

## In Search of Processes: The Early History of Cybernetics

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### ABSTRACT

This article is based on the inaugural address presented by the author at the University of Leiden on February 23, 1968. Due acknowledgement is given to De Koninklijke Maatschappij voor Natuurkunde "Diligentia" for their permission to translate this study, which was published in Dutch in *Natuurkundige Voordrachten* 47 (1969), 119.

The development of cybernetics began during the Second World War, after Wiener and Bigelow as well as McCulloch and Pitts had noticed that machines and organisms show considerable similarity in both structure and function, and that both can be described in terms of systems.

This starting point during the Second World War was, however, at the same time the terminal point of prolonged but isolated developments within this field. Although the discovery of regulatory systems is usually ascribed to James Watt (1787) and sometimes to Denis Papin (1680), the study of Arabic and Greek manuscripts shows that regulatory systems date back at least to 200 B.C. It was probably Archimedes (287-212 B.C.) who invented automatic water-level regulation to maintain a constant outflow rate in water clocks, and in A.D. 724, I-Hsing and Liang Ling invented an on-off control system, the escapement of the mechanical clock:

Considerations on control mechanisms in physiology (the science of functions and phenomena of living things) first arose in the seventeenth century (van Helmont, 1660 [72]; Descartes, 1664 [16]; and, perhaps, Harvey) and were published in a more developed form in the eighteenth century by Seguin and Lavoisier (1789) [65].

The theory of control and regulation dates from the nineteenth century, starting with Borgnis in 1818 [9]; it was worked out further by Maxwell [46], Farcot [21], and Wischnogradskii [85].

After the discovery of the triode around the turn of the century, electronic techniques made a rapid development during the next 50 years. During the Second World War, all these fields merged with computer techniques and the theory of automata to become cybernetics, supplemented after the war (1948) by Shannon's communication theory [66].

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Physiologists investigate organisms—that is, structures that reproduce themselves, grow, repair themselves, compensate for disturbing influences, and defend themselves; that take up and act on food and information from

their surroundings, and influence their surroundings in ways we may call purposeful; in short, organizations that show a relatively high degree of stability both in a changing milieu and during their own activities.

The enormous complexity of the structure and activity of biological organisms and their relations with comparable structures, by which they become part of still more complicated organizations, distinguishes them from the classic subjects of research in physics and chemistry, and corresponds to the (albeit still relatively simple) automata and man-machine systems in the technological sciences, among which medicine may be included. (The terms "process" and "system" are used synonymously. Under "system" is understood the blueprint, the anatomy of a process ; the concept "process" actually pertains to the operation and is furthermore used for the regulated part as well as for the whole system. For the sake of homogeneity, I have substituted the term "system" for the term "process" in the more comprehensive sense).

This article is devoted to the as yet mainly unwritten history of systems theory and its importance for physiology—to start with the oldest branch of science, technology in its still preconscious form. Rathenau has formulated this very clearly (in [62, page 119]):

Mechanisierung ist nicht aus freier, bewusster Vereinbarung . . . entstanden, sondern unbeabsichtigt, ja unbemerkt erwachsen . . . ein unwillkürlicher Prozess, ein dumpfer Naturvorgang.

The use of tools is important for the physiologist, because it means that processes occurring within the organism take place, via structures, at least partially outside the organism and are therefore visible to us.

In the animal world the use of tools occurs in a few highly divergent species. The burrowing wasp *Ammophila*, for instance, packs down the sand above its nest with a small stone. One of Darwin's finches, *Cactospiza*, pries insects out of cracks with a twig [19].

In contrast to these animals, our nearest cousin, Pan the chimpanzee, makes an extremely varied use of tools. Jane Goodall [29, 30] observed that chimpanzees threw stones at antagonists, employed chewed leaves as sponges to extract water from deep-lying pools, stripped leaves from small branches and scratched themselves with them, and with carefully prepared twigs, dug termites from their hills. Kortlandt's studies of chimpanzees living on savannahs have shown that these animals make clubs to use in fighting larger predatory animals (cf. [18, Chapter 1]). It is still an open question whether the use of the lever, the primeval machine, was invented by these animals or was copied by their ancestors from ours, but there is a Japanese monkey known to have invented the habit of washing its food; in the course of time this habit spread throughout the colony [25].

The manufacture and use of tools by anthropoids and anthropus went  
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through a remarkable development in prehistoric times, culminating in the production of stone implements in the Neolithic cultures of Amrat and Gerze in Egypt shortly before the First Dynasty [32, pages 237, 324]. More complicated machines, such as the spear-thrower and spear and the bow and arrow, date from the early Paleolithic period [27, page 161; 32, page 145]. These may be considered the earliest machines working in a single open chain.

Simple automata not requiring human agents to bring them into operation are also very old. The animal trap may date from the beginning of the Neolithic period [27, page 168; 32, page 158], and differed little from our mousetrap of the type in which by taking a bit of cheese from the trigger the mouse causes a trapdoor to close or a lethal weight to fall on it.

After about 5000 b.c., when man learned to use an external source of power to propel himself—by means of the sail (on the Euphrates, al'Ubaid culture; [32, page 328]) or by a vehicle drawn by animals or slaves—he became aware of the steering process and gave it a name. It is striking in this connection that the Dutch words *sturen* (steer) and *storen* (disturb), which concern the same process, both derive from the same Old Teutonic stem *steu* (cf. [78]).

In Greece, after the conquests of Alexander the Great (334-323 b.c.), technology went through a brilliant development within the short period of a few centuries. This technology, possibly inspired by many things the Greeks saw on their campaigns, reached its acme in the Graeco-Alexandrian School founded around 300 b.c. by Ptolemy I. The automatic temple-door opener (Fig. 1) mentioned in Hero's *Encyclopedia* [34] (100 ?) is as famous as the holy-water automaton, which emitted a measured quantity of holy water over the hands of temple visitors who inserted a five-drachma coin (MS *Scal.* 45, Leiden fol. 27r; [64, page 113]). Our coffee automats have a respectable age, therefore. It can be inferred from the descriptions in Hero's *Encyclopedia* that most of these apparatuses were used to impress simple people who came to the temples or served for the enjoyment of the very rich.

In Europe these techniques were forgotten, due to the nontechnical temperament of the Romans (both during and after the Empire). Baghdad took over the role of Alexandria, and reached the pinnacle of technological accomplishment under the celebrated Caliph Harûn-al-Rashid (A.D. 786-809). The achievements of the Greeks were maintained to a great extent, thanks to the Persian and, later, Arabic translations of Greek manuscripts [49]. The European necromancers owed their fame not only to their knowledge of herbs but also (perhaps even mainly) to these techniques, which occasionally reached Christian Europe from the East and from Spain.

The *Encyclopedia* of Hero and the works of Philon of Byzantium (third to second century B.C.) contain, in addition to descriptions of simple automata, accounts of completely developed self-operating machines [58]: feedback systems maintaining a constant level of the water or wine in containers (Fig. 2) or of the olive oil in lamps (Philon; cf. [64, page 488]). Thus, the technique of control is very old.

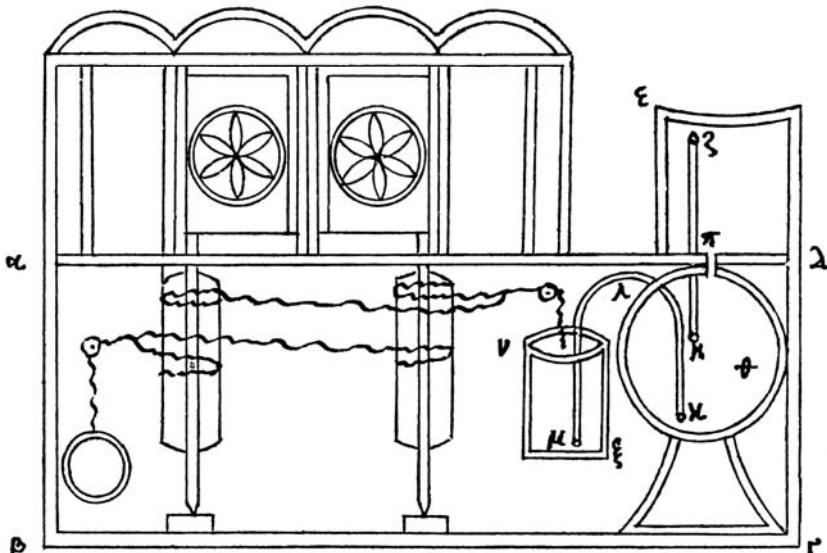


FIG. 1. Hero's automatic temple-door opener (taken with permission of the Librarian of Leiden University from MS Scal. 45, fol. 37v). When the fire at the upper right was lighted, it heated the air in the hollow altar. This warm air drove the water (not shown) out of the reservoir into the pail ( $\mu$ ), causing the pail to sink, which unwound the ropes around the axles of the temple doors. This opened the doors. As they opened, the ropes attached to the weight at the lower left were wound around the axles of the doors. When the fuel on the altar was consumed, the fire went out, the air in the altar cooled off, which drew the water out of the pail into the reservoir; and as the pail rose the doors closed.

In Europe it is not until 1300 that we see a more or less incidental occurrence of inventions or re-inventions of regulatory apparatuses. The first discovery of the regulation of the level of fluids was attributed to James Watt, in the eighteenth century [2, page 622]; and in 1893, more than 2000 years after the original invention, Maybach was granted a patent on a liquid-level regulator for the combustion motor designed by Daimler [26, page 168] the carburetor of today's automobile.

The question where the system for the automatic regulation of fluid levels came from can be answered after a study of the history of the *Mathematical Biosciences* 11 (1971), 5-29

measurement of time. Before 1500 B.C., because they wanted to measure time without having to know the position of the celestial bodies, the Egyptians developed the first clocks [40, page 123; 57, page 601]. These clocks consisted of jars with a small hole in the bottom that permitted water to escape at a slow rate. When the jars were filled with water, the time elapsed from that moment could be read in terms of the descending level of the water. With this contrivance the Egyptians created continuous

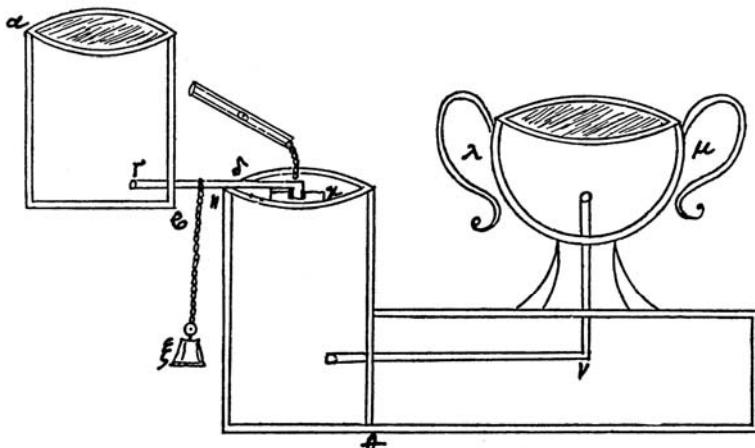


FIG. 2. Hero's system for the regulation of the wine level (taken with permission of the Librarian of Leiden University from MS *Scal.* 45, fol. 26r). The guests ladled their wine from the vessel on the right. This vessel was connected with the container in the center, which was concealed. At the upper left is the reservoir from which wine could flow into the concealed vessel via a pipe. The concealed vessel was provided with a float fitting the supply pipe. The lever and chain (due to a copyist's error not shown connected) kept the float in place. When the level of the wine dropped the float sank, permitting the wine to float out of the reservoir, at which the float rose until it again closed off the supply pipe.

uninterrupted (in our jargon, analogue) chronometry. The Greeks allowed the water from this effluent vessel to run into a second vessel, the affluent vessel, and in the latter measured the level of the ascending water. Because the dropping of the water level caused a reduction in the pressure at the effluent hole and thereby caused a reduction in the rate of outflow, they changed the shape of the effluent vessel: it became an amphora [63, page 41]. Around 250 B.C., Ktesibios provided the first vessel with an overflow and a feed pipe through which he allowed an excess of water to flow into this vessel [57, pages 601-603]. With this open system he obtained a reasonably stable water level (at the cost of a continuous loss of water).

In addition, he placed in the affluent vessel a float carrying a vertical rod indicating the elapsed time. This system was also used in the Tower of the Winds at Athens, which was built around 50 b.c. The overflow water fed a fountain in the tower. The entire dial of the clock was turned—the invention of moving hands dates from the fourteenth century—by a weight hung from one end of a cable wound around a shaft attached to the dial, the other end of the cable being attached to the float in the affluent vessel.

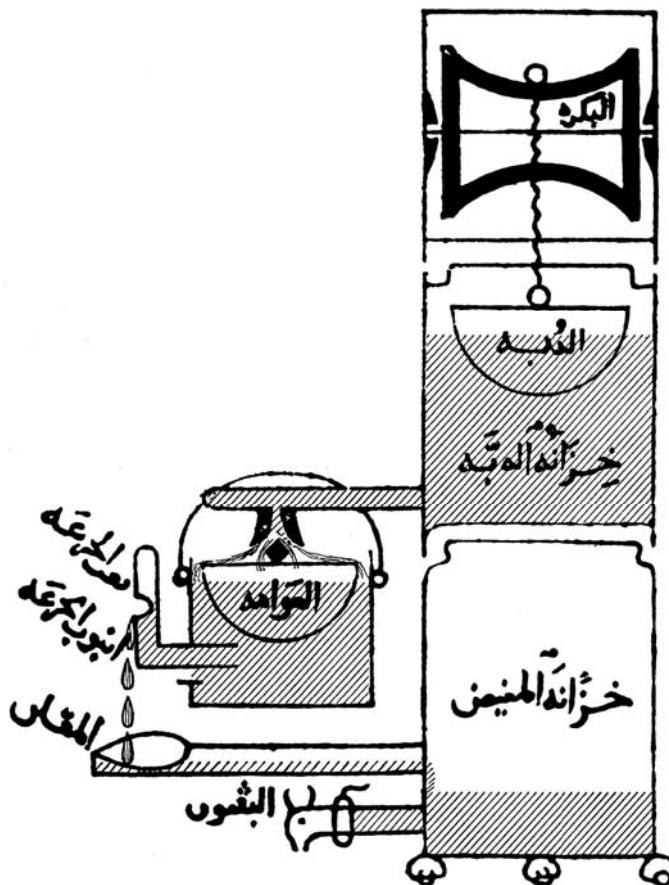


FIG. 3. The water clock of Archimedes (after [72, page 298]), from a manuscript of el-Gazari. For the sake of clarity, the path of the water is drawn in separately. The central compartment is the reservoir, the container on the left the outflow vessel, and the compartment at the lower right the inflow vessel. Due to a copyist's error, the outflow pipe is not drawn as closely fitting into the outflow vessel. In older manuscripts, such as [13, 117] in Leiden, this type is shown accurately, but because they are drawn in color they were not suitable for reproduction.

The steady rise of the float caused the weight to sink and turned the shaft of the clock at a constant rate. This is the so-called anaphorous clock of Ktesibios [73].

A work on clocks by Archimedes of Syracuse (287-212 B.C.), of which no original version is known, was translated from a Persian copy into Arabic by el-Gazari (1181-1206; [20]; [81, pages 32-48]). In this work (of which the Leiden University Library possesses two manuscripts, *Codex Orientalis* 117 and 656 [13]) we find the simplest feedback control system conceivable\*. Since Philon referred to a work of Archimedes on clocks [64, page 460; 82, page 164], we may assume that Archimedes was the inventor of the first regulatory system (Fig. 3). He conceived the idea of placing in the effluent vessel a float that (and this is the mark of genius) closed the opening of the feed pipe when the level rose and opened it when the level sank. This kept the water level in the effluent vessel constant, so that the outflow rate remained steady (and gave a more economical water consumption). Now the feed pipe could be connected to a reservoir [13, 117, fols. 7-10, 24]. Just as the float in the affluent vessel could trigger another mechanism by rising, a sinking float in the reservoir could serve the same purpose. The Greeks and later the Arabs devised many ways to make the passage of time visible; they also made it audible with many forms of chimes. There were clocks that moved small figures, blew on flutes, or dropped metal balls into basins.

As has already been mentioned, the regulatory system of Archimedes was also applied to other mechanisms. It seems likely that it were the Arabs who, a few centuries later, had the idea of letting the float operate a cock in the feed pipe (which made the system impervious to the effects of excess pressure). We may illustrate the operation of this regulatory system by the magic jar of Benū Musa (ninth century), which was used for various purposes (Fig. 4; [80, page 343]).

When cattle in the pasture drank water from this type of vessel or the rich man's guest filled his glass with wine from it, there was a drop in the fluid level in the vessel and therefore also in the container supplying it, which was provided with a float. By sinking, the float, a sensor, indicated this change, or disturbance of the situation, by means of a system of rods.

\* We see here the oldest described technical regulatory system with valves. Valveless regulatory systems in which the rising water, aided by air pressure, closes the pipe coming from the reservoir, are to be found in complex forms in the *Encyclopedia of Hero* (MS Scal. 45, e.g., fol. 25v), in the works of Philon [64, pages 484-489], and in the form of modifications in the work of Chinese authors [53, page 233]. The simplest form of this system (the inverted water-filled container placed in a drinking fountain for birds) must be much older, as indicated by the story of the widow of Zarephath [I Kings 17: 7-24], recorded shortly before the Captivity, 586 B.C.

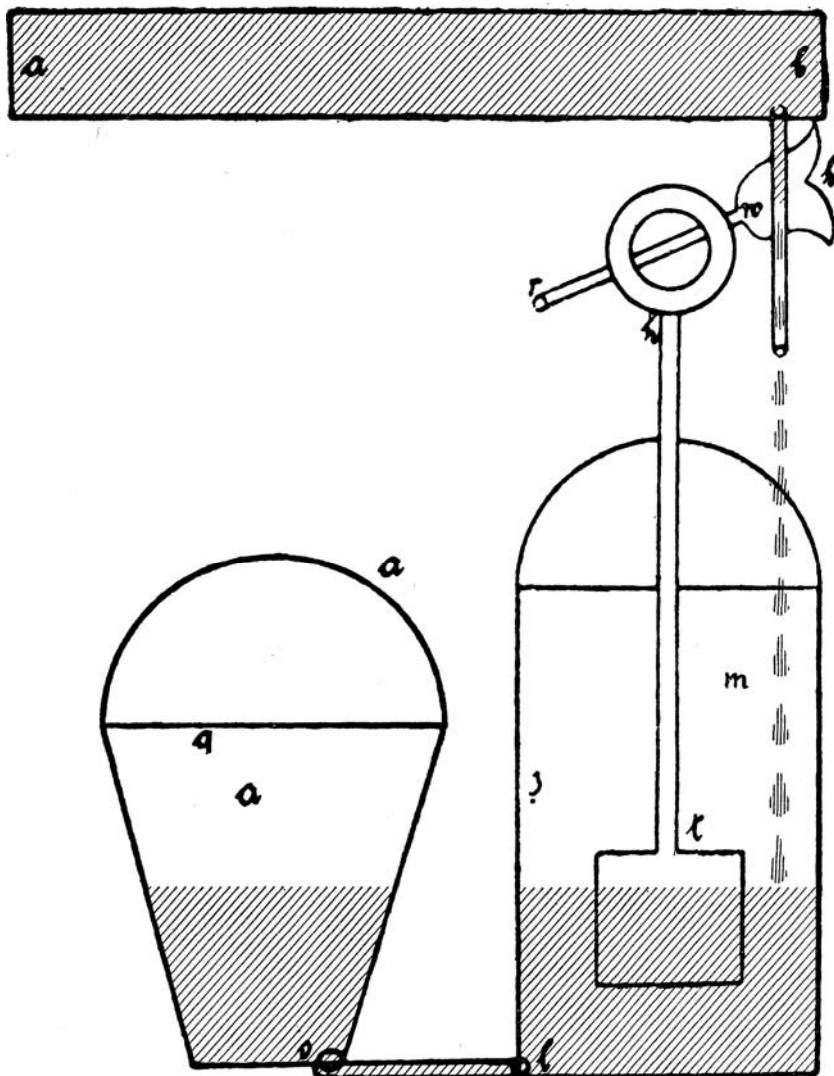


FIG. 4. The magic jar of Benū Musa (after [80, page 343]), taken from a Berlin manuscript. Here too the drawing is reproduced without modification, except for the water.

This system, the true feedback regulator, opened the cock at which fluid flowed from the feed pipe or the reservoir into the container. The level rose and by means of the system of float and rods the cock, the effector, was closed as soon as the desired situation had been reached. This situation was not only maintained when a disturbance was brought about by active

removal of fluid from the jar; this system also corrected the effects of evaporation and any leakages. That the system of rods formed the regulator becomes clear if it is kept in mind that a displacement of one rod over the other meant a change in the fluid level. As a result, there is a change in the set point of the system.

The development of this system did not mark the conclusion of the early history of control systems. We therefore continue to follow the history of the measurement of time, a line running from Alexandria and Baghdad to China and continuing in Europe only around the year 1300.

Water clocks could trigger all kinds of mechanisms as long as the machinery was not too heavy. The Chinese, who also knew the water clock, used large planetariums as components of their guidance mechanisms. (These conclusions concerning the regulatory mechanisms in Chinese clocks could be drawn thanks to the extremely detailed description of Chinese culture given by Needham in his admirable series [53].) These giant clocks could not be driven directly by water clocks; instead, this was effected by having the water from a water clock flow into one of the buckets attached to the circumference of a vertical wheel and kept in check by a balancing lever. As soon as this bucket had reached a given weight, it tipped. The weight of the water in the bucket caused the wheel to turn and brought the next bucket under the jet while the preceding one emptied. This system was developed around the year 100 by Chang Heng (A.D. 78-142, cf. [53, pages 483-488]). We may therefore consider Chang Heng to be the inventor of the counting of time: the discontinuous (in our jargon, digital) chronology. It is true that some of the playful chimes of the Greeks may also be seen as a form of digital time measurement, but Chang Heng's invention had historical consequences. His mechanism, a simple open automaton, still lacked precision, however. Directing a forceful jet of water at a turbine did not solve the problem, because this merely accelerated the rotation of the wheel. What was necessary was to adapt the rate of rotation of the entire system to the slow and steady rotation rate of the stars.

This problem led Emperor Hsüan Tsung of the T'ang Dynasty (685-762) to commission the Buddhist monk I-Hsing in 721 to design a more accurate system [53, pages 471-476]. I-Hsing, one of the most eminent universal physicists of his time, collaborated with Liang Ling Tsan, who was then a librarian, and found the solution. In 724, I-Hsing constructed an on-off control system, the escapement. This system can best be described on the basis of the propulsion system used in the famous astronomical clock tower of Su Sung at K'ai-feng in the province of Honan [53, pages 446-465]. This clock ran from 1090 to 1190, when it was damaged by a heavy storm. Under the Mongols, who had meanwhile

invaded the country, effective interest in this science could not be maintained; specialists were no longer trained in China and the art of clock-making disappeared there. Fortunately, information about these systems was preserved in various manuscripts, because the Chinese had invented the art of printing around 800 A.D.

The propulsion system used in I-Hsing's and Su Sung's clocks [53, pages 458-463] consisted of a vertical wheel equipped with buckets that could move to a limited extent and were filled successively from a water clock. As soon as the water in it had reached a certain weight, the vessel became detached from a scale and dropped a short distance. At the end of the drop it hit a rod, thus lifting a lever that released the wheel. The acceleration of the movement of the wheel due to the weight of the water was then arrested by the lever, which had meanwhile returned to its lower position. Thus, the wheel could revolve powerfully over exactly one position each time. The duration of the waiting time for the filling of a container was governed by the scale as well as by the outflow rate of the water, which was held constant by a level regulator (the first analogue-to-digital convertor).

The Chinese invention of digital chronology is certainly as important as that of the figure zero in India. The measurement of time in units of equal duration made it possible to count time, to measure its length just as the length of an object could be measured. Later, measurement in space and time, in combination with facility in computation, was to form part of the basis for the modern development of the sciences [79, page 172].

Along a still-unknown route, the principle of the on—off control for clocks must have made its way to Europe. There, around 1300, the water was replaced by a weight, a development arising from the anaphorous clocks. Furthermore, the escapement was made symmetrical by continuous alternation of the on—off elements, the sensor and the effector. Thanks to this symmetry, which made the essential operation of the clock more difficult to discern, the periodicity of the on—off system could be controlled by means of a reverberator. (The history of the technical development of reverberators and oscillators has not yet been written. The Arab contribution was probably very large. In the manuscript of el-Gazari, reverberating water clocks are described [13,11'7, fols. 152-161; 656, fols. 150, 154]. The European history of the pendulum is given by Morpurgo [51]. This development possibly goes back to the scooped wheel of Chang Hen [53, pages 483-488] and/or the periodically self-emptying water vessels of the Greeks [34, fol. 18v; 64, Chapters XIX and XX].) The first reverberator was placed in the horizontal position (the *foliot*) and was not very precise. In 1641, Galileo indicated that the precision could be improved by using the recently invented [51, pages 18-38] vertical oscillator, the pendulum.

Between 1657 and 1673, Christiaan Huygens developed this method of control further, and the pendulum clock became a serviceable instrument. (Reviews of the more recent development of the clock are to be found in [43] and [68].)

From these considerations on the operation of the clock, which can be traced step by step historically, it is evident that the digital mechanical clock is far from being a simple automaton. On the contrary, the clock represents a complex self-regulating and self-propelling machine. A weight or a spring accelerates the revolving shaft of the clock. The start-stop mechanism converts this into a jerky slow movement. An oscillating system drives this regulatory system and thus determines the duration and periodicity of this movement.

The further development of the digital mechanical clock is not relevant to our subject. But from the work he did in 1673, Huygens designed a quite new and very different type of clock based on a regular continuous movement [38, pages 157-161]. Like the ancient water clocks, this was an analogue clock. A symmetrical system of weights was mounted with hinges on a shaft. This shaft was made to turn by an energy source. Disturbances, such as variations in the load, caused the shaft to turn more slowly or more rapidly, as a result of which the space between the moving weights became smaller or greater. (The following is not stated explicitly in Huygens' work. The step to the actual application of this system is (still ?) unknown.) The extrusion of these weights had a retrograde effect on the energy source. This retroaction was executed in such a way that the energy supplied to the system was reduced when the rate of rotation increased, and vice versa. We now call this negative feedback. The system of revolving weights, the centrifugal regulator, thus provided for a roughly constant rotation rate of the system. Since then, centrifugal regulation has been applied not only in analogue clocks but also to windmills and water mills and, more than a hundred years later, to steam engines.

In fact, the steam engine is actually a very complicated clock that, because it can supply a large amount of energy, was developed as a source of power. There is no doubt in my mind that, had the Chinese developed the steam engine, they would in any case have used it as a chronometer in their planetariums.

Although a primitive steam engine was described as early as Hero's *Encyclopedia* ([34, fol. 46v]; and possibly a parallel development in Tibet: [53, pages 225-228]), the modern phase goes back to Papin [22, pages 93-110], who in 1680 constructed the high-pressure boiler as well as the system regulating the pressure in the boiler. The high-pressure boiler led Savery to the construction of a steam engine, but this machine was not usable in practice. Later, it was improved by Newcomen. On the basis of

his original invention of the automatic double-acting steam engine, Newcomen in 1717 created an oscillating system that functioned as an energy source and could be used for practical applications [59, pages 53-57 ; 24]. In the same year, Beighton applied Papin's pressure regulation to the boiler of the steam engine [59, page 106]. James Watt found a way to convert the oscillating motion of the piston into a rotating movement, and controlled the rotation rate of the shaft by incorporating the already well-known centrifugal regulator in 1787 [17, page 83]. By this and other improvements and inventions, he made the steam machine into not only a practical but also an economically applicable machine. The idea, which is still rather frequently entertained, that Watt was the father of the technology of control and regulation is probably to be ascribed to Weaver (in [44, page VII]) and Wiener [83, 84] (From the works of Wiener: "feedback, which . . . is at least as old, in fact, as the governor which regulates the speed of Watt's steam engine . ." [84, pages 151, 152] ; "in the original form designed by Watt . ." [83, page 97].) Apart from a single incorrect attribution to the Romans ("The ball-float valve, which controls the water level in plumbing, was an ancient invention of the Romans," [7, page 775]), most authors are more or less explicitly aware that the prior history began earlier than this, since they cite, for instance, Papin's safety valve, dating from 1680 [14, page 56; 8, page 2] or Huygen's centrifugal regulator, from 1673 [2, page 606], or Drebble's thermostat (1573-1633; [28, Vol. III, pages 679, 680; 61, page 11], which was described in 1666. This question is no longer relevant, however. Watt's application represents a milestone in the history of the technology of control and regulation, which began with the float valve before the commencement of the present era [58, page 7].

Another example of legend formation (here we can perhaps better speak of a myth) can be noticed in discussions about a fundamental difference between the first and the second industrial revolutions. One is said to have been the result of the large-scale industrial applications of such power sources as the steam engine and the other of data-processing machines. But this statement neglects the fact that acting and thinking can be distinguished but not separated. The steam engine could only be used after regulatory systems (i.e., systems that could take in information and process it, make decisions and execute them) had been incorporated into it. The steam engine even contained four such systems: for the regulation of the water level and pressure in the boiler, the action of the piston, and the rate of rotation of the shaft. Thus, even the steam engine could only "act while thinking" and therefore function as a source of energy. None less than Karl Marx discerned this aspect of the industrial revolution (in his letter to Engels written on January 28, 1863):

... I asked you . . . about the self-actor. The question is as follows : How did the so-called spinner act *before* the invention of the latter ? . . . there is no question at all that the industrial revolution starts not from the *motive power* . . . but from the transformation of the immediate process of spinning itself and from the displacement of that portion of human labour which is not merely "exertion of power" (as in the treading of a wheel) but which concerns the processing, the direct action on the material to be worked up. . . . The re-reading of my excerpts bearing on the history of technology has led me to the opinion that . . . the . . . bases on which the . . . industry proceeded . . . from the sixteenth to the middle of the eighteenth century. . . were the *clock* and the *mill* . . . Both were inherited from the ancients. . . . The clock was the first automatic machine applied to practical purposes; the whole theory of the *production of regular motion* was developed through it. . . . The *industrial revolution* begins . . . where, in the nature of things, man has not from the very first acted merely as *power* [45, pages 137-139, original italics].

Earlier attempts to build extremely complex automata failed because of the overriding effect of friction developed in purely mechanical systems of greater complexity. A classic example of this is Babbage's 1882 computer [52].

In electronic technology, which developed from Edison's incandescent light bulb after the diode had been invented by Edison (1885) and Fleming (1905), friction was insignificant. In 1905, De Forest discovered the triode. In 1912 he used it as an amplifier, and also found that an oscillating system could be obtained by connecting the output of the triode in series with the input (positive feedback). This was the genesis of wireless telephony. For purposes of long-distance telephone communication by means of cables, Black developed a feedback amplifier in 1924, on which he later collaborated with Bode and MacColl. All these developments made it possible to construct more complex systems. (Reviews of the developments in electronic regulatory techniques are to be found in [8] and [61].)

But with respect to the industrial revolution, all this boils down to a difference in emphasis between acting and thinking. The "thinking" aspect was always present but emerged rather slowly.

It is evident from this review that the technology of control and regulation is more than 2200 years old and that its genesis was gradual, as it were, unconscious. The more conscious (i.e., more theoretical) thinking concerning these systems, the theory of control and regulation, developed much later. In 1818, 150 years ago, Borgnis published the first classification of regulatory systems in his *Traité Complet de Mécanique* [9]. His systematization of the components of machines comprises six main groups [9, pages VII, VIII; 23, page 210]. He gave these groups names that for us are suggestive of physiology : *récepteurs*, *communicateurs*, *modificateurs*, *supports*, *régulateurs*, and *opérateurs*. Although his subdivision of the regulators is now obsolete, this chapter [9, pages 324-383] contains some remarkable descriptions supporting his identification as a precursor in this field of science.

In 1868, Maxwell wrote the first mathematical treatise on regulators, almost a century after Watt's application of the centrifugal regulator to the steam engine. He was clearly inspired by the many variants of regulators and certainly not only by the centrifugal regulator "of" Watt [46, page 271]. In this paper Maxwell demonstrated that these systems are susceptible to mathematical analysis and that conditions could be given under which these devices would have a regulatory function, a partially regulatory function, or no regulatory function. This article also contains a summons to mathematicians to undertake the analysis of the operation of regulators [46, page 272].

In 1876, Wischnegradskii published, in an extremely short and elegant paper [85], a mathematical analysis of a regulatory system. Like Maxwell, he also added the conditions under which the system is stable and regulates adequately, only regulates after an initial oscillation, or oscillates (we now call these conditions overdamped, underdamped, and undamped, respectively). In the last of these cases no regulation occurs (a situation that must be distinguished from systems demanding oscillation, such as the drive mechanism of the digital clock). Furthermore, on the basis of the conditions he had derived, Wischnegradskii stated that these systems must always have a finite following velocity (i.e., a high-frequency cutoff). He concluded that an ideal regulator cannot be constructed, but that the constructable and almost ideal regulator is quite satisfactory for practical purposes [85, page 321].

Meanwhile, in 1873, Farcot had made an entirely original contribution by his theoretical development of the servomotor, which he tested in French warships. The earliest steamboats had motors with a capacity of at least 1000 horsepower, but they were extremely difficult to steer. Eight men were required to turn the wheel, and the ships responded much too slowly to changes in course. To lighten this work and to increase the capability of these ships to react, Farcot developed the principle of the servomotor. This auxiliary motor regulated the action of the main motor, if necessary via a second and more powerful auxiliary motor, but was itself controlled from a command post. To indicate that this represented a system servilely following all commands, he gave it the name *servomoteur* or *moteur asservi* [21, page 4]. In this publication he already spoke of these systems in terms of order (*ordres*), indication (*indications*), and command (*gouvernement absolu*), and about holding the reins (*un système de rênes, de tenir en bride*). Such with the exertion of minimal effort *rune action . . . de la plus faible intensité* [21, pages 2, 3]. He was also the first to picture a circular structure in space [21, Fig. 1]. Some of his sentences can perhaps be interpreted as a statement that (negative) feedback was present in them ("*le système . . . qui commande le tiroir . . .*

*a course réduite" ; "il fait tirer ou pousser . . . en sens inverse du mouvement . . .*"; [21, page 5]).

Despite Maxwell's summons to mathematicians and except for a few technical reviews [42, 56, 75], the theory of control and regulation made only a slow and rather incidental start in the nineteen twenties. The papers by Minorsky on the automatic pilot [50, 50a], by van der Pol on oscillating systems [70], and in the thirties, by Nyquist on feedback theory [54] and Hazen on servo systems [33] are among the most important prewar publications in this field directly motivated by problems of control. (Modern developments in control theory and the relevant mathematical tools are described in [3] and [61].) This historical consideration has shown that practice was 2000 years ahead of theory. The fraternal communion of the technology and theory of regulation and control is only a few decades old, but during that period development has been extremely rapid.

Although the histories of computation, the relevant parts of mathematics, the theory of computers (the history of the development of external memories, such as writing, goes back to prehistoric times ; that of mechanical programs and programmed systems, key and lock, to ca. 2000 b.c.), and the development of system concepts in economics and related fields actually belong in this review too, I shall bypass them to sketch the development of thinking in terms of systems in physiology. (Thanks to Adolph [1], the sources for the developments in physiology are easily found.)

Except for vague statements by pre-Socratics (Alkmaion, a physician, referred around 500 b.c. to the balance between opposing forces in organisms [12, page 107] and about 100 years later Hippocrates mentioned internal animal activity associated with feeding, growth, and disease [10, page 60]), physiological thinking in terms of systems began in the seventeenth century with Descartes (1596-1650), Van Helmont (1577-1664 ?), Spinoza (1632-1677), and perhaps Harvey (1578-1657).

According to von Brunn [74, page 34], Harvey gave a complete description of the action of the right auricle in the form of a regulatory system, but since von Brunn does not give detailed references to the relevant passages in Harvey, I must for the time being consider this an open question.

Descartes, in his *Traité de l'Homme* (1664), gave the celebrated comparison between man and the clock and other automata, one of the first physiological models.

. . . les fonctions . . . d'un vrai homme: je desire, dis-je, que vous considériez que ces fonctions suivent toutes naturellement, en cette machine, de la seule disposition de ses organes, ne plus ne moins que font les mouvements d'une horloge, ou autre automate, de celle de ses contrepoids et de ses roues; en sorte qu'il ne faut point

à leur occasion concevoir en elle aucune autre âme végétative, ni sensitive, ni aucun autre principe de mouvement et de vie, que son sang et ses esprits, agités par la chaleur du feu qui brûle continuellement dans son cœur, et qui n'est point d'autre nature que tous les feux qui sont dans les corps inanimés [16, exactly cited after page 873].

If we read the first page of *Traité de l'Homme* carefully, it becomes clear that Descartes arrived at this comparison (although it remains possible that contemporary views compelled him to this formulation) in analogy with the story of creation in Genesis, which says that God created man in His own image. In the same way man makes the machine in his image [16, page 807].

It is evident from Descartes' comparison with the clock that he saw the human organism as an open chain of causes and effects. Although he was on the verge of closing the circle and formulating the concept of the signal [16, page 866]—his work implies the concept of self-defense as well as the basic idea of the reflex [16, pages 824-827]—he failed to cross this threshold. Like so many others, Descartes did not really understand how a clock works. This model is actually far more elegant than it was for a long time thought to be, as the foregoing has shown.

The comparison of organisms with the clock in the Cartesian sense continued to be used, sometimes negatively and sometimes positively, up to the beginning of the present century by many authors. But as early as 1660 the concept "control" was introduced into physiology by van Helmont, who did understand the working of the clock. He used this apparatus in a parable, and remarked that although it is true that a clock only works if the weight is hung from it, its operation is based on a control mechanism in the clock itself [71, page 106]. He firmly rejected all Aristotelian ideas about external control of the human being [71, pages 28, 106, 107].

Er is, zei van Helmont, een "werckmeester" in het lichaam, "eenen algemeynen bestierder, die den toom houdt . . . [met] gesach over alle . . . sijne besondere stiermannen der leden." (There is, said van Helmont, a "supervisor" in the body, "a general manager that keeps order . . . [with] authority over all . . . his special managers in the limbs" [71, page 44].)

It should be noted that here he even mentions a hierarchy of systems. It is clear from the rest of his discussion that he considered these controls to be natural phenomena in organisms [71, page 110]. Van Helmont developed this idea further in his study of the functioning of the stomach: the entrance and exit of the stomach (*bovenslot*, upper lock; *onderslot*, lower lock) are opened and closed by keys located elsewhere in the body [71, page 226].

As the last of the seventeenth-century group of four, Spinoza laid *Mathematical Biosciences* 11 (1971), 5-29

the foundation in his *Ethica* [69, pages 61-63] for the concepts "structure" and "organization." These concepts were explicitly used by Cuvier at the beginning of the nineteenth century in his introduction to *Le Règne Animal* [15, pages 15, 16], where he stated that the term "organization" expresses the communal structure of living beings and that only organized bodies can maintain life.

In the second half of the eighteenth century Lavoisier published his articles on respiration and temperature. His physiological discovery in 1777 that respiration is a process of slowed-down combustion was followed in 1789 by a paper written together with Seguin, one of the classics in the field of physiological systems. On the basis of their experimental results they came to the conclusion that in the animal there are a number of regulators that control the animal machine ("*la machine animale est principalement gouvernée par trois régulateurs principaux*"), compensate for defects, and have a well-defined range of action. If this range is exceeded, the individual becomes ill. But even then there are mechanisms for repair, so that a cure is possible [65, pages 580-582]. The result of the collaboration between these mechanisms was stated by them as early as this and in an extraordinarily poetic manner (exactly cited after [65, page 581]: "*Dans la course, dans la danse, / dans tous les exercices violens, / ... l'équilibre de l'économie animale / n'est pas troublé . . .*" [solidus inserted by author.]

The theoretical equivalent of these findings concerning the regulation of respiration (i.e., that the accelerating effect of the weight hanging on the clock is converted into a slow and steady movement by a regulatory mechanism) was not formulated until 30 years had passed, in 1818, by Borgnis in his chapter devoted to regulators in the work already mentioned [9, pages 336, 337].

Just how difficult it was to proceed from the concepts of open causal chains to closed-loop processes can be illustrated on the basis of Palmer's discussion in the collected works of Hunter dating from 1837. Palmer remarked that Cuvier's statement that life is dependent on organization meant for him "nothing less than a complete reversal of the actual relations between cause and effect" [36, page 127]. How close Palmer was here to the discovery of one of the most important concepts of physiology, and how long before this concept took form! But the battle between the mechanists, who in fact thought exclusively in terms of open chains of cause and effect, and the vitalists, who postulated an intangible vital principle, had already begun.

A little less than a hundred years later, in the latter half of the nineteenth century, Claude Bernard placed physiology on a high experimental level [4]. On the basis of his investigations, he distinguished in 1859 [5, pages 51, 52] between the external environment, the milieu in which the organism

is located, and the internal milieu, the fluid surrounding the tissue elements. In 1878 he stated, on grounds provided by his experimental findings, that the constant composition of the internal milieu forms the condition for free and independent life; that this milieu remains constant because in all cases variations are compensated for and brought into equilibrium [6, page 113]; that this occurs under the influence of the nervous system [5, page 49]; and that the animal possesses reserves that enable it to cope with anomalies. But he was in such sharp opposition to the vitalistic tendencies of his time (*"tout phénomène a un déterminisme rigoureux"*) that he rejected ideas about statistical processes [4, pages 134-140], and although he once used the concept "regulation" [5, page 450]), he actually resisted it, because for him this concept implied the presence of an intangible controller. He then [6, Vol. II, page 161; lecture XXV] attacked not Lavoisier but van Helmont! It is one of the ironies of history that van Helmont, who like Bernard opposed the use of intangible concepts, was labeled a vitalist in later times.

In the years between 1929 and 1932, Cannon brought to completion the concept of the closed regulatory loop in relation to systems responsible for keeping the internal milieu constant. Between 1921 and 1934, von Uexküll did the same for the reflex arcs in relation to the external milieu [77, pp. 23-30]. Cannon began by distinguishing between the concepts "equilibrium" and "regulated steady state," for which he introduced the term "homeostasis" [11, page 24]. He concluded that the autonomous nervous system observes disturbances and upon receiving signals activates adjusting mechanisms [11, page 59]. He expressed the hope that the way in which this occurred would be clarified by further research, research that Sherrington and others were already pursuing. But Cannon already saw more distant horizons, and remarked that the investigation of regulatory systems in physiology was important for other organizations, both industrial and social, since it could contribute to the compensation of disturbances in these fields [11, pages 24, 25].

The Second World War had the effect of a giant melting pot into which disciplines were cast that until then had been developing more or less separately: the technology and theory of control and regulation, automata and computation, and physiology.

Until this war, for instance, man had been an essential component of fire-control systems in antiaircraft batteries. This vulnerable and not always equally reliable component (an insight already formulated by Farcot in 1873 [21, page 68]) had to be replaced by a fire-controlling automaton; this problem was assigned to Bigelow and Wiener. In their analysis of this man-machine system they arrived (as Lincke had done 60 years earlier; [42, pages 589, 603-608] at the view that feedback pro-

cesses play an essential role in human actions. Together with the physiologist Rosenblueth, these mathematicians set up a program that they published in 1943 in the journal *Philosophy of Science* under the title "Behaviour, Purpose, and Teleology." In this "physiological manifesto" they stated that feedback processes occur in all living structures [60, pages 19, 22]. Furthermore, they pointed out that living systems and complex machines are comparable in structure and operation, although the nature of the structural components may differ. Specific narrow classes can occur exclusively in one system or another, for instance the wheel [60, page 22]. In 1946 they demonstrated experimentally that physiological processes could indeed be measured quantitatively on the basis of the approach supplied by control theory [84, pages 19-22]. (It must be kept in mind that the above-mentioned exclusiveness must be regarded with some reserve. Even the most striking difference between organisms and machines, the wheel, is only relative. Some joints can be considered as wheel segment and ground; after the completion of a movement, this segment is again in apposition to the "ground" belonging to it.)

Meanwhile, McCulloch and Pitts had combined neurophysiology and the theory of computing automata. In 1943 they published an article entitled "A Logical Calculus of Ideas Immanent in Nervous Activity" in which they demonstrated that networks of simple nerve cells can perform all logical operations (paper 2 in [48]). Sixteen years later, in 1959, this idea was taken as the basis for a physiological investigation that was to have primary importance for modern systems physiology. Lettvin *et al.* [41] gave this work the intriguing title "What the Frog's Eye Tells the Frog's Brain." They found that the nerve cells in the frog's retina are linked such that these animals can only perceive a few simple patterns. An example of this is given by the bug detectors. These are cells connected in such a way that they only become active when a small dark spot enters the central part of the field of vision of the cell. Since these studies were done, great advances have been made in the analysis of pattern-detecting networks. Here it will suffice to mention that the entire system, from the perception of the fly to its capture, can be analyzed, and in animals more closely related to us, such as the cat and monkey, the pattern-detecting elements have been shifted to the cerebral cortex, elements that detect successively lines, parallel lines, and angles between lines. These elements are already present at birth.

Just as the Cartesian system of three spatial dimensions can be considered the analogues of our vestibular organ, the Euclidian system of axioms (ca. 300 B.C.) can be seen as the analogues of the elements in the pattern detection of the visual system. It begins to seem as though for physiology mathematics is not only a tool but also a source of inspiration.

I willingly admit that the use of analogies is dangerous. They do, however, form an extremely important part of our associative-creative thinking. The misuse of an analogy is forgivable if it is later corrected, but the investigator who fails to recognize isomorphy will never forgive himself. To muddle or to model, that is the question.

Complex physiological systems can also be described in terms of simple systems to begin with. Such simplified descriptions can serve very well, at least if the simplification is consistently taken into account. The important thing in the end is the level at which or the purpose for which a given description is applied. Ultimately, according to Rosenblueth *et al.* [60, page 23], "the ultimate model of a cat is of course another cat, whether it be born of still another cat or synthesized in a laboratory of the future" (and programmed). In the latter case someone would have made it and would therefore possess the necessary formula, but what went on inside such an animal at any given moment would be concealed from the investigator, just as is already the case with the modern computer.

The simplified description is also important for the physiologist, no matter what his background, because it permits him to determine what information about a system is still missing, so that he can fill this gap by research before proceeding to the analysis of the more complex form of that system.

For the physician the simplified description, albeit dangerous, is important because insight into the structure and functioning of systems implies insight into deviations from the normal pattern. This means that the traditional distinction between normal and pathological physiology is of secondary importance.

The multidisciplinary symposia initiated in 1943 by Wiener and McCulloch inspired von Neumann after the war to design a computer (1946/1947) that is still the model for all modern calculating machines. In partial fulfillment of Cannon's prediction, physiological data contributed to the basis on which this machine was designed (cf. page VIII in [76]).

In 1948 Wiener published his book *Cybernetics, or Control and Communication in the Animal and the Machine*, and in the same year Shannon's paper on communication theory appeared. Shannon's work led those working in cybernetics to see that in systems theory the important thing is not so much the consideration of energy concepts as the perception and processing of data, a concept that was already implicit in Farcot's work.

The sensation of *déjà vu* experienced by physiologists, and with them many others, in reading these publications, led a large number of them to a rather careless use of the terms "information" and "feedback." In practice, physiological research on systems made a slow start. Apart

from a few precursors, it only commenced in the fifties and began to increase after 1960, as shown in Table I, which is based on a limited survey of the literature made in 1962 [39].

TABLE I

Period	No. of studies	Duration of period (years)
1930-1939	2	10
1940-1949	2	10
1950-1954	6	5
1955-1959	20	5
1960-1962	83	2½

In closing I should like to make special mention of two principles that have recently emerged from practical experience and that in my opinion are extremely important (even though they are unproven and may remain unprovable).

The first of these, which derives from neurophysiology and was inspired by the cooperation within a large fleet of warships, I may call the *flexibility postulate* of McCulloch (1964, article 21 in [47]). According to this principle, cofunctioning abstract systems demand redundancy of the potential command without which the whole will disintegrate. This principle carries the implication that several potential commanders must always be present and that the one possessing the most data about the immediate and expectable situation exerts command at that moment.

The second principle, which is to be found in embryonic form in the works of van Helmont but was independently derived in modern systems theory, I should like to call the *structural postulate* of Habermann [31]. According to this principle, when several abstract machines cooperate there must be a hierarchical structure if they are to work harmoniously as a single unit.

These principles imply, for instance, that complex systems such as organisms or larger organizations must have many redundant levels of command; that command disassociation can occur in each of these levels; that pathological processes in redundant systems, such as the cerebrum, can proliferate unobserved for long periods; and that the commander *ego* in the nervous system will never, or only very briefly, be localizable, although it may be possible to localize the structure with ego-redundancy.

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In search of processes: the early history of cybernetics  
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See my signature below.

Translation of my February 23d, 1968 inaugural lecture for the chair in physiology at the medical faculty of the University of Leiden.

My research on the subject was finished in 1968.

I, hence, missed the delightful and thorough paper and book by Otto Mayer, 1970. The origins of feedback control. *Cientific American*, 1970, 223 (4): 110-118,  
and

Otto Mayr, 1971. Feedback mechanisms in the historical collection of the National Museum of History and Technology. *Smithsonian Institution Press*, City of Washington.