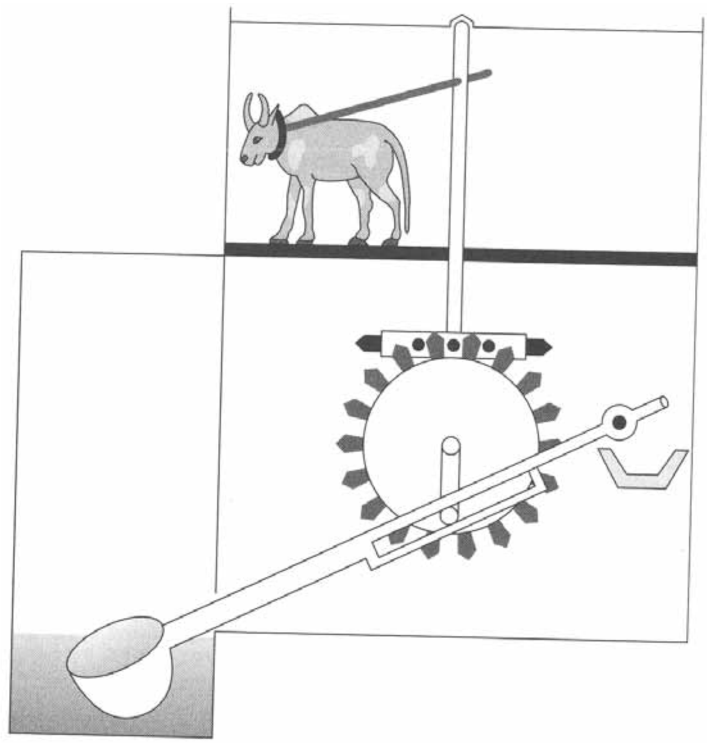
Badî' al-Zamân b. Ismâ'îl al Jazarî is considered as the most famous and innovative of Arabic engineers. He was born in the middle of the XIIth century and he lived in the region of al-Jazîra, situated between the Tigris and the Euphrates. In 1174, he entered into the service of the Princes Banû Artaq who governed the region of Diyarbakir, today in the south of Turkey. At this time, this was a prosperous region, which enjoyed peace and stability. Living at the court of the Princes Artulides and benefitting from favourable work conditions, al-Jazarî rose in grade and ended uP functioning as Ra'is al-a'mâl (chief engineer) of the principality. It was at the behest of the ruling prince that he conducted his great treatise in mechanics, the only one that has been left to posterity. According to all probability, al-Jazarî died in 1206, some months after having completed his work.

The book in question is a monumental work in fifty chapters, which represented some impressive mechanics. These fifty chapters were divided into six categories: ten chapters were dedicated to clocks and clepsydras, ten for receptacles to serve drinks, ten for receptacles and vases for ablutions and bleeding, ten for fountain spouting and intermittent and constant flutes, five for machines to raise water and five to diverse machines.

The work contains such details that show the technological mastery of the author. In fact, this was one of the best engineers of pre-modern times. Also he improved the design of several machines in existence at the time, al- Jazarî fully explained the methods of construction and assembly of fifty machines that he studied in his book.

Mechanism of the water pump

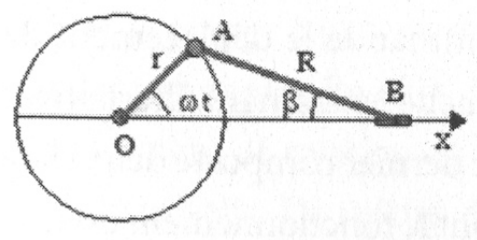
Al-Jazarî dedicated the fifth chapter of his book to machines that rose water, of which two were pumps. The first of these pumps (see the design on the following page) had a fixed crank on a toothed wheel whose circular movement is fed by a stalk moved by an animal installed on a raised platform.



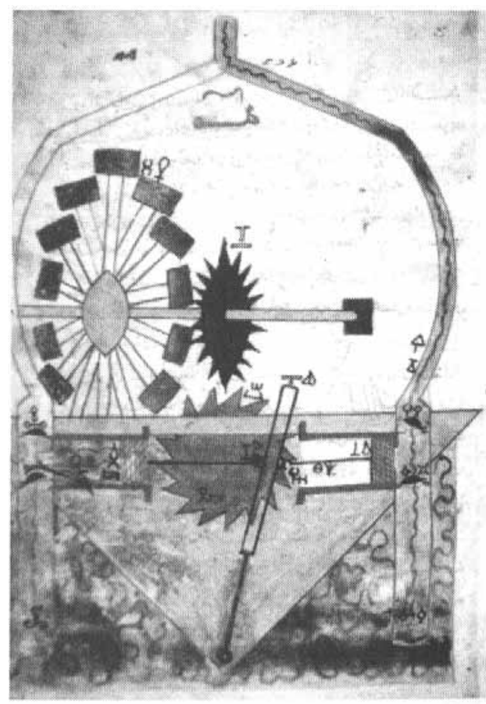
The crankpin of the crank slips over the interior of a practical opening in the sleeve of the ladle, which is fixed at its extremity in a way to not let it spill out to the sides. In turning under the effect of the circular movement of the toothed wheel, the crank makes it displace at the top, then the bottom, the sleeve and the ladle and, by consequence, the scoop of the latter. The scoop is refilled as it passes into the water on its downward pass as it becomes horizontal; the water is poured out by the extremity of its hollow sleeve into an irrigation channel and from there, to the chosen place.

The second of the two al-Jazarî pumps, bore an important technological innovation, fairly significant in the history of technology. It consists of the first complete application of the crank with connecting rod, some three centuries before this technique made its appearance in Europe.

The principle of the crank with connecting rod is: a stalk OA of length r turns around O at the constant speed ώ. A stalk AB allows the transformation of the movement of rotation of A into a rectilinear movement. It is hinged in A and a slippage obliges point B to rest on Ox. This system permits other things, to transform a rotation movement in one alternative transformation movement (to and fro). Several modern machines are based on this simple mechanism in theory but quite complex to put into operation as the jigsaw, sewing machine and piston engines.



The al-Jazarî pump is in fact made out of two pumps, one sucking the other exhaling in an alternate manner. In this double pump (see document below and page 137 also), a water wheel turns a vertical toothed wheel which, in turn, turns a horizontal wheel. The latter making the oscillation of two opposed pistons made out of copper. The cylinders of the pistons are linked with sucking and exhaust pipes which have opening and closing valves, they only open in one direction (upper). The sucking pipes put the water into a ditch, at a lower level and the exhaust pipes discharge it in the irrigation system, situated 12 m beneath the pump installation.



The al-Jazari pump (taken from the manuscript of Ahmet III 3472, Topkapi museum, Istanbul.

The working of this sucking and exhaling pump can be described as follows. The fixed blade wheel at the end of a horizontal beam is powered by running water. In turning, it powers the toothed wheel placed at the other end of the beam. The teeth of which enmesh with the teeth of a crank-pin disc placed at the end of a beam parallel with the first. The fixed crank-pin on the toothed disc forces the deplacement of the sliding beam to the right and left, operating alternatively one and the other pistons in its cylinder. This latter has two valves, one for sucking and the other for exhaling, its operation being carried out by variations in pressure. Each piston is made from two discs placed at the end of a stalk. Between these two discs a linen file is rolled which plays the role of a watertight joint and increases the efficiency of the pump. The piston and the stalk form a solid movement action of translation in relation to the axis of the cylinder.

The two pumps operate in the following manner. The sucking valve of one of the two cylinders being open, the piston, in its movement pulls in a volume of fluids at a constant pressure; after which the sucking valve is closed, compressing the fluid without any change in volume and opening of the exhaust valve. Then, the piston, in its inverse movement, re-pushes the volume of the fluid upwards at a constant pressure. When the cylinder is completely empty, the exhaust valve closes whilst the inlet valve opens to allow the water to be again sucked into the cylinder by the piston.

The to and fro movement of the two pistons is powered by a connecting rod crank system which transforms the continuous circular movement of a crankpin disc in an alternative rectilinear movement of the stalks of the two pistons.

According to the sketch of the figure on page 137, the output of the two pistons and, accordingly, the sucking and exhaling cylinders [inlet and outlet] can be described as follows: On the instigation of piston N, the water is sucked from the river into the cylinder T and put out into the tube F towards the ditch and, from there, to the chosen dispersal point. Reciprocally, on the return of the piston N, the water is drawn into the cylinder S before being put out via the tube Z.

From the innovation of the principle that rules, the ingenuity of its concept, the complexity of the different phases of its operating, the difficulties of the construction of its components, the al-Jazari piston pump is in a prime position in the evolution of technology. In effect, it incorporates an effective means in converting rotational movement into a rectilinear movement thanks to the connecting rod crank. Also, it makes use of the principle of double action and introduces for the first time pipes that can suction liquids. Moreover, our mechanic describes its everyday usage, and does not make a big deal out of it, as he does with his other inventions and his advanced originality at the beginning of his book. This "nonchalance" perhaps indicates that this pump was already in use when it was described by al-Jazari. However, the fact that it was singled out for presentation at the end of his penultimate series of inventions (the last, from the appendix, did not show any new machines) lets us think that he was aware of its value in that such an original invention represented the summit of his craft.

By his innovations, the al-Jazari pump can be considered as the first suction pump. The claim that the Italian engineer Mariano di Jacopo Taccola was the first to describe a drawing up pump has not been proven. It is probable that the appearance of the suction pump in the mechanical treatises of the European Renaissance came from an Islamic source. Until the present time, we do not have any information about the circulation of the al-Jazari treatise in Europe in this era, but it cannot be excluded, at least by virtue of the large amount of works in the Islamic world and the multiple means of exchanging information and the transmission of scientific technology between the two banks of the Mediterranean during medieval times, a communication network for science existed in several disciplines.

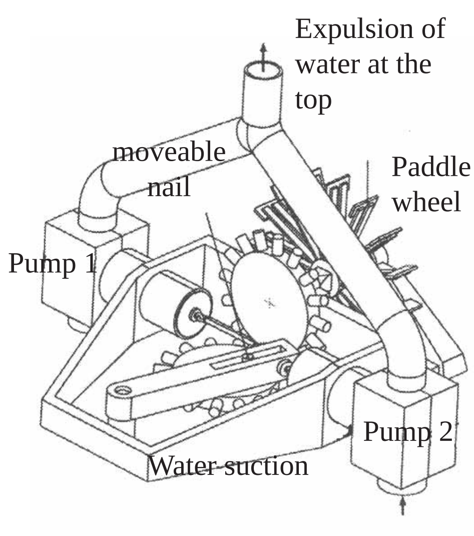


Diagram of the al-Jazari pump

How to draw up water from a river?
The invention of the al-Jazarî pump

Objectives

There are devises allowing the transmission of rotational movement:
Toothed wheels.
The connecting rod crank system allowing the transformation of rotational movement into translated movement.

Reference to the science and technology program for year 3 primary school

“The world constructed by man : transmission of movements”.

Equipment

Dishes, water, supple pipes, plastic T squares for diversion, syringes, Celda© technology kit, wooden beams, cardboard roundels.

It has been a long long time since the human race deployed its powers of thought and invention to fathom out the various ways to get the water necessary to irrigate their fields. The recourse to pumps, especially, allow us year around to draw up water from the rivers. This itself is then transported by canals, sometimes far away from where it was drawn, to different parts to be irrigated. The invention of pumping machines was undertaken in the Middle Ages. They were the fruit of contributions from several Arab speaking savants. It is the one of al-Jazarî that we propose to study with the pupils.

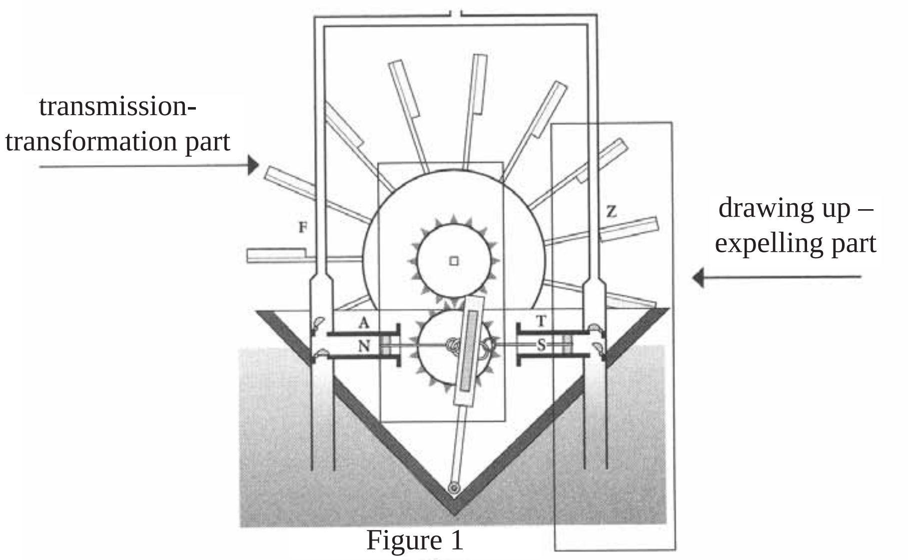


Figure 1

The model presented here is structured around four activities. The first looks at the suitability of the problem for the pupils; “How to draw up water from a river?” The following two parts have the purpose of getting the pupils to discover the specific parts of the pump that we choose to study separately in a way so as to not overload the pupils’ learning curve. The hydrostatic part “drawing up / discharging” will therefore be studied in itself (activity 1, see the following figure), whilst the mechanical part concerns the transmission and the transformation of the movement (activity 2, also see below); the fourth activity having the purpose of associating these two parts, studied separately, whilst understanding the overall mechanics of the pump.

Introductive activity:
Exploitation of the text for children

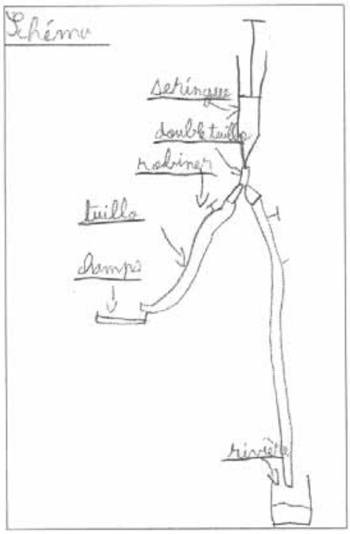
The debut activity: reading of the text by children. The pupils should discover there the problem that they are going to have to solve, the problem about which we are concerned: “Imagine that the savant al-Jazarî could have suggested to Nabil to pour water on his sister Fadilla even when he finds himself higher than the river bank”. In this first phase, that we call “introductive activity”, the role for the text is therefore to introduce the question to the pupils. They are asked to imagine (in an individual manner) a way to draw up water from a river, which would then be able to be used to irrigate fields that are higher up.

The children's text contains a certain number of clues about the roads that the pupils could explore in order to solve the question in hand. The movement of the "winch" Nabil's arms lead onto the road of the bladed wheels: some of the pupils have in their head images of windmills whose wheel is powered by the river current. They understand that will allow the drawing out of the river's water, but they are at pain to conceive the manner in which this water can be gathered before it returns to the river, as it is carried by the movement of the wheel. It is therefore necessary to find a way to "push" the water to the edge of the wheel when it is higher up. We have a discussion here to form a collective result where everyone can express his ideas. The construction of such a machine would need a double reply; first the water needs to be raised, and then pushed on. All this needs to be done without tiring you out.

Activity No. 1 :
Draw the water by suction and expulsion

The children are equipped with basins full of water, taps, a syringe, supple pipes, T squares to divert it. They must find out how to get the water from a basin on the floor to a basin on the table. They notice that it is possible to lift the water by suction but that it is then impossible to re-gather this water into a receptacle. A problem is asked then: how to conserve the water that you succeed in raising to a certain height? This difficulty necessitates imagining a complementary device: to draw up the water, certainly, but you need to have the means to recover it. The pupils share this problem out between them and discuss possible the solutions. The idea of an intermediary reservoir, higher up, is then introduced; it is the water of this reservoir that will then be expelled.

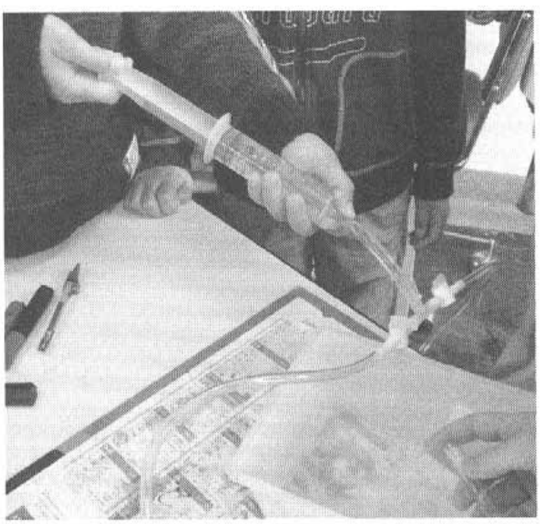
The full device as thought up by the pupils comprise of the following elements: a first pipe on which is placed a tap R^1, a T square on which the syringe is placed, a second pipe with a second tap R^2 placed on it (see following schemas and drawings)

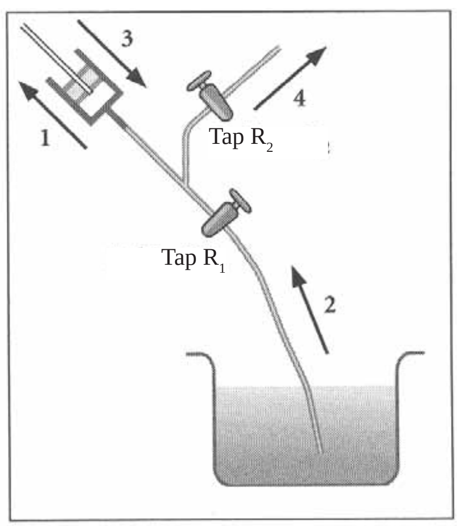


Benjamin’s drawing (CE2)

Myriam’s drawing(CE2)

The device therefore works in two stages. First, the water is drawn up into the reservoir of the syringe by suction (1 and 2 in the below schema) via a first tube. The tap R^1 is open, R^2 is closed. You close R^1, and open R^2, then you push the piston of the syringe (3) in a way to expel the water to the intended place (4).





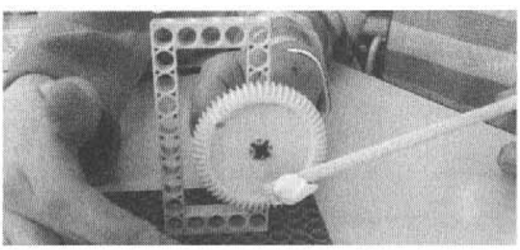
At the end of this activity, the pupils understand that the drawn water depends on the coming and going movement made by the piston of the syringe. We still have to find the means to do this without human intervention.

Activity No.2 :
To transmit and transform a movement

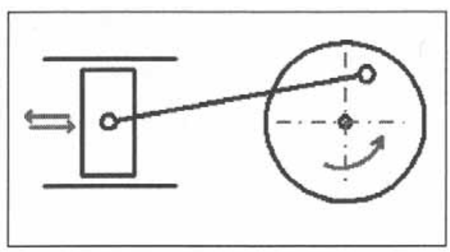
The aim of the preceding activity was to draw up water from a basin. Now, in the children's text, it is a question of water from a river. This is a movement, contrary to the water from a basin, and this movement allows the turning of wheels. This idea did not escape the pupils when they read the children's text. It is carried out in the following sequence.

Stage 1 : Transforming a rotational movement into a to and fro movement

After having reminded the pupils of the problem that was left in suspension at the end of the preceding activity (to find the means of maintaining a coming and going motion of a piston without human help), the teacher comes back to the idea of the paddle wheel as some had suggested. He explained to them that it is possible to use the motion of a wheel to create a coming and going motion. But how to do it? To reply to this question, the children equipped with a wooden beam at the end of which there was a cardboard roundel adapted to the reservoir section of the syringe; this beam replaces the piston, which was too difficult to insert in the syringe's reservoir. They also had a toothed wheel and some glue. This stage needs a little research which the master determines. The idea of motion having been researched, it is necessary to fix the beam on the wheel itself (see figure below on left). They will discover through the system "connecting rod crank" (see figure below right).



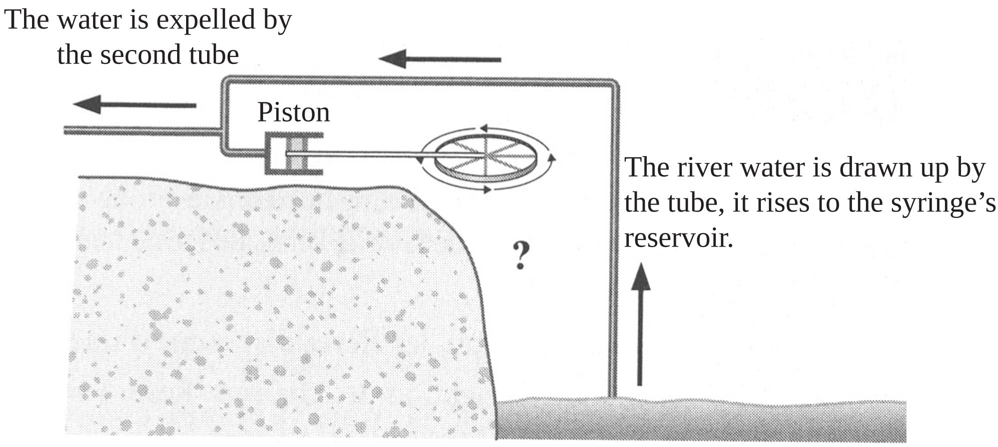
The coming and going movement of the wooden beam connecting is obtained by a connecting rod crank; in turning the wheel (rotation), the beam is moved forwards and backwards (translation)



Drawing of the rod system

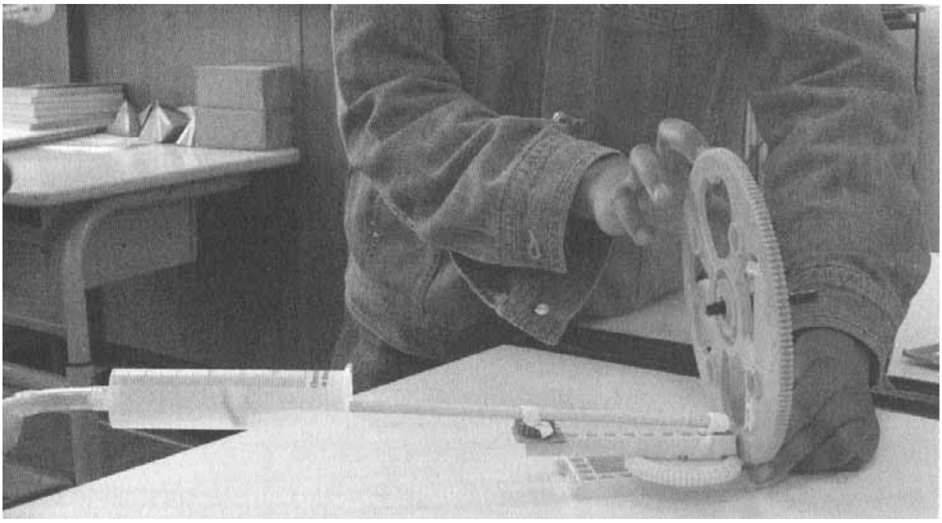
Stage 2 : Changing the rotation plan

We have from now on the means to maintain the coming and going motion of the piston without using human strength and this is due to the rotation of a wheel. always, there is a new problem that crops up this wheel relies on the wooden beam being situated near to the beam, at the same height and in a horizontal plane. It cannot be in direct contact with the water in the river. The schema of the figure below explains this. It is reproduced in the table.



Here, the wheel is not vertical, (see the two preceding illustrations), but horizontal. In the same way as in the preceding example, the movement of the wheel’s rotation makes the coming and going movement of the piston. It is now necessary to add a second wheel, this time vertical. This is what will drive the horizontal wheel due to the current of the river.

To power the horizontal wheel, it needs a second wheel, placed vertically and sufficiently big to be in contact with the water. This is what will be powered by the current. It will be called the “leading wheel”. The pupils will discover by this bias that two toothed wheels can be enmeshed one to the other in a rotational manner, when they are not situated on the same plane (see following photo). They put this in place with the Celda© kit. The first wheel is vertical and powered by the current in a rotating movement. This powers the second wheel set horizontally in an identical movement. The latter plays the role of the crank; it powers the wooden beam in a coming and going motion which allows the suction then the expulsion of the water to be drawn.



The rotation movement of the horizontal wheel (crank wheel) is obtained thanks to that of the vertical wheel (driving wheel)

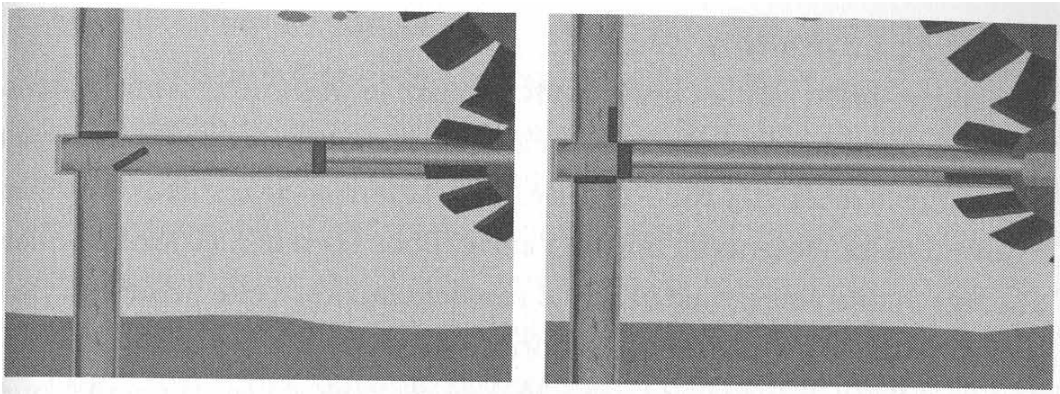
Following the outcome of these two activities, the students have now the means to solve the irrigating fields' problem. We now need to know if this solution is similar to the one imagined by the scientist al-Jazari.

Activity No. 3:
Understand the functioning of the al-Jazari pump

The animation "The al-Jazari's water pump" presented on the project site allows the students to discover and understand the suggested solution by al-Jazari during the XII century, and to compare it to their own solution. The purpose of this activity is for them to grasp the general idea about the functioning of the al-Jazari pump (in particular, the role played by the valves and the principle of double suction) and to lead the students to describe the different components of the pump, as well as their role played in the river water routing.

The role of the valves

The pump invented by al-Jazari is composed of a piston moving inside a cylinder and of valves allowing the fluid to enter and exit the pump – they replace today's water taps used by students.



This animation extract shows the piston rotating by the slider crank mechanism. When the rod moves backward (left drawing), the first valve opens and lets the water from the river flow in by way of suction. The forward movement of the rod pushes back the piston, causing the valve to close (Right drawing). The water is then pushed backwards, leading the second valve to open, causing the water to flow upwards into the upper pipe, under the pressure of the piston.

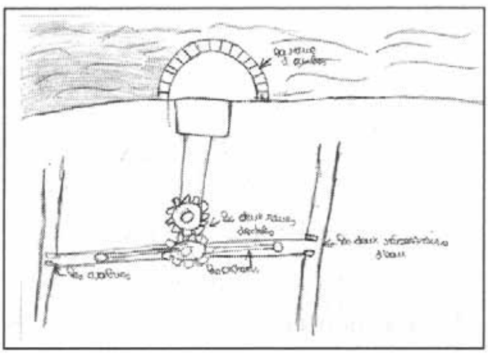
When the piston moves towards the right (Left drawing), this creates a pressure drop in the cylinder; the valve rises up with the pressure from the suction of the fluid, allowing the cylinder to be filled up. When the piston moves towards the left, the fluid inside the cylinder is put under pressure, causing the suction valve to close up, preventing the suction of the fluid. The delivery valve rises up under the pressure, causing the fluid to flow towards the delivery pipe (Right drawing). The shift of the piston is obtained through a rotating movement of a gear wheel (the crank wheel), powered by several other wheels, with the last wheel placed under water in the river, being powered by the current.

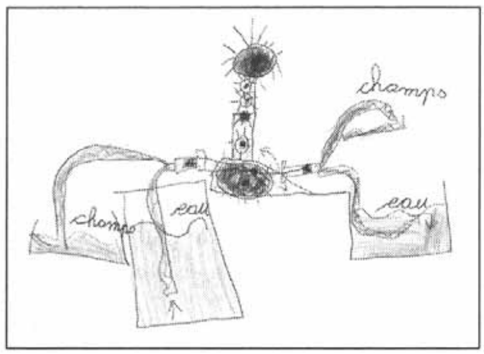
Second step: the double suction

In fact, the al-Jazari pump is composed of two identical suction systems: while a piston creates a suction effect on one side of the crank wheel, on the other side, a second piston pushes the water out of the cylinder. The advantage of this mechanism is discussed in class.

Stage 3 : the number of wheels

There is another difference, which concerns the number of wheels. In the al-Jazarî pump, the vertical wheel driven by the river is not directly linked to the horizontal crank-wheel for these two wheels are situated at a distance further away from each other. To link them, al-Jazarî uses a beam and a supplementary small vertical wheel. This small wheel is engrained in the horizontal crank-wheel and linked to the big wheel by the intermediary of the fixed beam at the centre of these two wheels: the vertical big wheel turns under the effect of the river current, with it, it drives the beam which turns the small vertical wheel that in turn drives the horizontal crank-wheel. Finally, the pupils have no problem in retracing the different parts of the pump and their roles in the transfer of the water, as is witnessed by the following drawings:


Marcelle's drawing (CM2)



Kevin's drawing (CE2)

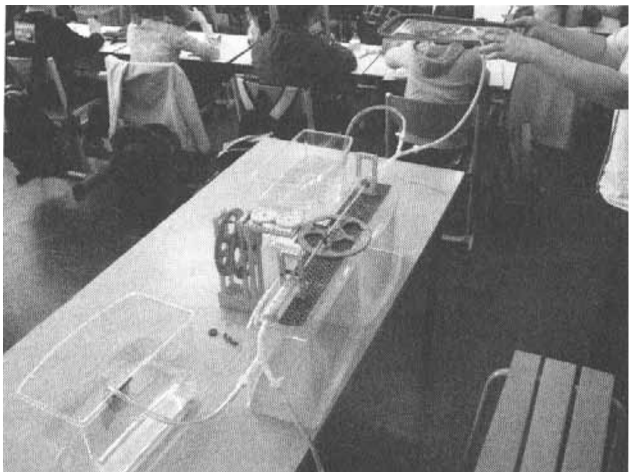
This series of activities is undertaken by the realisation in class of al-Jazari's pump with the help of the teacher. There you find the double suction, the assembly of the vertical wheel (the wheel driven by the current) with several horizontal wheels. The valves are replaced by the taps used during the first activity, and the pistons of the syringe's by the wooden beams in the second. The pump thus realised by the role of the model but with the following modifications:

— the leading role not being in direct contact with the water, had to be driven by hand;

— the piston roundels not being perfectly adjusted to the reservoir of the syringes, the suction was not perfect and the quantity of water recovered was small;

— the taps were not replaced by valves, the operation of the pump necessitated the involvement of several people.

These inconveniences and the constraints that they were under (no river in the classroom, no valves etc.) were discussed in class and made clear to all. The construction is a tenable support for reasoning and an opportunity for all to make an association with "hydrostatic" part of the pump and the "mechanics". It also gives the opportunity for the pupils to explore other systems for the elevation and carriage of water (such as Archimedes, scoop pump, etc) as a written exercise and to compare them with the al-Jazarî pump.



The details of the pump constructed in class

The pupils are now ready to send a letter to Nabil and Fadilla, in which they can describe in great detail the machine that they conceived and constructed. The problem of drawing the water from the river has given them the opportunity, in a concrete fashion, to visit one of the best technical inventions in the history of Arab science.

Note

1. You can draw water by suction with the piston of the syringe and a pipe (or straw). But be aware that you cannot raise the water to an infinite height. Any further than 10 metres high the atmospheric pressure on the water surface is no longer sufficient to compensate for the pressure exercised by the water in the pipe (or straw).

The favourite game of Nabil and his sister Fadila was to resolve the enigmas which occurred when they were observing what happened around them, or in them. They were more passionate about this, than others of their time were, a little magic was about them, like the day when they were trying to think of a machine that would draw up water for them.

It all started with their favourite walk along the riverbank. It was hot that day. They decided to leave the little dry path and went down into the middle of the reeds. Their feet in the water, Fadila closed her eyes while delighting in damping her face and neck. Seeing her, Nabil, always ready to tease, suddenly had an idea. He wanted to agitate her and started by splashing her, making windmills with his arms on the water's surface.

— Stop it right now Nabil, you are such an idiot!

— Didn't I do what you wanted? Are you not refreshed now?

Fadila, furious, climbed up the riverbank to seek refuge:

— I am soaked, but cunning as well! Up here you can't splash me.

Nabil stopped directly. Effectively, even with the most vigorous of windmills he could not reach his sister. Puffed out, he went further into the rushes. In front of her scowling brother, Fadila came down from her refuge and approached him laughing:

— So Nabil, you're in the huff!

— No, not at all, I'm thinking! I am thinking about inventing a machine to soak you, even up there!

What a good idea! It could water the fields, it would be more useful than annoying me! Come on stop making that face, I am going to help you. Firstly, we have to make a windmill on the riverbank that will take the water from the surface of the river. That you know how to do, because you know about windmills!

And Fadila was trying to dry her wet hair. Nabil replied to her with a grimace, then said:

— After that, we have to push the water further on. But how can we do it?

Fadila put her hand on his arm to signify to him, to be quiet. Coming out from behind the rushes, a man with a turban on and a blue overcoat came to sit down near them. He observed the course of the river quietly then spoke to them with a smile:

— I have been watching you since you were on the riverbank. Did you know that your games provide some interesting experiments and that you have had some good ideas? I am called al-Jazari and I have made the machine that you tried to imagine. If this interests you, I can explain to you how it works. Come on!

The man got up and took out from his coat some plans with toothed wheels, beams and pipes on. Nabil's and Fadila's eyes shone with curiosity. They got up in one bound and followed the man who disappeared with them into the rushes.

What happened next has not come down to us, it was such a long time ago, the memory is lost! It only remains that al-Jazari was the first to conceive the ingenious machine to pump water . . . And in one way or another, as he accompanied Nabila and Fadilla, he can accompany you today and all those who ask the same questions. In one way or another. . .