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# On the prehistory of programmable machines: musical automata, looms, calculators

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**Abstract**

An important characteristic of modern automation is the programmability of the machinery involved. Concentrating on the aspect of programmability, in this paper an attempt is made to study the following three kinds of machines in their pre-twentieth century development: computers, weaving looms and music automata. © 2001 Elsevier Science Ltd. All rights reserved.

**Zusammenfassung**

Zusammenfassung: Die Programmierbarkeit von Maschinen ist ein wesentlicher Zug der modernen Automatisierung. In diesem historischen Aufsatz wird die Entwicklung von drei Typen von programmierbaren Maschinen – Rechner, Musikautomaten und Webestühle – kurz im Zusammenhang skizziert. Der Autor beschränkt sich auf die Zeit vor dem zwanzigsten Jahrhundert und auf die Wechselwirkungen, die es zwischen der Entwicklung dieser drei Automatentypen gibt. © 2001 Elsevier Science Ltd. All rights reserved.

*Keywords:* History; Automation; Programmable machine; Loom; Music automaton

## 1. Introduction

In this paper, I will consider pre-twentieth century programmable mechanical devices and I will try to answer the question: "What were the earliest programmable machines and what was their development?" I will use the following definitions: "*An automaton (Greek, 'self-mover') is a mechanical device which (after releasing a brake) executes a function on its own and in a completely*

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*determined way*" [19, p. 131]. Moreover, "*A programmable machine is an automaton that can execute (significantly) different functions depending on the information stored on one or more material information carriers, that are part of the automaton*". A restriction to pre-twentieth century developments makes life conceptually easy. For example, we do not have to answer the question in what sense devices like software robots or agents are automata.

## 2. Heron's automatic theatre

The Greek inventor Daedalus is the prototype of a mechanical genius. He is well known because of the wings that he allegedly designed for his son Icarus. It is, however, also reported that he built moving statues. The wings as a working design, undoubtedly, belong to the realm of fiction, but it is said that he used mercury to change the centre of gravity of a statue and make it move, which does not sound impossible. There are also reports of the existence in Antiquity of heads that spoke. Also in the Indian and Chinese cultures there are stories about mechanical men or animals moving autonomously. Undoubtedly the stories are a mixture of fact and fiction. Central elements in antique mechanical engineering are winches, toothed wheels (with triangular teeth), levers, pulleys, wedges and screws. Drachman's description of the mechanical theatre of Heron of Alexandria (1st century A.D.) gives a good idea of what could actually be done in Antiquity:

> The moving force is a heavy weight fitting into a container full of millet or mustard seeds; the seeds run through a narrow hole, the weight comes down at a determined rate, and it turns an axle from which it is suspended by a cord. All the movements are taken from this axle by means of strings. A puppet or any other thing is turned by a string going round a drum; if it has to turn back, the string is passed over a peg in the drum and wound the other way. [...] If a thing has to happen only once, as a backcloth being dropped, it may be worked by a separate weight which is released by a string pulling out a pin. [...] A movement of the arm of a puppet, e.g., hammering, is produced by pins on a wheel acting on the short end of the lever [7, p. 197].

## 3. The Banu Musa's automatic flute player

Heron's automatic theatre was an automaton, but it was not, in my sense of the word, programmable. The earliest known design of a programmable machine is the automatic flute player that was described in the 9th century by the brothers Musa in Baghdad, at the time a major centre of knowledge. The Banu Musa's work was influenced by their Hellenistic predecessors, but it contains notable advances on the Greek work. They ingeniously used small variations in air and water pressure and they used conical valves as automatic regulators [13, p. 60]. The basic idea described in *The Instrument that Plays by Itself* is that pins on a rotating drum open via little levers one or more of the nine holes of a flute, which is positioned parallel to the drum. The wind for the flute is generated by water that fills a reservoir and forces the air to escape. The drum is driven by a water wheel [8, pp. 88–118] (see Fig. 1).

Strandh [20, p. 176] states that the Arabs could easily have invented the mechanical clock, had not the Mongols attacked the eastern parts of the Arabic empire. Baghdad fell in 1258. However,

Fig. 1. The Banu Musa automatic hydraulic flute player (Reconstructed by Farmer [8, p. 101]).

the raids of barbaric tribes were only one of several factors that brought about the decline of Islamic science. According to Al-Hassan and Hill [13] religious fundamentalism, following economic and political erosion, was another factor. The more liberal early Islam had been the driving force behind the Arabic interest in science and technology.

## 4. Clocks and carillons

During the early Renaissance developments accelerated. We find the earliest description of an, in principle, programmable music automaton in a manuscript from Catalonia in Spain, dating from about 1300. It is a carillon of bells on top of a waterclock (clepsydra). The drawing is not very clear. It shows a carillon consisting of five bells and a wheel carrying ball-headed pins (Fig. 2). There is also music for the carillon in the manuscript, from which it follows that the number of bells must have been ten [10]. Presumably the carillon started playing after the water clock released a crank. The drawing in Fig. 2 is intriguing. It is not clear how the carillon could have played the accompanying music with only one wheel. The wheel in the drawing may represent a cylinder.

It must have been one of the last water clocks that was made in the West, because clocks using weights and a mechanical escapement were at that time introduced everywhere. Those first mechanical clocks left a great impression on the people. The Strasbourg clock, for example, with its wrought iron cock that moved, became very famous. It was built in 1354. "At noon the cock opened its beak, stretched out its tongue, flapped its wings, spread out its feathers, and crowed, the crowing being produced by bellows and a reed" [6, p. 81]. For many 17th and 18th century

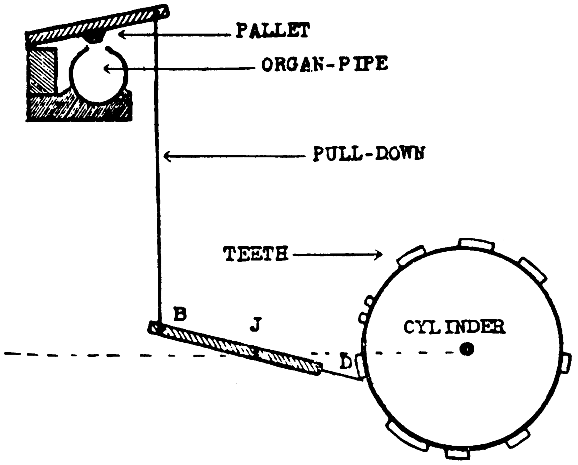


Fig. 2. Catalonian carillon, ca 1300 [10].

philosophers the first mechanical clocks also made clear how God's creation could be understood; it should be seen as an immense clockwork.

The first automatic carillons were small and used in monasteries and churches. Still in the fourteenth century the mechanical clocks on the towers were at most connected with a few small bells that rang when pins on wheels hit levers. These simple carillons were in principle programmable. Lehr gives the example of the Dutch town of Oudenaarde, that acquired in 1504 new wheels that played "Veni Sancte Spiritus" on the whole hours and "Peccatores" on the half hours [16, pp. 89–90]. Apparently the entire wheels had to be replaced to get another tune. Soon, however, about 1530, the cylinder with removable pins was introduced in the automatic tower carillon. At that time such carillons possessed two octaves. In the 17th and 18th centuries the automatic carillon was in particular popular in The Netherlands, Belgium and Northern France. In the automatic carillon of Bruges in Flanders even 120 keys could be played [12, p. 62].

Parallel to the development of carillons, from the 15th century programmed music was often incorporated in astronomical clocks in churches and palaces. In the 16th century also chamber musical instruments with a program on a drum became rather popular. The early automatic mechanical and hydraulic organs also date from that period. For details I refer to [12].

## 5. The first programmable looms

Although much more could be said about the further development of music automata in the 17th and 18th century, I will now turn to the history of weaving, basing myself largely on Van Gorp's work [11]. A loom must provide for "shedding": raising and lowering the "warp" threads so as to form a space through which the "weft" may be passed. The warp threads are raised and lowered by means of "healds". In a "handloom" healds usually consist of a number of strings, which are secured above and below to wooden "shafts". Each string is knotted near the middle to form a small eye. Large figured effects were produced in "drawlooms", where the warp threads were separately controlled by strings so that each assortment could be lifted separately. A draw boy would pull the strings while the weaver attended to the picking and the batten. The drawloom is very old. During the late Han Dynasty (China, 25–220 A.D.) highly figurated silk textiles sometimes had 5000 warp threads on 38 cm width and 1000 weft threads on a height of 38 cm. The weavers of these textiles must have used either a big handloom or a drawloom. From the Han period there are no illustrations, but we have pictures from the Ming showing big drawlooms with a drawboy or drawgirl sitting on top of them (Fig. 3). The weaver shouts his instructions to the drawboy or the boy has a description in front of him, and the boy pulls the strings accordingly.

In the course of time the drawloom reached the Middle-East. Syria and Byzantium were important centres. Islam brought the drawloom to Europe. First to Spain and later to Sicily. For some time Palermo was a major textile centre. In the 13th century, the drawloom spread from Sicily to the rest of Italy and from there to France. The Italians, undoubtedly, improved the looms, but no names of inventors are known. The technical problem that interests us is the drawing problem. The more complicated the pattern, the more complicated the drawing problem. An interesting invention is the button drawloom. It is sometimes described as a French invention.

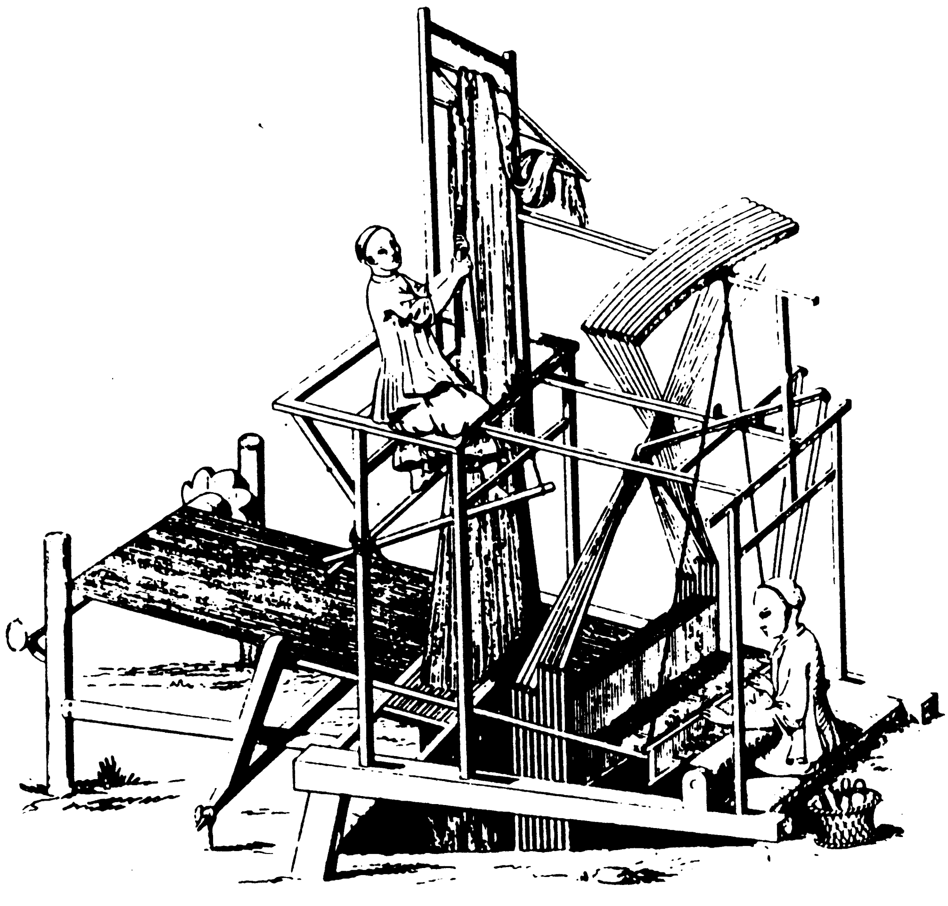

Fig. 3. Sketch of a Chinese drawloom of the type that presumably goes back to the Han Dynasty [11, p. 2000].

In France, silk weaving was done in Royal state-owned ateliers and data on new inventions were collected and centrally kept. This was later, from 1798, done in the Conservatoire des Arts et Métiers in Paris. Because French history is well documented some of the early inventions are sometimes wrongly attributed to French engineers. Button drawlooms existed already in the 14th and 15th centuries in Italy. Rodon y Font believes that already in 4th century Syria button drawlooms were used [11, p. 260]. In a button drawloom healds or shafts are connected to buttons that hang in front of the weaver, so that he can weave without a drawboy. Van Gorp [11, p. 258] writes that according to Pariset, two Frenchmen, Galantier and Blache, invented the button board (planche á bouton) in 1687: the strings leading to the buttons run through holes in a rectangular board. The buttons in this way have a fixed position on the board and in particular when they are numbered the job of a drawboy becomes much easier and mistakes are avoided.

The "simple drawloom" was not a French invention either. It came from Italy as well. In the simple drawloom combinations of healds are tied to simple-strings. By pulling combinations of simple-strings a pattern can be woven. The simple-strings are, for example positioned vertically in front of the drawboy. For each combination of simple-strings to be pulled lashes tied to those simple-strings are tied together in a "gavacine" (Fr.) (Fig. 4). The pattern to be woven is determined by the series of gavacines that the drawboy must pull successively and that hang above his head. He moves one gavacine after the other down into the pulling position and pulls it. The simple drawloom in this form is clearly almost programmable. The task of the drawboy is in fact reduced to a few simple movements, that are repeatedly executed. One is reminded of the Eniac (1946), one of the first programmable electronic computers, that had to be rewired in order to execute another programme.

We do not know when the simple drawloom in this form was invented. It may have been in use already in Renaissance Italy. However, the next step forward was made by Bouchon in 1725 (Fig. 5). Bouchon's invention at heart consists of an ingenious device which automatically separates the vertical simple-strings that must be pulled from the simple-strings that must not be pulled by means of a row of needles and an endless perforated tape. The draw-lashes and the gavacines are no longer needed. The needles are pushed against the tape. If the needle finds no hole the corresponding simple string is pushed backwards and the "pearl" that is fixed below on the string moves also backwards out of the reach of a lever that is pushed downwards by means of a pedal. Bouchon's invention was brilliant. Yet its success was limited, mainly because only one row of simple-strings could be varied so that it could only be used to weave simple patterns. Bouchon's design was improved by Falcon. Falcon's 1742 loom had a needle-case that contained four rows of needles. The paper tape was also replaced by a string of punched cards. From 1762 dates an even further improved version of that programmable loom. In 1775 in Lyon more than 100 looms had a Falcon control. Yet, although the task of the drawboy had become extremely simple, he was still needed to push the punched cards against the needles.

## 6. From De Vaucanson to Jacquard

Jacques de Vaucanson (1709–1782) exhibited in 1738 an automaton that made his designer immediately famous. De Vaucanson is only one of several great 18th century builders of automata. De Vaucanson's automaton was a mechanical flute player, that played so well that the

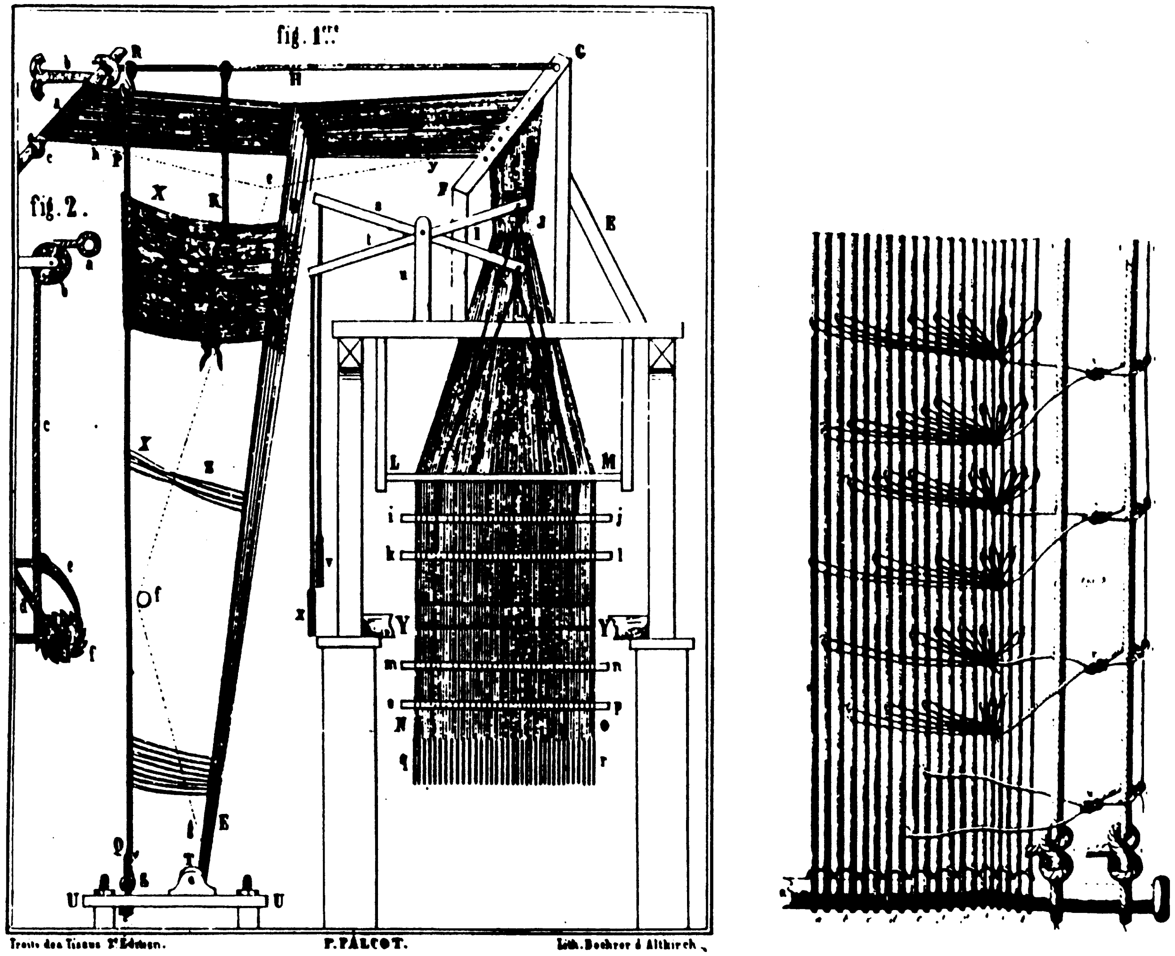

Fig. 4. Sketch of a simple drawloom. On the left side one can see the vertical simple springs connected by means of "gavacines" to the "gavacinière". The sketch to the right shows the "gavacines" in more detail [11, p. 268 and p. 270].

audiences refused to believe that it was an automaton. In the same year De Vaucanson exhibited a mechanical duck that ate, drank and evacuated the digested food afterwards and a mechanical shepherd, which played tunes on a shepherd's pipe with its left hand, while beating a drum with its right hand. The three figures were soon exhibited all over Europe. Voltaire wrote: "Le hardi Vaucanson, rival de Prométhée, Semblait, de la nature imitant les ressorts, Prendre le feu des cieux pour animer les corps" (Quoted by Lasocki in his 1979 preface of [23]).

The fact that the fluteplayer imitated in a very realistic way a real fluteplayer is the really amazing characteristic of the automaton. We will restrict ourselves to the way the fluteplayer was programmed, although it is, in a way, a minor aspect of the automaton. De Vaucanson himself wrote: "In the anterior face of the pedestal on the left, there is another movement, which is by wheel-work, turns a cylinder two foot and a half long, and sixty four inches in circumference: This cylinder or barrel is divided into fifteen equal parts, of an inch and a half each. On the posterior

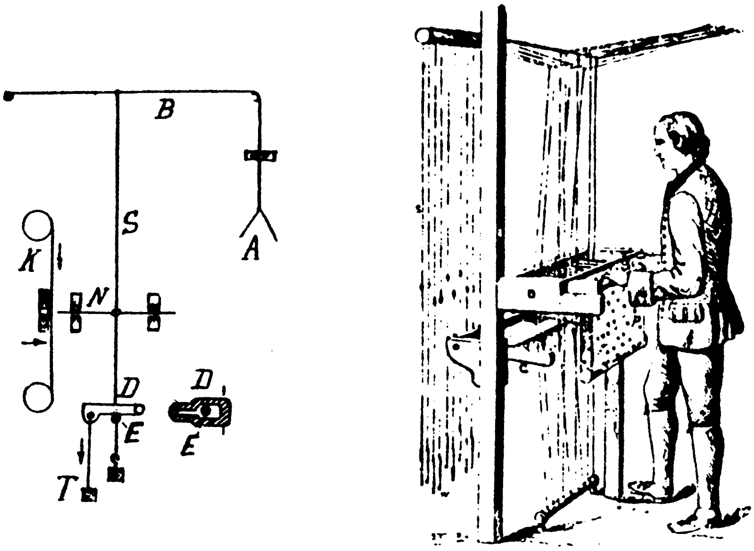


Fig. 5. Bouchon's invention [11, p. 282].

face of the pedestal in the upper part of it, there is a key-frame, drawing or bearing on the barrel, made of fifteen very moveable levers, whose ends on the inside have a little nib or lifting piece of steel, which answers to each division of the barrel. At the other of these levers are fasten'd wires and chaines of steel, which lead to the different receptacles of wind, to the fingers, to the lips, and to the tongue of the figure". (Translated from De Vaucanson's own description on the occasion of the exhibition of the three figures in London [23, p. 12].)

It is remarkable that the idea that had already occurred to the Banu Musa in the 9th century, became reality 900 years later. In 1740, De Vaucanson was sent to Lyon by the Academy of Sciences to study the weaving industry and suggest improvements. In the period from 1747 until 1750 De Vaucanson constructed and improved his "barrelloom". It boils down to a mechanism that can be put on top of a loom and makes the drawboy superfluous. A central element is a drum with a punched tape around it (Fig. 6).

It is possible that De Vaucanson got the idea to use a drum from Reignier, who designed a loom with a drum carrying pins in 1740. Reignier's loom was not successful. De Vaucanson's design was also definitely inspired by Falcon's work. According to Van Gorp [11, p. 307], De Vaucanson could easily have perfected this brilliant design, but he had to dedicate his attention to other matters. The result was that his looms finally wound up on the attic of the Conservatoire des Arts et Métiers.

Joseph Charles Marie Jacquard (1752–1834) had designed a rather primitive machine to make fishing nets. Carnot and Napoleon ordered him to improve the design in the *Conservatoire des Arts et Métiers*, where Jacquard ran into the remains of Vaucanson's looms. He reconstructed the machine and combined it with elements from Falcon's machines. Historians judge his contribution differently, but there seems to be some concensus that the 1804 machine that made his name immortal was to a large extent the result of the genius of others (Fig. 7). For more on the history of French weaving see [1].

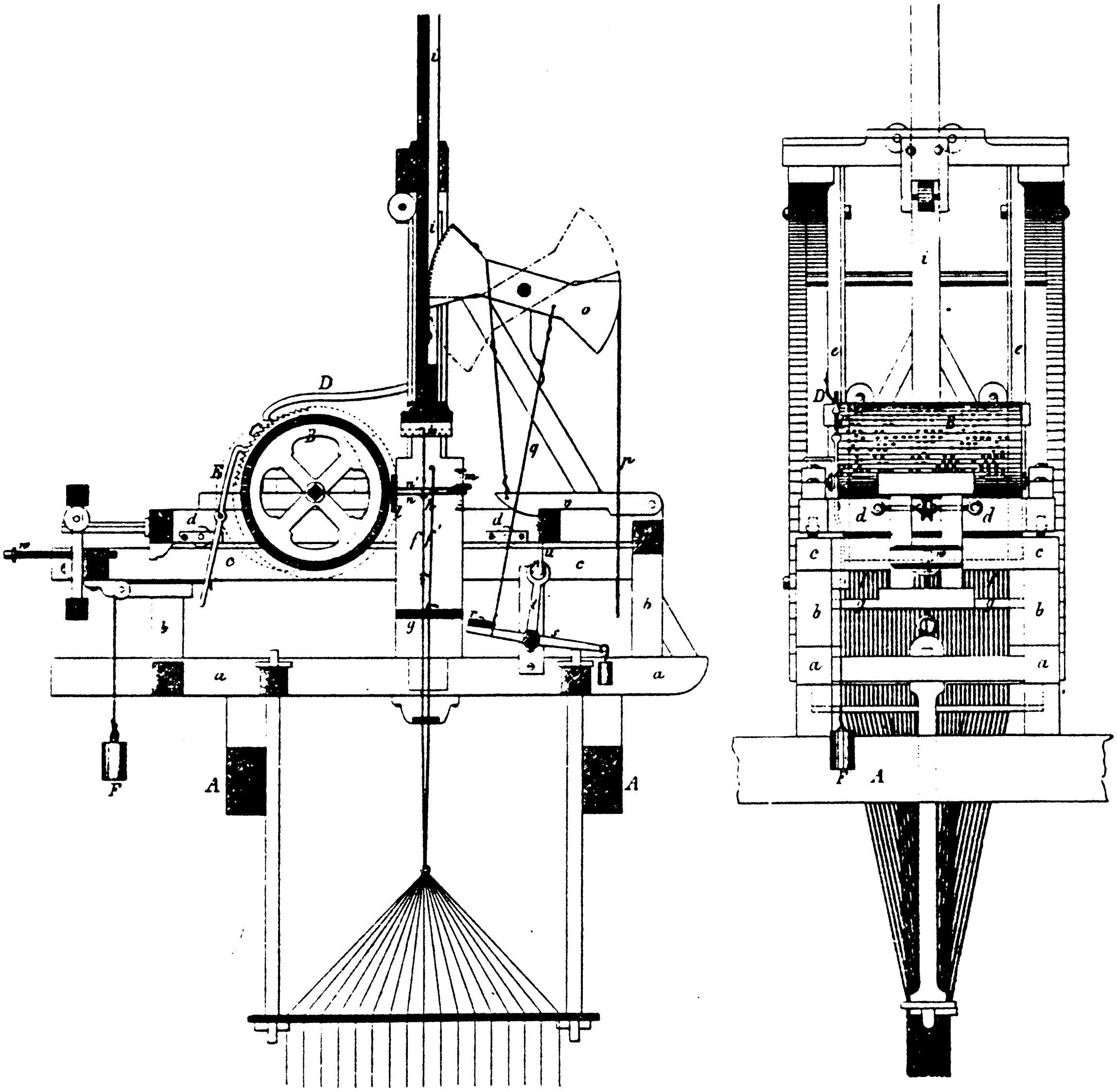

Fig. 6. Vaucanson's loom [14, p. 307].

## 7. Mechanical calculators

The first mechanical calculators were built in the first half of the 17th century. Wilhelm Schickard (1592–1635), professor for Biblical languages, mathematics and astronomy, constructed the first machine (Fig. 8). It consisted of an adder in the form of a rectangular box with on top of it an adaption of the so-called Napier-bones (which are merely a handy representation of the tables of multiplication). The adder contained a series of number wheels, each with 10 clearly distinguished positions. When a wheel moved from position 9 to position 0, a carry

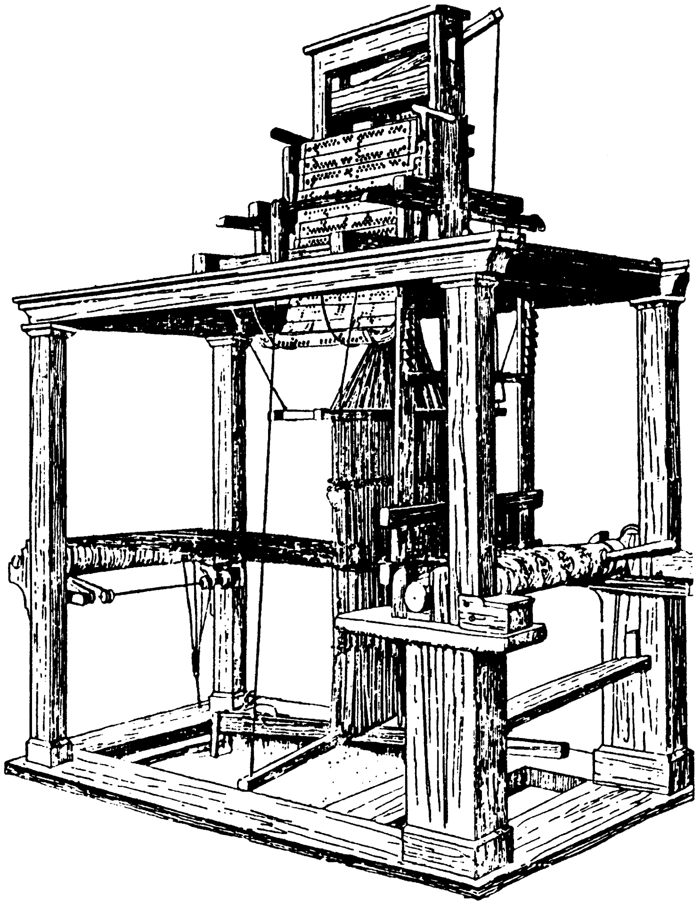

Fig. 7. Model of the original Jacquard loom by Marin in 1855 [11, p. 333].

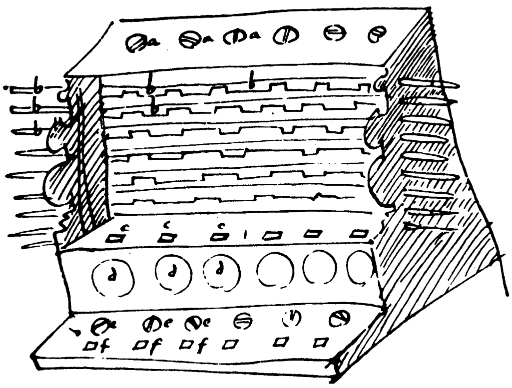

Fig. 8. Schickard's calculator [22, p. 143].

mechanism made the next wheel move one step forward, so that additions could be performed by simply repeatedly putting in numbers digitwise. The user could also perform a multiplication by reading the required results of the multiplication of two digits from the adapted Napier-bones and putting them in the adder. Schickard's calculator was forgotten until its description was rediscovered in this century by Hammer and a model was constructed by Von Freytag Löringhoff [24, pp. 122–128; 9, pp. 361–365]. Very well known became the next mechanical calculator, the machine built by Blaise Pascal (1623–1662) in the beginning of the 1640s. It was an adder in the form of a box like Schickard's but with a different carry-mechanism and without the Napier-bones. It could also perform subtractions by reducing them to additions [24, pp. 128–134].

Above we saw that for many philosophers the Strasbourg clock revealed how God's creation should be viewed. *L'Homme-Machine* by La Mettrie (1709–1751) contains maybe the clearest expression of the view that animals and human beings in their entirety are organised as machines. Also human thinking was considered as a mechanical process. Thomas Hobbes (1588–1679) wrote, for example:

"Rational understanding is for me calculation. [...] Rational understanding is the same as adding and substracting." (quoted in [15, p. 94]).

This conviction was strengthened by the appearance of the first mechanical calculating machines. In this context, Gottfried Wilhelm Leibniz (1646–1716) was led to his brilliant utopian programme of a *characteristica universalis*. Although Leibniz nowhere expresses it in this way, the basic idea boils down to the following: If every area of human experience can be understood by means of mathematical thinking and if thinking is a form of calculation and calculation can be mechanised, then all questions about reality can, in principle, be answered by means of a calculation executed by a machine. Central to the programme was the design of a universal formal language (characteristica universalis) that could be used to formulate problems and solve them in an algorithmic fashion. Leibniz, obviously, was close to the idea of a universal programmable problem-solving machine. He developed fragments of this universal formal language. Bos mentions the ideal of a characteristica universalis as one of the things that led Leibniz to the discovery of the differential- and integral-calculus [3]. Leibniz also designed a calculator [22, pp. 134–140]; cf. also [17]. In comparison with Pascal's calculator Leibniz' computer could do more. It could execute multiplications by means of a stepped drum mechanism in combination with a complicated carry mechanism. On the calculators of Schickard, Pascal and Leibniz see also [22]. A good source for the history of the early mechanical calculators is also [18].

Remarkable in this context is also Friedrich von Knauß (1724–1789), the court mechanic in Vienna. He built the "All writing miracle machine" about 1760. It is the fourth in a series of writing automata that he built. Zemanek described the machine as an automaton that is controlled partly in an analogous way and partly in a digital way. The letters of the alphabet and some other characters could each be written "analogously" with a real pen. The precise 68-character long sequence to be written was programmed "digitally" by placing pins on a drum [26, 1959].

## 8. The nineteenth century

The Jacquardloom became very popular and with it the idea of control by means of punched cards spread over Europe. The first to use it outside the textile industry was Charles Babbage

(1792–1871), the designer of the first programmable calculating machine. Babbage first conceived of the *Analytical Engine* in 1833 and by mid-1836 a workable design had evolved. Fig. 9 gives an impression of the general plan of the huge machine that Babbage had in mind. In the drawing Fig. 8, most of the circles denote columns of wheels. The ten digits are represented as the ten positions of the wheels; numbers are represented as columns of wheels. The complete machine was never built, although a simplified version was finished after Babbage's death. Babbage called the section of the machine where numbers were stored the "store" and the section of the machine where calculations were performed the "mill". Not only this terminology came from the textile industry but Babbage also applied the punched cards technique to make the Analytical Engine programmable: three strings of, respectively, number cards, operation cards and directive cards determined the precise task the machine would execute. Only a part of the machine was built, but Bromley [4] concludes that the 300 sheets of drawings and the 6000–7000 pages of notebooks that Babbage left on the machine represent a highly complex but workable design. Bromley writes: "Only in the adaption of the barrel, from automata and music boxes, and punched cards from the Jacquard loom, is there any significant borrowing from existing technology". [4, p. 197]. The barrels are positioned vertically in the machine and vertical rows of studs can be screwed on them (Fig. 10). By rotating the barrel in position and moving it sideways the studs act on the ends of control levers. The barrels are used as a control

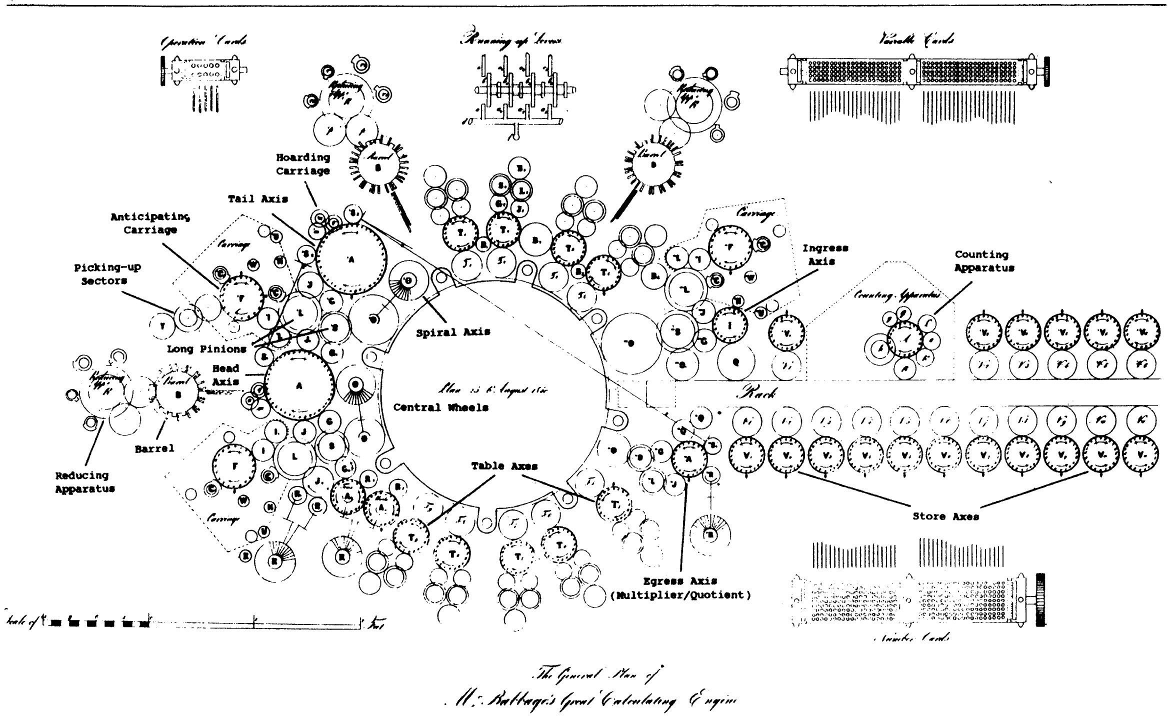


Fig. 9. General Map of Babbage's Calculating Machine.

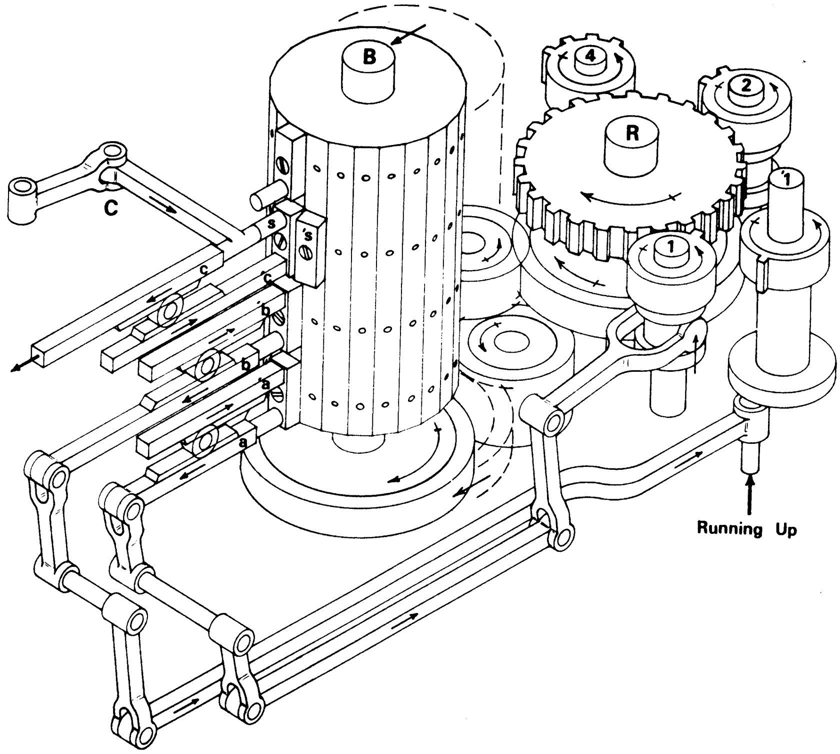


Fig. 10. The use of a "barrel" in the Analytical Engine [4, p. 205].

mechanism to coordinate storing, transfer, addition, etc. Bromley describes the use of the barrel as "*microprogramming*" [4, p. 205].

However, although workable, Babbage's design became no success. It was soon forgotten. It is well known that after Babbage the first programmable calculating machine that was really built, was designed by the German Konrad Zuse. It became operational in 1941. Zuse had not heard of Babbage at the time.

But also in the realm of musical instruments the punched card was soon introduced. According to Buchner, J.A. Testé from Nantes applied in 1861 a cardboard tape in a tongue-organ, called the *Cartonium* [5, pp. 18&19]. Apparently in 1842 A. F. Seytre from Lyon got a patent on an organ with a keyboard of which the keys are pushed upwards by springs if there are holes in punched cards. I have not been able to check this. The idea was freely used after 1861. The actual history is complex. J. Mc Tammany, the designer of the so-called player piano (a well-known pianola) wrote in 1915:

> Certain men in Europe and America, by name Morse, Bain, Pape, Dawson and Seytre in Europe, and Hunt & Braddish & Van Dusen of America, dating back as far as 1731 and extending to 1847, seemed to have had some vague, indefinite and hazy idea of a mechanical musical instrument to be actuated by a perforated device consisting of wood or other substance, instead of by pin cylinder, the method in universal use [...] Up to 1863 no European or American had succeeded in producing a practical working instrument of

> any kind for the mechanical operation of keyboard instruments by means of a perforated device [. . .] [21, p. 2].

I have not been able to check the details, but, roughly speaking, this seems to be correct. Let me add one more remark. From about 1800 the first attempts are made to design a mechanically playing orchestra. In 1805 J.G. Kaufmann's *Belloneon* came out and in Paris J.N. Maelzel presented his *Panharmonicon* to the public. In 1851 Kaufmann's "Orchestrion" came out and that is the name such instruments usually had afterwards. The older types use replaceable drums, but in particular after 1887 paper tapes are used. One author wrote:

> These tapes do not only carry the pattern of the music but also automatically programme the sometimes very complicated mechanism, turn the different registers on and off and some automatically rewind the tapes. A nineteenth century computer! [25, pp. 30–31].

## 9. Conclusions

(1) The earliest programmable machines were musical automata. Next came the programmable drawloom. The first designs of programmable drawlooms are from the 18th century. It is remarkable that the main predecessor of the Jacquardloom was designed by De Vaucanson, the well-known 18th century builder of music automata. Following the success of the Jacquardloom the idea of a programme in the form of punched cards was used by Babbage in the 1830s in his design of the first programmable computer. Later punched cards were also used widely to programme music automata.

(2) We saw that Babbage's first programmable computer was forgotten. As for music automata, they were replaced in the 20th century by the gramophone, which emphasized an already occurring shift away from programming to recording and replaying. The Jacquardloom was further improved and widely used, but, as far as I know, it did not exert any special influence outside the textile industry.

(3) I slightly speculatively draw the following conclusion: Although the fact that an important characteristic of modern automation is programmability motivated my interest in the "pre-history" of programmable devices, this prehistory in no way explains the post-worldwar II developments in automation. The rise of computer science took place to a large extent independently of the events that we described.

## Further reading

See [2].

## Acknowledgements

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## References


[1] Ch. Ballot, L'Introduction du Machinisme dans l'Industrie française, Lille et Paris, 1923.
[2] B. Brentjens, S. Richter, R. Sonnemann, Geschichte der Technik, Darmstadter Buchgesellschaft, 1978.
[3] H.J.M. Bos, Differentials, higher-order differentials and the derivative in the Leibnizian calculus, Archive for History of Exact Sciences 14 (1974/75) 1–90.
[4] A.G. Bromley, Charles Babbage's analytical engine, 1838, Annals of the History of Computing 4 (1982) 196–217.
[5] A. Buchner, Les instruments de musique mécanique, Paris, 1992.
[6] John Cohen, Human robots in myth and science, Woking and London, 1966.
[7] A.G. Drachman, The mechanical technology of greek and roman antiquity, Copenhagen, 1963.
[8] H.G. Farmer, The organ of the ancients from eastern sources (Hebrew, Syriac and Arabic), London, 1931.
[9] B. Baron von Freytag Löringhoff, Über die erste Rechenmaschine, Physikalische Blätter (1958) 361–365.
[10] E. Farré-Olivé, A medieval catalan clepsydra and carillon, Antiquarian Horology and the Proceedings of the Antiquarian Horological Society, Winter 1989, London, 1974, pp. 371–380.
[11] P.J.M. van Gorp, De Jacquardmachine en haar voorlopers, Bulletin tot behoud van monumenten van bedrijf en techniek in het zuiden van Nederland (1983) 185–359.
[12] J.J.L. Haspels, in: Automatic musical instruments, their mechanics and their music 1580–1820, Zwolle, Netherlands, 1987.
[13] A.Y. al-Hassan, D.R. Hill, Islamic Technology, An illustrated history, Cambridge, 1986.
[14] E.H.O. Johannsen e.a., Die Geschichte der Textil-Industrie, Leipzig, 1932.
[15] S. Krämer, Symbolische Maschinen, Die Idee der Formalisierung in geschichtlichem Abriß, Wissenschaftliche Buch Gesellschaft, Darmstadt, 1988.
[16] A. Lehr, in: Beiaardkunst in de Lage Landen, Lannov Tirion, Tielt, 1991.
[17] I.I. Locke, The contributions of Leibnitz to the art of mechanical calculation, Scripta Mathematica 1 (1932).
[18] M. d'Ocagne, Le Calcul Simplifié par les procédés mécaniques et graphiques, Paris, 1905.
[19] K. Steinbuch, in: Automat und Mensch, Springer, Berlin, 1971.
[20] S. Strandh, A History of the Machine, New York, 1979.
[21] J. Mc Tammany, The Technological History of the Player, New York, 1915.
[22] R. Taton, Sur l'invention de la machine arithmétique, Revue d'histoire des sciences et de leurs applications 16 (1963) 139–160.
[23] J. de Vaucanson, Le Méchanisme du Fluteur Automate, Buren, 1979 (reprint of the original 1738 edition together with a 1742 English translation and a preface by D. Lasocki).
[24] M.R. Williams, A History of Computing Technology, New Jersey, 1985.
[25] J. van Witteloostuijn, R. Maas, Muziek uit stekels en gaten, Buren, 1984.
[26] H. Zemanek, Vor 200 Jahren: ein Schreibautomat mit kombinierter Analog-Digital-steuerung, VDI-Nachrichten 7 (1959) 6.