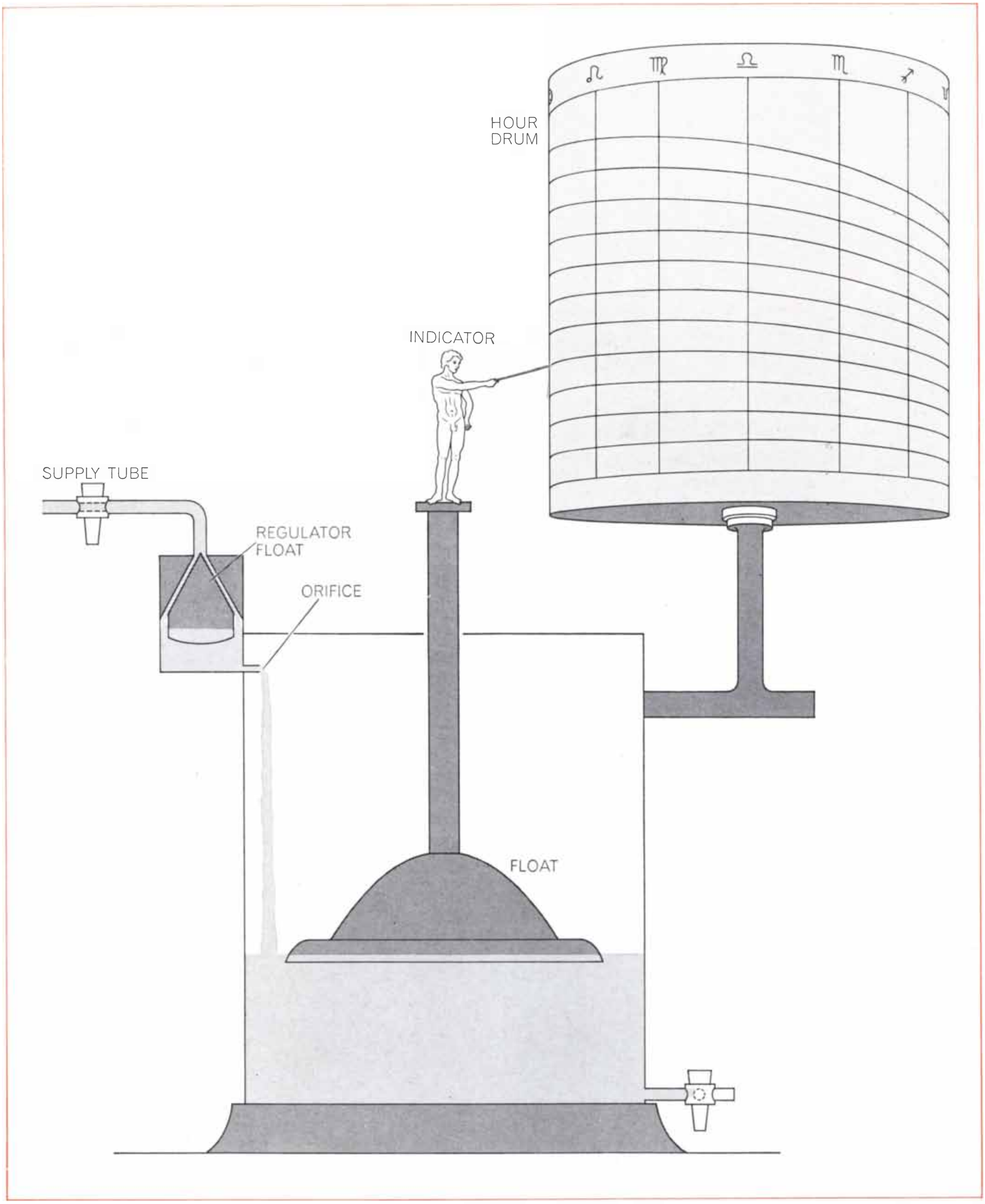
SCIENTIFIC
AMERICAN

The Origins of Feedback Control
Author(s): Otto Mayr
Source: *Scientific American*, Vol. 223, No. 4 (October 1970), pp. 110-119
Published by: Scientific American, a division of Nature America, Inc.
Stable URL: http://www.jstor.org/stable/24927641
Accessed: 22-09-2017 15:57 UTC



ANCIENT WATER CLOCK is the earliest known device for feedback control. It was invented in the third century B.C. by a Greek mechanician named Ktesibios, working in Alexandria. This drawing is based on a reconstruction by the German classicist Hermann Diels. The indicator figure is mounted on a large float (*bottom*), which rises inside a tank as a result of a slow trickle of water into the tank. The 12 hours, which vary in length with the seasons of the year, are indicated on the drum at top right. The change in the length of the hours can be represented by simply turning the drum to the proper month. The float regulator at top left controls the rate of water flowing into the main tank by maintaining a constant water level in the adjacent regulator vessel. If the level rises (as a result, say, of an increase of static pressure in the external supply line), the regulator float will rise, throttling the inflow into the regulator vessel. The device is remarkably similar in operation to the carburetor of a modern automobile.

The Origins of Feedback Control

The evolution of the concept of feedback can be traced through three separate ancestral lines: the water clock, the thermostat and mechanisms for controlling windmills

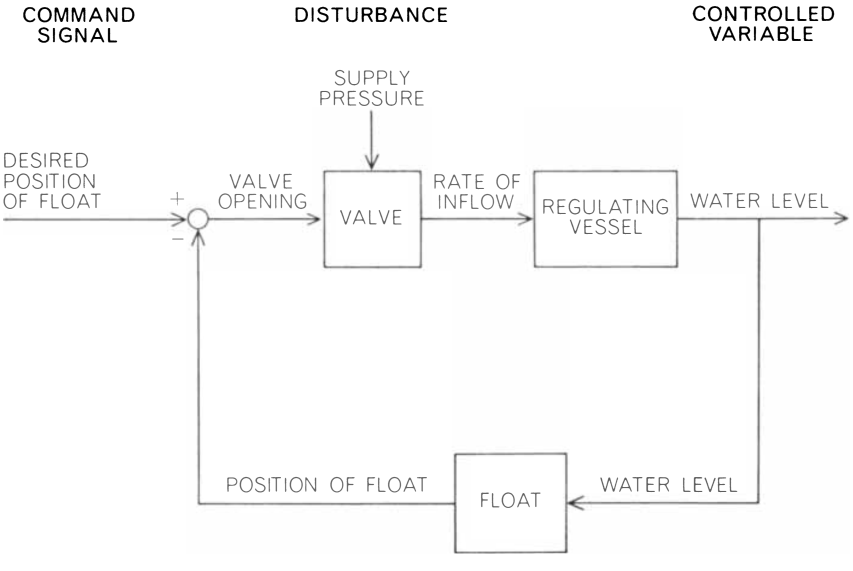
by Otto Mayr

Every animal is a self-regulating system owing its existence, its stability and most of its behavior to feedback controls. Considering the universality of this process and the fact that the operation of feedback can be seen in a great variety of phenomena, from the population cycles of predatory animals to the ups and downs of the stock market, it seems curious that theoretical study of the concept of feedback control came so late in the development of science and technology. The term "feedback" itself is a recent invention, coined by pioneers in radio around the beginning of this century. And the exploration of the implications of this principle is still younger: it received its main impetus from the work of the late Norbert Wiener and his colleagues in the 1940's.

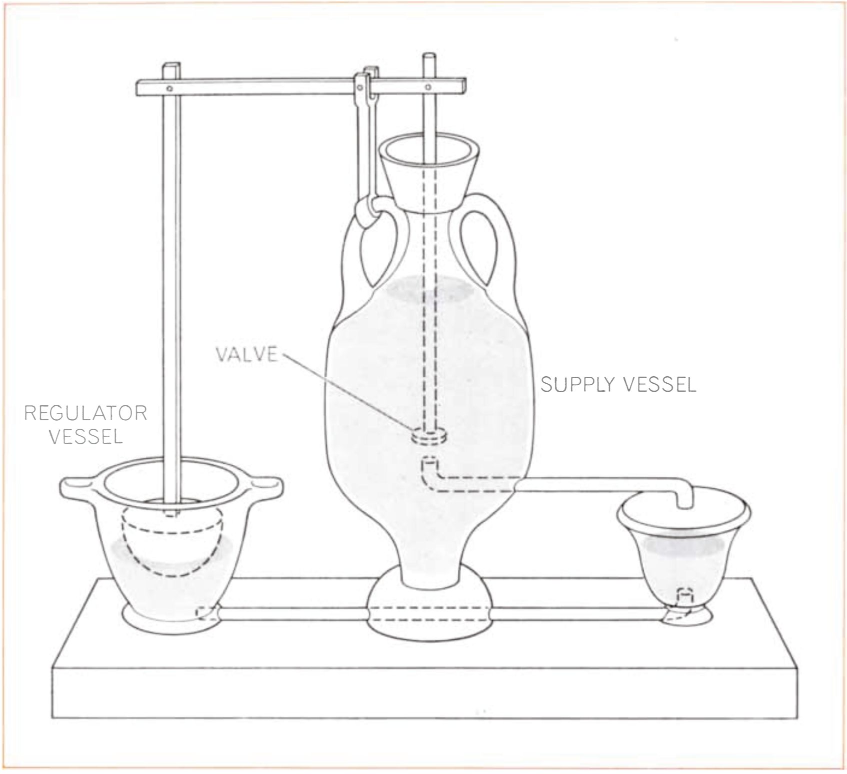
Feedback control is an instance of technology giving birth to science. Application of the feedback principle had its beginnings in simple machines and instruments, some of them going back 2,000 years or more. The thermostat and the flyball governor are well-known modern examples. Although the simple early inventions have been developed to a high order of sophistication, feedback control as an abstract concept did not receive much attention until the 1930's, when biologists and economists began to note striking parallels between their own objects of study and the feedback control devices of engineers. Certain regulatory processes in living organisms and in economic behavior showed the same cyclic structure of cause and effect and apparently obeyed the same laws. It became evident that the concept of feedback control could be a versatile and powerful tool for investigating many forms of dynamic behavior. Today the feedback control principle is not only widely embodied in hardware but also recognized as an important unifying concept in science.

The subject of this article is the historical growth of the concept. Its career can be traced with some assurance because feedback control can be rigorously defined. Wiener described it as "a method of controlling a system by reinserting into it the results of its past performance." A more formal definition, offered in 1951 by the American Institute of Electrical Engineers, states: "A Feedback Control System is a control system which tends to maintain a prescribed relationship of one system variable to another by comparing functions of these variables and using the difference as a means of control." The purpose of such a system is to carry out a command automatically, and it functions by maintaining the *controlled variable* (the output signal) at the same level as the *command variable* (the input) in spite of interference by any unpredictable disturbance. The command signal may be either constant, as it is in the case of the temperature setting on a thermostat, or continuously variable, as it is in the case of the steering wheel position in the power-steering system of an automobile. In all cases, if the feedback control system is to function effectively, it must be so designed that the controlled variable follows the command signal with the utmost fidelity.

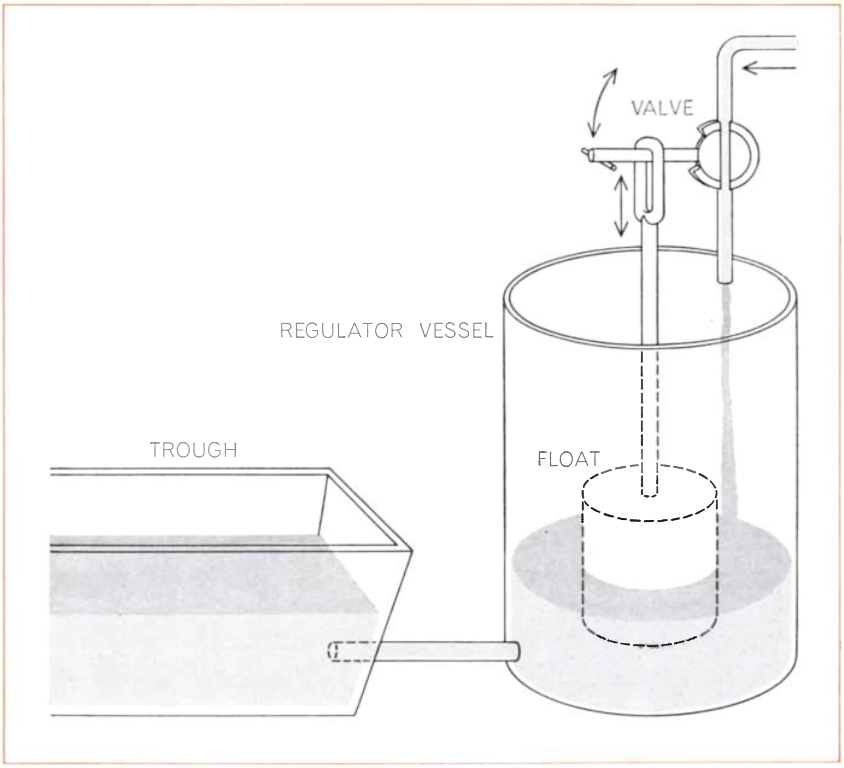
The main characteristic of a feedback control system is its closed-loop structure. The state of the output signal is



TYPICAL CLOSED FEEDBACK LOOP is evident in this simplified block diagram depicting the operation of Ktesibios' water-clock flow regulator. The arrows represent signals and the blocks represent the physical components on which the signals operate. By expressing the signals as mathematical variables and the blocks as functions, the diagram can be reduced to a differential equation describing the dynamic behavior of the system.



"WINE DISPENSER" designed by Hero of Alexandria around A.D. 50 incorporated an improved float regulator in which the valve (the control element) was not directly attached to the float (the sensing element). The level in the communicating vessels was maintained by the float in one of the vessels (*left*) acting on the valve in the supply vessel (*center*).



FLOAT REGULATOR for an animal drinking trough was described in a ninth-century book titled *Kitāb al-Ḥiyal* (*On Ingenious Mechanisms*) by three brothers from Baghdad named Banū Mūsā. Water was drawn from a river through a pipe into two communicating vessels. The float in the regulating vessel controlled a stopcock valve in the intake pipe.

monitored by some sensing device that feeds the signal back to the input side. There it is subtracted from the command signal; if the result is not zero, the system responds with a corrective action whose size and direction depend on the magnitude of the deviation, or "error signal." In the case of a home thermostat, for example, if the room temperature has dropped below the desired temperature, the system responds with an increased supply of heat, that is, a negative change in the output signal evokes a positive corrective action. In general a signal that has traveled around the loop of a feedback system returns with a reversed sign. The change of sign is essential for the stability of the system; if the signal were not changed in sign, it would create a vicious circle, building up the deviation of the output from the desired level.

The origin and main lines of development of the feedback concept are illustrated by three devices: the ancient water clock, the thermostat and mechanisms for controlling windmills. Let us trace the history of each of these applications and see where they led.

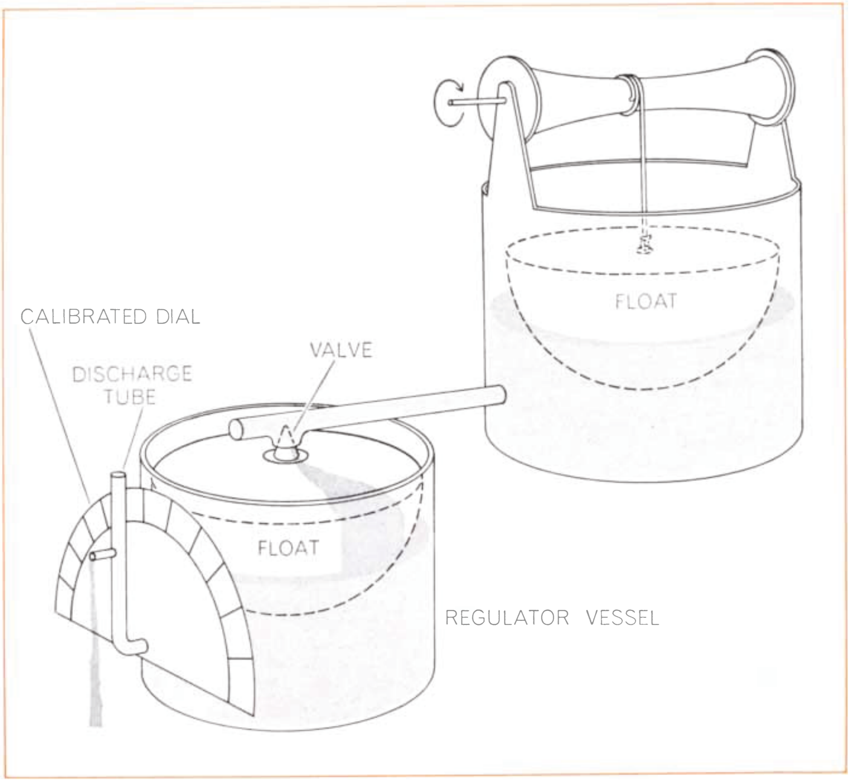
The earliest known construction of a device for feedback control was a water clock invented in the third century B.C. by a Greek mechanician named Ktesibios, working in the service of the Egyptian King Ptolemy II in Alexandria. He was probably associated with the illustrious museum that was then the principal cultural center of the Mediterranean world and attracted Greece's foremost scholars. Ktesibios' own descriptions of his inventions (which in addition to the water clock included a force pump, a water organ and several catapults) are now lost, but fortunately an account of them is preserved in *De Architectura*, the great work of the Roman architect and engineer Vitruvius.

Vitruvius' description of Ktesibios' water clock is not clear; however, the German classicist Hermann Diels translated its obscurities into a plausible reconstruction of the device. The water clock measures the passage of time by means of a slow trickle of water, flowing at a constant rate into a tank where an indicator riding on the water tells the time as the water level rises [*see illustration on page 110*]. Ktesibios solved the problem of maintaining the trickle at a constant rate by inventing a device resembling the modern automobile carburetor. Interposed between the source of the water supply and the receiving tank, this structure regulates the water flow by means of a float valve. When the float is at a certain level, the valve attached to it is open just far enough to feed water into the timekeeping tank at the desired rate. If for some reason the water in the regulator falls below or rises above that level, the float responds by opening or closing off the water supply until the float returns to the specified level.

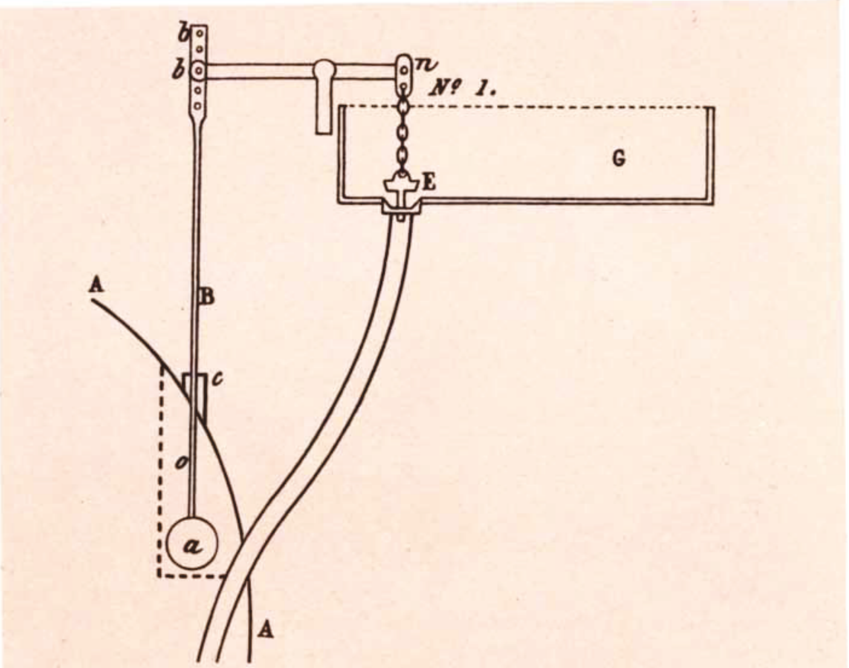
About three centuries after Ktesibios we again encounter automatic regulators of the float type in the *Pneumatica* of Hero of Alexandria. Hero was a prolific author of books on mathematics, surveying, optics, mechanics, pneumatics, automatons and military engineering, and his *Pneumatica* contains a number of amazing anticipations of modern inventions. Among other things, it describes several float regulators considerably more refined than that of Ktesibios. In one, called a "wine dispenser," the valve is not directly attached to the float, thus demonstrating that in a feedback control device the sensing element and the control element can be widely separated from each other [*see top illustration on opposite page*]. The playful applications Hero suggested for his devices are frowned on by some scholars; it is clear, however, that he was a serious scientist who was primarily interested in describing principles and used trivial but readily understandable examples the better to make his points.

In the ninth century, some 800 years after Hero, we find the float regulator cropping up again, this time in Arabic. In a book called *Kitāb al-Ḥiyal* (*On Ingenious Mechanisms*), evidently inspired by Hero's *Pneumatica*, a trio of authors in Baghdad presented eight applications of the float valve for feedback control. The authors were three brothers, Banū Mūsā, who were high officials at the court of the Abbaside caliphs. Their devices added a few refinements to the float-valve system. One was the use of a proper stopcock as the regulating valve instead of the primitive contrivance of a plate held against the end of a pipe [*see bottom illustration on opposite page*].

The float valve inspired some of the proudest achievements of Islamic technology in the period preceding the Middle Ages. Its artisans built monumental water clocks in which the time was told by elaborate theatrical displays performed by automatons. These are described in detail in three surviving books on water clocks. The first, probably written in the ninth century, is by an anonymous author usually called "Pseudo-



NINTH-CENTURY WATER CLOCK was described by the Islamic author known as "Pseudo-Archimedes." The time-indicating mechanism (*not shown*) was driven by the constantly falling water level in the main float chamber. A constant discharge from this chamber was maintained by means of a float valve in the regulating vessel. The outflow from this vessel could in turn be calibrated by turning the discharge tube around its axis, thereby making it possible to adjust the clock for seasonal variations in the length of the hour.

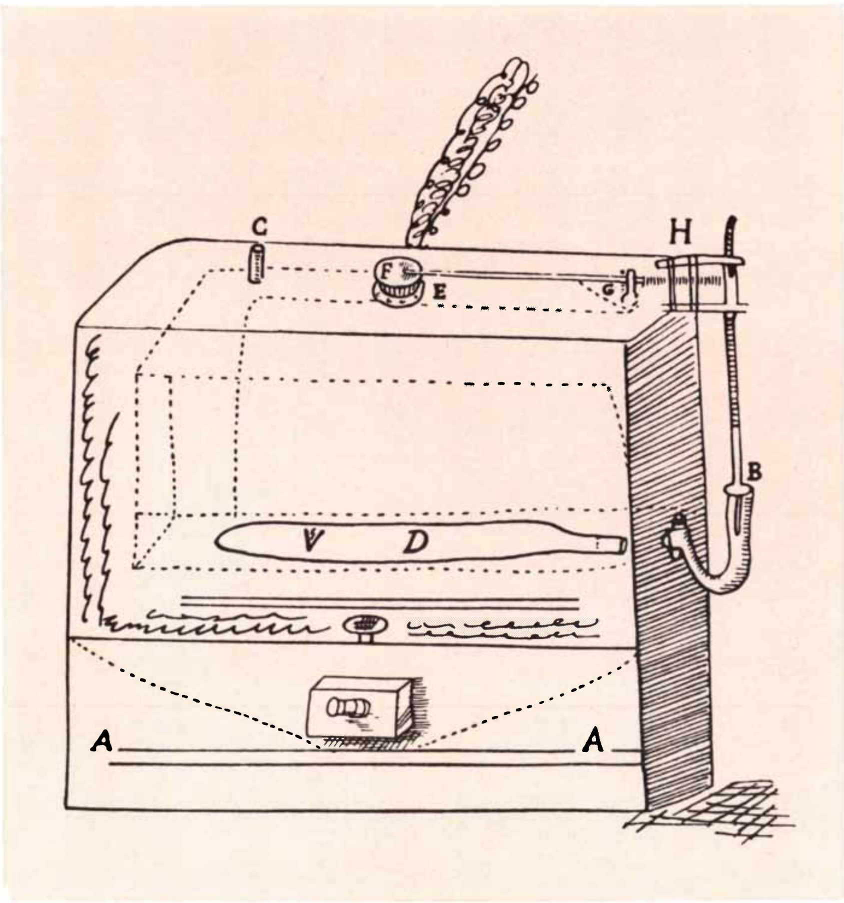


FLOAT REGULATOR WAS REINVENTED in 18th-century England, apparently without knowledge of its earlier career. This drawing, showing a water-level regulator for steam boilers, is from a British patent awarded to Sutton Thomas Wood in 1784. The level in the boiler (A) was sensed by a float (a) that controlled the water supply through a valve (E).

Archimedes"; the other two, based on that work, are by 13th-century writers named Ibn al-Sāʿātī and al-Jazarī. The clocks described in these three books employ the float-level regulator of Ktesibios, but it now regulates the *outflow* from the main float chamber instead of the flow into the chamber. Hence time is measured by the sinking, rather than the rise, of the water level [*see top illustration on preceding page*].

After these accounts in the early 13th century the float valve drops out of sight. No references to the employment of the device for water-level regulation have been found in the technological literature of the Middle Ages or the Renaissance or Baroque periods. Even a beautifully illustrated Latin translation of Hero's *Pneumatica,* which was published in 1575 and had a powerful impact on the development of technology, failed to induce engineers to take up the float regulator as a method of feedback control.

In the middle of the 18th century the device was reinvented in England, apparently without knowledge of its earlier career. The float regulator's rebirth was first mentioned in a 1746 building manual, *The Country Builder's Estimator,* by William Salmon, as a device for regulating the water level in domestic cisterns. In 1758 the British bridge and canal builder James Brindley obtained a patent for a steam engine that incorporated a float valve to regulate the water level in the steam boilers. A few years later I. I. Polzunov, a Russian pioneer in the development of the steam engine, designed such a device for the same purpose. In 1784 Sutton Thomas Wood in England patented the same invention once more in a design strikingly similar to Hero's 17-centuries-old system [*see bottom illustration on preceding page*]. The float regulator soon won general acceptance as a method of feeding water to boilers. Today it is widely used for many purposes.

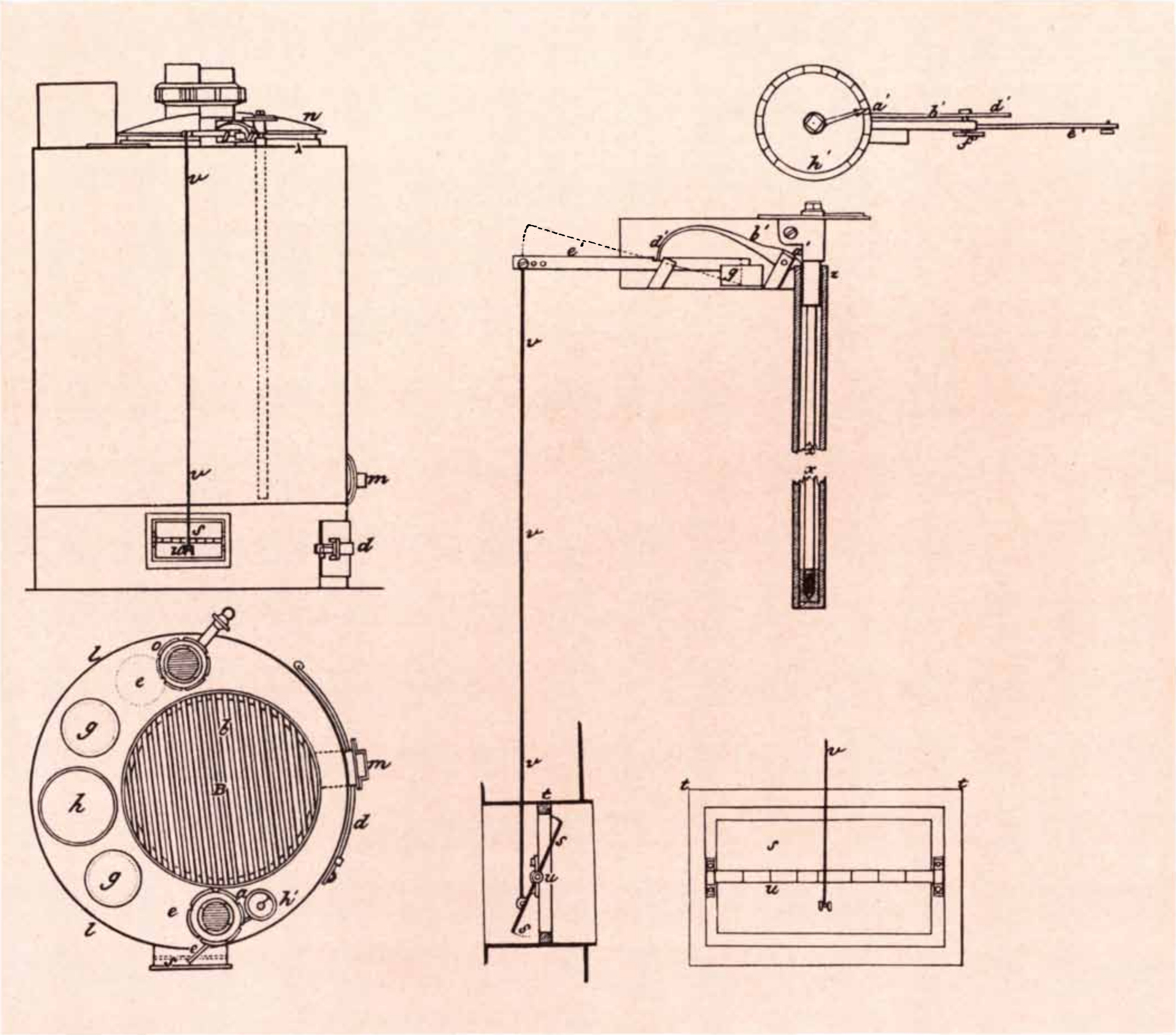


FIRST THERMOSTAT was invented early in the 17th century by Cornelis Drebbel. In this drawing, made by Drebbel's grandson, the device is shown adapted as a temperature regulator for an incubator. Smoke rising from the fire (A–A) passes by the water-jacketed incubator box (*dotted lines*) and escapes at the top through an opening (E). A glass vessel (D) containing alcohol is inserted into the water jacket and is sealed by mercury contained in a U-shaped portion of the vessel (*right*). As the temperature rises the increasing volume of the evaporating alcohol forces the mercury to rise in the right leg of the vessel, raising a float (B) and, through a linkage (H) pivoted at a point (G), closing a damper (F).

The thermostat does not have so ancient a history. Its first prototype was invented early in the 17th century by Cornelis Drebbel, a Dutch engineer who had migrated to England and worked in the service of James I and Charles I. A highly original inventor, Drebbel would be much better known today if he had committed his inventions to writing. According to an account by Francis Bacon, Drebbel devised his temperature regulator only incidentally, as an instrument to serve another purpose: alchemy. He believed he could transmute base metals to gold if he could keep the temperature of the process constant for a long time.

Drebbel's apparatus consisted basically of a box with a fire at the bottom and above this an inner compartment containing air or alcohol with a U-shaped neck topped by mercury [*see illustration at left*]. As the temperature in the box rose, the increased pressure of the heated air or alcohol vapor pushed up the mercury, which in turn pushed up a rod; this mechanical force was applied to close a damper and throttle down the fire. Conversely, if the temperature in the box fell below the desired level, the gas pressure was reduced, the mercury dropped and the mechanical linkage opened the damper.

Drebbel used his contrivance not only for smelting experiments but also to maintain an even temperature in incubators. His regulator seems to have worked with some success; members of the Royal Society of London, including Robert Boyle, Christopher Wren and in the following generation Robert Hooke, showed interest in it. Detailed descriptions of the device were given in a laboratory book by Drebbel's grandson (whose manuscript is preserved in the University of Cambridge library) and in the journals of a French devotee of science, Balthasar de Monconys, who investigated Drebbel's furnaces. Over the following century there were occasional reports of similar furnaces, evidently inspired by Drebbel's, that were built in Germany, France and America. None of these reports gave credit to Drebbel. The French natural philosopher and inventor René-Antoine de Réaumur described such a furnace for the artificial hatching of chickens and attributed its invention to a member of the French royal family, the Prince de Conti.

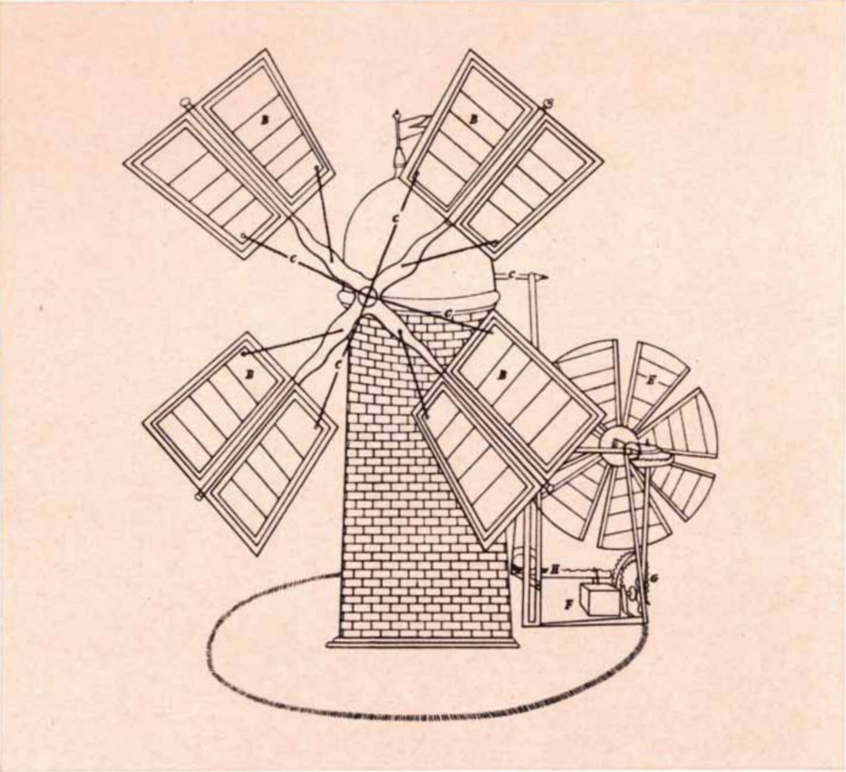


IMPROVED THERMOSTAT, shown here as it was applied to regulate the temperature in a hot-water furnace, was designed in 1783 by a Parisian inventor named Bonnemain. A sensitive two-metal temperature feeler, consisting of an iron rod (x) surrounded by a lead tube (z), was immersed in the water to be heated. The motion of the upper rim of the lead tube caused by thermal expansion was then employed to adjust the air damper (s). The desired temperature inside the furnace could be set on a dial (h).

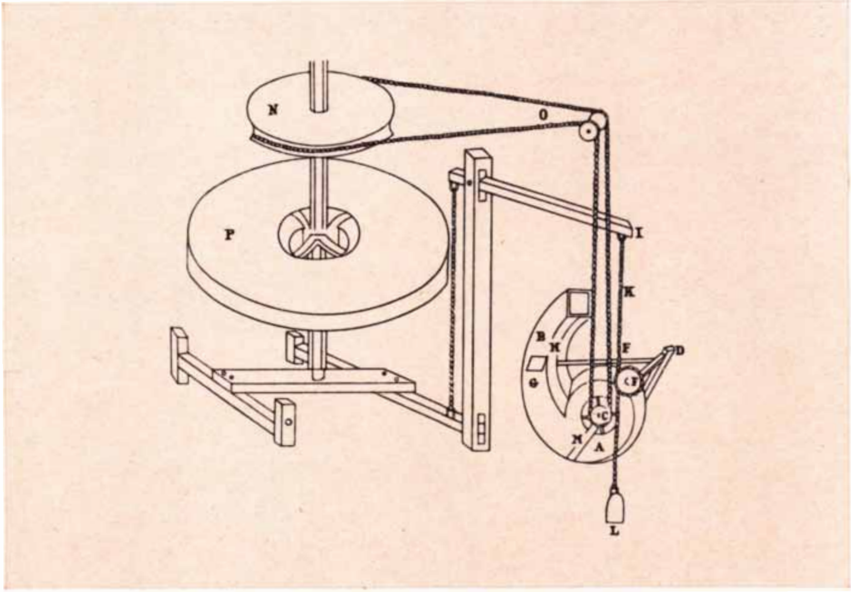
For two centuries Drebbel's idea of temperature regulation by feedback drew little notice apart from these few sporadic reports. Then the idea suddenly aroused the interest of the entire engineering community. Credit for this achievement belongs to a Parisian inventor named Bonnemain. In 1783 Bonnemain, presumably having got the idea from reading of Réaumur's success in hatching chickens with an artificial incubator, built a *régulateur de feu* himself and obtained a French patent for it. He proceeded to employ his self-regulating incubator with success in a large farm supplying chickens to the royal court and the Paris markets. Bonnemain's apparatus was far superior to the earlier temperature regulators: it had a sensitive temperature feeler made of two metals (an iron rod encased in a lead tube) and several refinements in design [*see illustration above*]. Bonnemain refrained from sharing the details of his apparatus with the world at large until he was over 80; in 1824 the French Society for the Encouragement of National Industry finally prevailed on him to publish a detailed description of his system of temperature regulation. The leading technical journals in Britain and Germany promptly published translations of this account, and Bonnemain's temperature regulator soon found its way into encyclopedias. The author of one of these, the Scottish chemist Andrew Ure, coined the term "thermostat" in his *Dictionary of Arts, Manufactures, and Mines,* which in 1839 described Bonnemain's regulator and some that Ure himself had designed.

The third ancestral line of feedback mechanisms originated in the invention of devices for the automatic control of windmills. They were devised in the 18th century by millwrights in England and Scotland, a resourceful group who combined craft skills with the beginning of a scientific attitude. Many of the famous British mechanical engineers of the 18th and 19th centuries began their careers as millwrights.

The first of the millwrights' feedback devices, patented in 1745 by Edmund



EARLY WINDMILL CONTROLS are shown in this drawing, from a British patent awarded to Edmund Lee in 1745. The regulatory devices consisted of a fantail designed to keep the windmill facing the wind and a mechanism to control the speed of the mill in spite of changes in the wind velocity. The tail wheel (*E*) attached to the movable cap of the mill drove a chain of gears that engaged a circular rack on the ground. If the mill was not facing the wind, the fantail would rotate, turning the main wheel into the wind. The main sails (*B*) of the mill were pivoted along the crossbeams and were held forward by means of a counterweight (*F*), to which they were attached by chains (*C*) running through the hollow main shaft.



"LIFT-TENTER" was a control device designed by the 18th-century British millwrights to counteract the tendency of millstones to move apart as their speed of rotation increased. In this drawing of a lift-tenter invented by Robert Hilton in 1785 the "runner" millstone (*P*) was lowered in proportion to the speed of the mill. The speed was measured by means of the displacement of a baffle (*B*) in the discharge shroud of a centrifugal fan (*A*).

Lee, was a fantail designed to keep the windmill facing the wind [*see top illustration at left*]. The fantail is a small windwheel mounted at right angles to the main wheel. It is attached to the rear side of the movable cap that turns the big wheel into the wind. Through a train of gears the fantail controls the turning of the cap, so that any rotation of the fantail will cause the cap to turn. When the main wheel squarely faces the wind, the fantail, at right angles, is aligned parallel to the wind direction and does not rotate. Whenever the wind shifts so that the main wheel no longer faces it squarely, the wind will strike the tail wheel, causing it to rotate and slowly turn the mill cap until the fantail again is parallel to the wind and the main wheel faces it. In short, the system forms a closed loop. Under actual conditions, with the wind direction constantly changing, the fantail can be considered a rudimentary servo system.

Lee's windmill also contained an invention that was designed to control the speed of the mill in spite of changes in the wind velocity. Regulation of the speed of rotation was needed to protect the millstones from excessive wear and to produce flour of uniformly fine quality. Lee attacked this problem by allowing the windmill sails to pivot around the arms that held them. The sails were connected to a counterweight that pitched their leading edge forward in moderate winds. When the wind rose to excessive velocities, so that its force on the sails was greater than that of the counterweight, the tilt of the sails was reversed and the wheel's rotation velocity was checked.

This system was not a case of feedback control, because it does not try to sense the controlled variable: speed. For genuine feedback control of a windmill's speed a method of measuring the speed with some sensitivity had to be found.

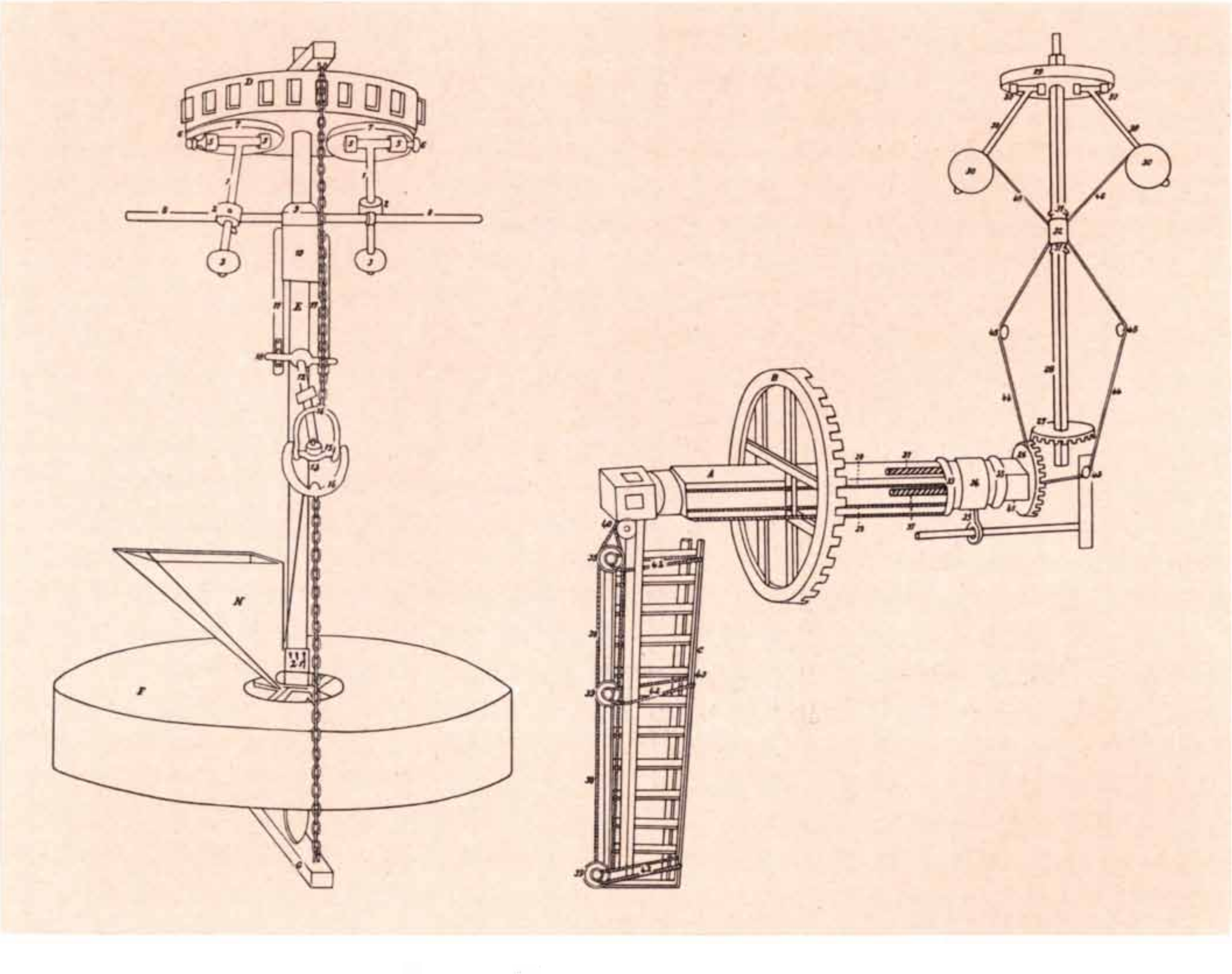
An approach to meeting that need was discovered in a mechanism known as the "lift-tenter." This device was designed to counteract the tendency of millstones to move apart as their speed of rotation increased. The lift-tenter operated to press the millstones together with a force proportional to the rotation speed [*see bottom illustration at left*]. In 1787 Thomas Mead, an English millwright and inventor, combined the lift-tenter idea with the use of a centrifugal pendulum to produce a speed-control system that genuinely embodied the feedback principle. The whirling pendulum measured the speed of the millstones' rotation, and through appropriate mechanical connections it adjusted the area of the windmill sails to keep the wheel rotating at the desired speed [*see illustration below*].

The idea of the centrifugal pendulum was immediately greeted with gratitude by the pioneers in the new technology of the steam engine, just then emerging. James Watt and his partner Matthew Boulton were building a large mill (later to be named the Albion Mill) where the capabilities of Watt's new rotary engine were to be demonstrated. The new engine presented totally new requirements for its regulatory system. There was no way to adapt the existing devices to the continuously operating rotary engine.

Watt and Boulton hired John Rennie, then a young man of 23, to supervise the construction and operation of the Albion Mill. Rennie (who was later to become one of Britain's most famous builders of bridges) had just finished his apprenticeship under the noted Scottish millwright Andrew Meikle. In a visit to the Albion Mill in May of 1788 Boulton found that a lift-tenter had been installed, presumably by Rennie. Boulton promptly sent a detailed and enthusiastic description of it to Watt. The idea fell on prepared ground. By November, Watt and his colleagues had designed a "centrifugal speed regulator," and around the end of the year the first governor was installed on the "Lap" engine. The picture of Watt's governor was to become perhaps the most familiar one in the entire history of technology.

Watt did not take out a patent for the governor. He considered the device merely an adaptation of the centrifugal pendulum to a new use. He and Boulton tried to protect it from competitors by keeping its existence secret; the first customers who ordered it were asked to hide the governor from public view. The device soon became known, however. Within a few years after its invention it was recognized everywhere as a symbol of the steam engine. Rotating dramatically at the top of every steam engine, it demonstrated the action of feedback control more widely and more forcefully than words could have done. The governor soon entered the textbooks and handbooks of engineering, and inventors began to develop feedback devices in other areas of technology.

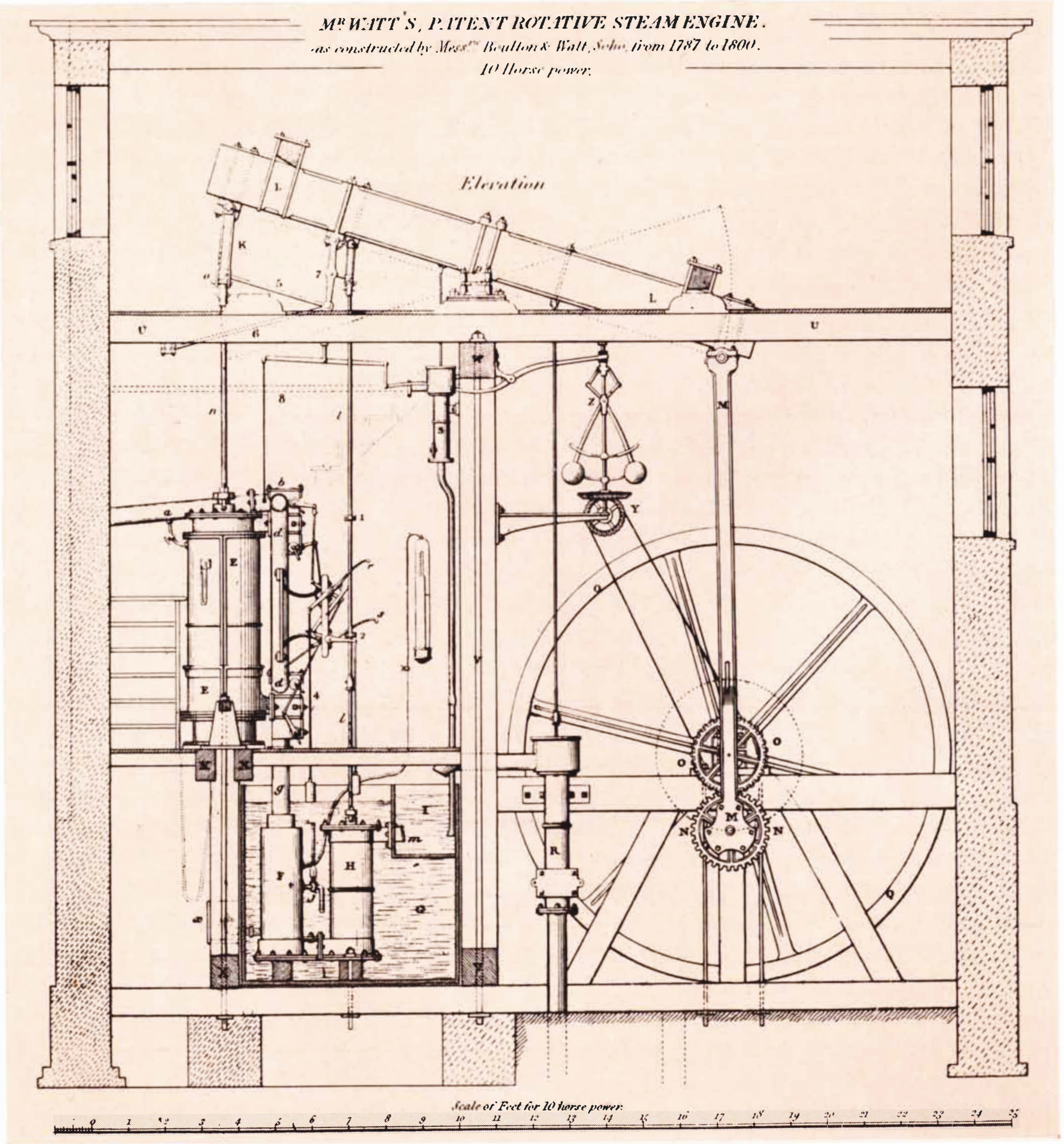
It is curious that all the inventions of feedback devices that came in with the beginning of the Industrial Revolution originated in Britain. Even those inventors who were not British-born, notably Drebbel and Denis Papin (the Frenchman who invented the safety valve, a rudimentary feedback device), presented their inventions while working in England. Why was the Continent so backward? Why was it, for instance,



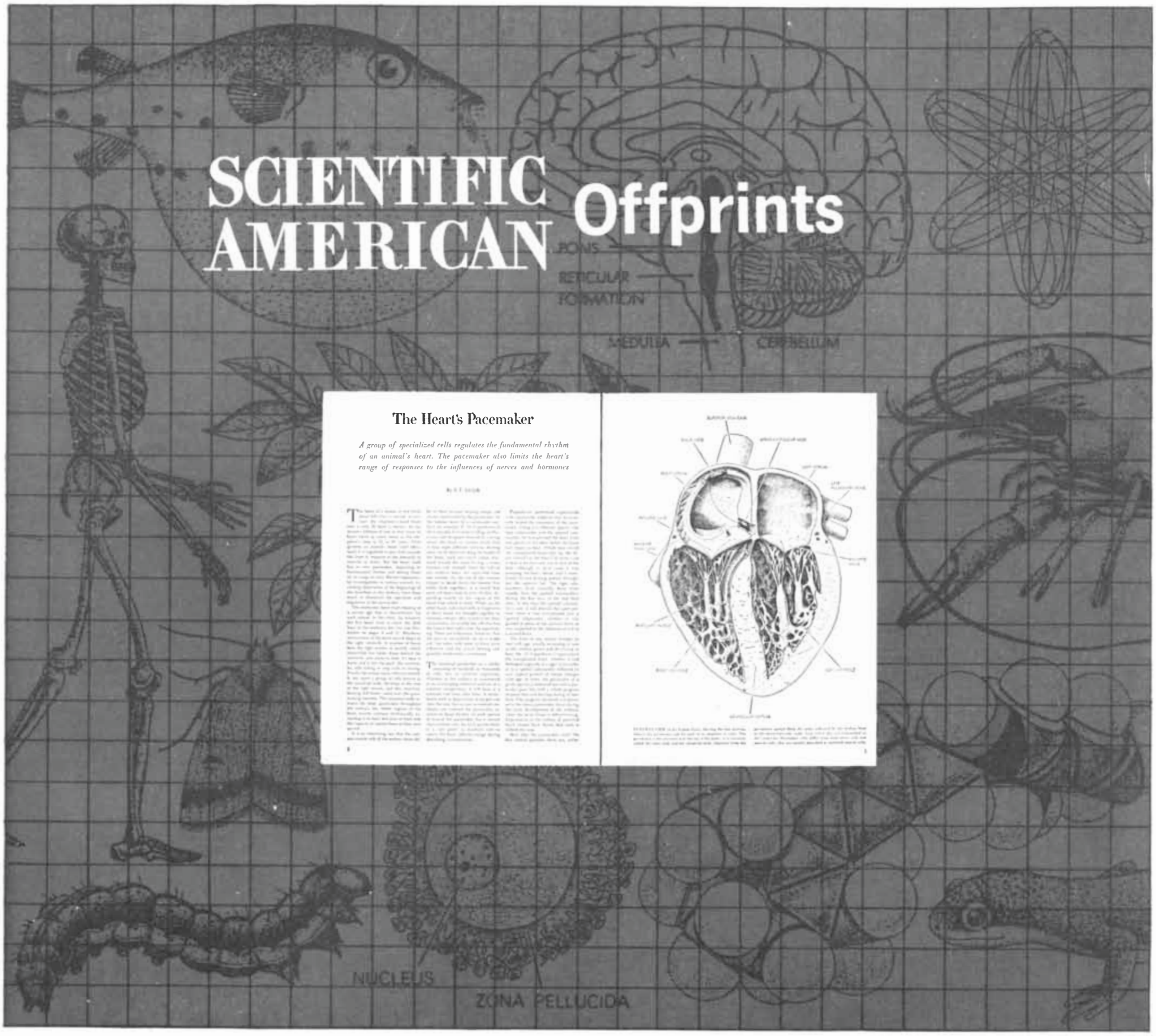
CENTRIFUGAL PENDULUMS were employed as feedback control devices by the English millwright Thomas Mead in his 1787 windmill patent. The speed of rotation of the mill sensed by one set of centrifugal pendulums drove the mill's lift-tenter mechanism (*left*). The motion of another set of pendulums in turn regulated the speed of the mill by reducing the area of the sails (*right*).

that engineers and inventors on the Continent ignored the float valve presented in the widely read translations of Hero's *Pneumatica* in 1575 and took serious notice of it only after the device was rediscovered in Britain two centuries later?

One can speculate plausibly that in the 16th to 18th centuries the Continental mind rejected feedback control because it was preoccupied with a different conception of control: control by rigidly predetermined program. In technology this was evidenced by almost countless inventions of automatons, monumental clocks, music boxes and clock-driven planetariums. The fascination with ordered programs was reflected in the Continent's prevailing attitude toward the state (absolute government) and in the economic system (mercantilism). In Britain, on the other hand, scientists, inventors and philosophers early in the 18th century began to turn to a different concept of control, one in which the system was truly autonomous, containing inherent mechanisms that maintained its equilibrium and viability. In technology such thinking led to the creation of feedback devices, in economics to the free-market system of Adam Smith and in political science to the division of powers and constitutional government.



FLYBALL GOVERNOR incorporated into the first continuously operating rotary steam engines in the 1790's by James Watt and Matthew Boulton was based directly on the windmill lift-tenter. In this 1826 drawing the centrifugal pendulum (*top center*), driven by a pulley, is linked to a throttle valve in the engine's steam line, enabling it to throttle the steam supply with increasing speed.



The Heart's Pacemaker

A group of specialized cells regulates the fundamental rhythm of an animal's heart. The pacemaker also limits the heart's range of responses to the influences of nerves and hormones

> *"...Certainly, the reading of this number of good articles in science must be making some impact on the educational process in this country..."*

Philip E. Hartman, in THE QUARTERLY REVIEW OF BIOLOGY, 41(2), 1966 [commenting on the fact that some 9,000,000 SCIENTIFIC AMERICAN Offprints had been sold up to that time. The number has nearly tripled since then.]

SCIENTIFIC AMERICAN Offprints are self-bound articles reproduced from the magazine for educational use. There are more than 600 of these articles now available, reprinted in the original format with full text, full illustration, and full color. They cover a broad range of topics in the life sciences, the behavioral sciences, the physical sciences, technology, and the earth sciences.

Offprints are available in any assortment or quantity at 20¢ each; thus teachers can conveniently provide their students with inexpensive supplementary readings closely coordinated with the design of their courses. Most teachers who use Offprints do so on an adoption basis, that is, they assign them to their students and order them through the bookstore just as they do textbooks. The publisher collates each student's set of Offprints and ships it to the bookstore with its own envelope.

For a free descriptive catalogue, write to Dept. 2

W. H. FREEMAN AND COMPANY
660 Market Street, San Francisco, California 94104
58 Kings Road, Reading RG1 3AA, Berkshire, England