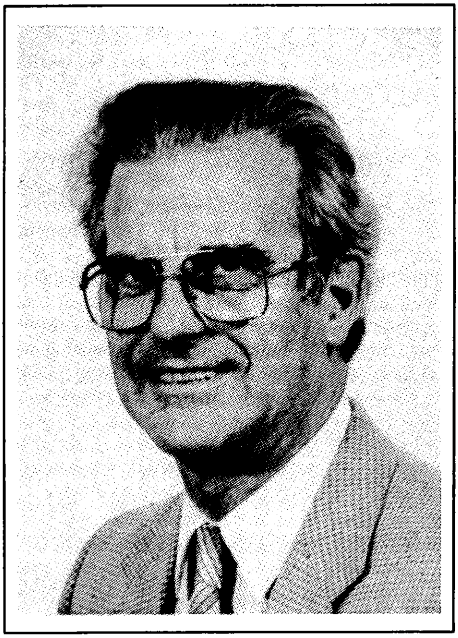

UNCERTAINTY AS AN ASSIGNMENT: THE FEEDBACK CONTROL PRINCIPLE THROUGHOUT THE AGES

Pieter Eijkhoff

Abstract

Since time immemorial man has been trying to fight the uncertainties with which he is confronted during his life. To that end *feedback*, a continuous intervention based on observations, has proved to be a very effective means. Some examples, applications from the distant and the more recent past, are presented. A proper theoretical foundation and the systematic implementation of this discipline in terms of *control theory* and *control engineering*, are only of rather recent origin.

It turns out that the fighting of uncertainty by use of feedback implies the implicit and/or explicit use of a model of the process under consideration. Until now, still some basic questions have been answered only partially. Nevertheless, feedback control has widely been proved and is recognized to be a very effective means in many branches of engineering and in society at large.

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Prologue

'They who know do not speak;
they who speak do not know.'
Lao Zi (580-500 BC)

Since the 6th century BC this saying of the famous Chinese sage has been impressed upon us. You can imagine, dear reader, what a dilemma this presents to a speaker (or writer) ...

Introduction

These lectures are named after George Alfred Leon Sarton (1884-1956), a famous son of the University of Ghent. His whole life was devoted to the history of science. He published extensively and founded two journals: Isis (1912) and Osiris (1936). At the onset of World War I he emigrated to England and then went to the USA. Among other appointments, he was professor of the History of Science at Harvard University (1940-1951). His outstanding devotion to this field is still manifest in the quality and the extent of his publications. In his time he was an illuminating example; so he still is for our generation.

Another name that I would like to mention with respect and appreciation is prof.ir. J.B. Quintyn, who worked at the Ghent University and promoted enthusiastically and ably the 'Museum Wetenschap en Techniek' and its publications.

Uncertainty

'What a man has, so much he 's sure of.'
Miguel de Cervantes (1547-1616)
Don Quixote, book IV, chapter 43

Man has an inborn dislike of uncertainty; much of his efforts have been and are directed to guarantee the perpetual availability of goods and conditions that form the primary breath of life, like: health, food, shelter, ...

Let us evoke our theme by a down-to-earth, every-day experience: taking a shower. Immediately you recognize a goal: to attain a pleasant temperature of the water. By a type of *'control'*, i.e. by adjusting the taps, this goal can be reached ... provided it is being done with some care. If the control action is too impulsive then very unpleasant things may happen.

Translated into technical terms we are dealing with:

- a *process*, which is a general term for a 'cause ⇒effect' relation; in this example the cause is the adjustment of the taps and the effect is the temperature of the water that leaves the nozzle;
- a *controller* that, based on the desired situation on the one hand and the observation/measurement of the actual situation on the other hand, acts in such a way that the difference between wish and actuality is made as small as feasible.

Process and controller together form a *control system*, which may be defined as:

> '*means, natural or artificial, by which a variable quantity, or a set of variable quantities, is caused to conform to a prescribed norm.*' [Enc. Brit., 1998]

The goal or prescribed norm can be of different kinds:

- **norm**: to keep a quantity constant
  name: *regulator system*
  example: a constant, pleasant temperature of the water during a shower
- **norm**: to follow in time a varying quantity
  name: *servo system*
  examples: the position on the road when driving a car
- **norm**: to bring a quantity from an initial to an end-value in some optimal way
  name: *optimal control system*
  example: the task to drive a car from A to B in minimal time or with a minimal fuel consumption

A general scheme for such a feedback control situation is given in fig. 1a, where P and R represent the characteristics of the process and the controller respectively. With adequate mathematical tools it is simple to show that feedback can be instrumental in diminishing the influences on the process output that are caused by:

- disturbances (changes) inside the process P;
- disturbances working from the outside on the process P.

These effects on internal and external uncertainties are elegant and very desirable properties of feedback indeed. Feedback can also affect:

- an unstable process, making it into a stable system;
- a stable process, making it into an unstable system.

In view of the last property, feedback has to be applied with much care and with serious consideration. Feedback can also provide changes in other system characteristics, but a discussion of those effects is outside the scope of these notes.

Another general characteristic of the feedback control situation is given in fig. 1b. The essence is the closed loop in which observations or measurement data, hence *information*, about the process output is being fed back to its input. By this information an *'energy flow'* (or materials flow) is being influenced; so, roughly speaking, 'energy' is being dosed by 'information'.

A few examples from early history

> *'One must learn by doing the thing;*
> *for though you think you know it*
> *you have no certainty, until you try.'*
> Sophocles (496-406 BC), Trachiniai

Already the early species of man depended on control actions, e.g. in regulating the fire, which was of paramount importance to him; cf. fig. 2. This implied: observing the fire (process) ⇒ action ⇒ observing again ⇒ if necessary action again, etc. The *'internal'* uncertainties that had to be counteracted include: the kind and the homogeneity of the fuel, its specific heat of combustion, the percentage of moisture. As *'external'* uncertainties we recognize: wind, rain, ambient temperature.

In spite of such uncertainties our early ancestors had various types of norms to approximate: sufficient radiation for ambient heating, adequate heat for cooking or roasting, light for enabling work or light for frightening wild animals, ... The eminent importance of fire and hence the predominance of this specific control action for the ancient people can be judged from many myths (Prometheus et al.). Another proof is the fate of the Vestal Virgins in the ancient Rome who had to maintain the permanent fire. When they neglected the control, and consequently the fire extinguished, the punishment was straightforward: being buried alive!

For an early written report on applications of control we refer to the Iliad by Homer. There we read in chapter 18 about the workshop of Hephaestos:

> *'Female slaves of gold, looking just like real girls, made haste to assist their master. Not only could they speak and move their graceful arms and legs, but they also possessed intelligence and they were gifted enough to do everything the god ordered them to do.'*

For the expert reader it will be clear that this refers to robots that could be programmed by way of speech. Probably they included an expert system based on neural nets ...

Let us look at two examples from the early Chinese development. Zhuang Zi (ca. 369-286 BC) writes about the processes in the human and animal body:

> *'It might seem as if there were a real Governor, but we find no trace of his being... But now the hundred parts of the human body, with its nine orifices and six viscera, all are complete in their places. Which one should one prefer ? Do you like them all equally ? Or do you like some more than others ? Are they all servants ? Are these servants unable to control each other, but need another as ruler ? Or do they become rulers and servants in turn ? Is there any true ruler than themselves ?'* [Ronan, 1978].

He does not give an answer, but the questions are highly pertinent.

An early documented control example that appears in the annals of Chinese history is the **South-pointing carriage**; sometimes it is called 'the first cybernetic machine' [Temple, 1986]; cf. fig. 3. For its origination several dates are mentioned : about 1030 BC, 120 AD or around 250 AD. The purpose of this device was to combat the uncertainty of direction; the figure on the carriage had to point constantly to the south, in spite of all turns that the vehicle is making. This was achieved by the principle which nowadays is called differential gears. When making a turn the two wheels follow paths of different lengths. This difference is changed by the gears into a proper correcting rotation of the pointing figure. It becomes a control system if the loop is closed by a human driver who steers by using the information of the south-pointer or, more automatically, by a carrot which is kept in the proper direction by the south-pointer before the nose of a pulling ox.

The control examples mentioned so far for fighting uncertainty on fire and on direction, include the human being as the controller ('human operator'). The next question is what early examples there are of systems without the need of human intervention: *automatic control systems*. In the excellent book on this topic by Otto Mayr [Mayr, 1970] a number of examples is given, including:

Ktesibios (Alexandria, first half of 3rd century BC) designed a waterclock, in which the flow of water is regulated by a float, swimming in a regulating vessel upstream of the metering orifice. Such a regulation of the fluid flow seems to have been used extensively also in later water clocks.
Philon (Byzantium, second half of 3rd century BC) constructed oil lamps with a vessel in which the level of the fuel is regulated automatically at a constant level in order to get a steady amount of light.
Heron (Alexandria, probably 1st century AD) constructed a mechanism for automatically opening the temple doors when the fire on the altar was lit. He also made several float regulators (e.g. an automatic wine dispenser) using floats and valves.

A real landmark in the early developments of feedback techniques is the oven with an automatic temperature control, invented by **Cornelis Drebbel** (Alkmaar, 1572-1633). Again this is an application used to regulate a combustion process. Fig. 4 shows the original sketch. Its working is as follows: the glass tube D is filled with alcohol and its U-shaped part is filled with mercury. A rise of the inside oven temperature causes an expansion of the alcohol, which is transmitted by the mercury to some bars. These bars close the opening E at the top of the oven, such that the fire will be tempered. If the inside temperature lowers, then the reverse happens and the fire will be fanned. Both the desired temperature and the sensitivity of the control can be adjusted by the geometry of the bars. The first application of this device was an incubator.

Denis Papin (1647-1712) designed a pressure cooker in which the pressure was controlled by a weight-loaded valve (1681).

A few examples from more recent history

A line of early engineering applications of automatic control in Western Europe was used on windmills for two purposes: (1) for keeping the mill continuously and automatically into the wind, and (2) for speed regulation. **Edmund Lee** invented a windmill with fan-tail and self-regulating sails that adjust the sail-surface area to the effective driving force of the wind (patent dated 1745). **Thomas Mead** designed a speed regulator for windmills using a centrifugal pendulum, where the movement of the pendulum is used to control the sail area of the mill (patent dated 1787)

The most celebrated early industrial applications start with the adaptation of the centrifugal or flyball governor by **James Watt** (1736-1819) to a rotating steam engine (1788). The stability problems that were encountered in such applications of feedback were studied by **James Clerk Maxwell** (1831-1879) [Maxwell, 1868]. This started the development of theory on automatic control.

The advent of the radio valve/electronic tube has given rise to a wide variety of circuits in which feedback is being applied. [Bennett, 1993]. In some early cases a *positive* feedback was used to bring the system close to instability, in this way increasing the amplification of the signals of interest. One example is the regenerative amplifier by **Charles S. Franklin** (1913). The radio- and audio-frequency feedback invented by **Edwin Armstrong** (1915) must also be mentioned.

The use of *negative* feedback was extensively studied by Harold S. Black (1934, patent 1937) and **Harry Nyquist** (1932) at Bell Telephone Labs for the design of stable repeaters for transatlantic cables [Bissell, 1997].

Since that time the variety of engineering applications, as well as the recognition of control principles that occur in non-engineering situations, have increased tremendously. A rough and incomplete listing includes:

- fine-mechanical, optical, electronic and mechatronic systems;
- information and communication engineering;
- energy production and -distribution;
- flexible industrial production; automation;
- industrial chemical and physical processes; 'process industry';
- means of transportation on land and sea;
- aero- and space travel;
- scientific instruments;
- climate conditions at home, office, etc;
- household applications;
- agriculture and environmental care;
- biology and medicine;
- economy; sociology, enforcement of the law.

Each of these fields would warrant further discussion, considering the uncertainties encountered and the feedback techniques used for counteracting them.

Models

> *'If a man begin with certainties,*
> *he shall end in doubts;*
> *but if he will be content*
> *to begin with doubts,*
> *he shall end in certainties.'*
> Francis Bacon (1561-1626),
> The Advancement of Learning

Many years ago Conant and Ross Ashby [1970] published an interesting statement: *'Every good regulator must be a model of that system'*. So let us devote some attention to models.

A classical domain where the concept of modelling developed over many centuries was the movement of celestial bodies. For a long time the Ptolemaic model of cycloidal motions stood as a *conceptual* model, mimicking the observed planetary movements. This was rendered out of date by a physical, viz. the Copernican, model that was based on both the motions of the earth (observer) and of the observed planet. The next development was into a *mathematical* model consisting of Kepler's laws, which permits numerical predic-

tions. Further contributions to this modelling by Newton are well known, as well as the explanations by Einstein of some anomaly in the observations.
In fact it was the estimation of planetary orbits based on imperfect observations that inspired **Carl Friedrich Gauss** (1777-1855) to the development of his statistical techniques [Gauss, 1809].

Since that time the growth of the notion of models in modern science and in engineering is tremendous [Popper, 1934]. Models are used for a wide variety of purposes:

- to explain physical laws and insight, based on previous observations;
- to predict future observations;
- to check on the proper performance of a process (fault detection and diagnosis by comparison of the process with a model);
- to derive control signals for influencing the behaviour of a process.

Considering such a wide spectrum of purposes, the intended use of the model is of dominant importance.

Now let us explore in a simple way the relation between feedback and models. Fig. 5 indicates the development of thought in *improving the response of a process.*

a. In mathematical terms P represents the transfer, the relation between the process input u and output y : $y = P u$.
b. If it were feasible to build a block, a 'model', with the transfer 1/P, the inverse of P, then the total transfer would be $1/P \cdot P = 1$, meaning that the output is an exact copy of the input.
c. Here the ∞ sign indicates an 'operational amplifier' with infinite gain; this provides a means to make 1/P.
d. is identical to c. and follows from it by shifting the feedback part of the loop to the process output.

So in principle we have derived a feedback control system, in which the process provides its own model !! This *implicit* model changes automatically if internal uncertainties cause changes in P. Of course the fundamental and practical restrictions imposed by the physical realizability of the inverse of a transfer should be discussed in more detail, but that topic is outside the scope of these notes.
The same type of reasoning using a model can be done for deriving a feedback system which handles external uncertainties that act on the process [Smith,

1958].

From these considerations the reader might accept the statement by Conant and Ross Ashby: *'Every good regulator must be a model of that system'*, although these authors used a different type of reasoning. However, judging from the citation index, that paper received far too little attention; particularly the control engineering community responded below expectation.
Yet since that time, from many research efforts it became clear that the role models play in control systems is an important one [Eykhoff, 1994], for:

- in many types of optimal control theory a perfect a priori knowledge of the process dynamics (model) is required. The early experiences in trying to apply such optimal control schemes lead, generally speaking, to disappointments because no internal uncertainty is considered. However, there proved to be situations in space engineering where the models were good enough (consisting of inertial mechanics, a conservative force field, disturbances that can be calculated). In most down-to-earth applications, however, the complexity of reality, including the disturbances, was not suitable for such optimal control schemes; the optimality of the control is too sensitive to uncertainty, to imperfect modelling.
- more recently, ways were found to include non-perfect models of complex processes for the improvement of the control characteristics. Even in industrial situations with process changes and many disturbances, the explicit use of an approximating model may lead to excellent results, i.e. contributes significantly to the quality of the control, i.e. the uncertainty reduction [Zhu and Backx, 1993]. Cf. also [Schoukens and Pintelon, 1991].

In practice it is not a trivial problem to attain an adequate model of a process. The techniques used to this end are called *process* or *system identification*; it is a way of arriving at knowledge on a complex process, based on partial (uncertain) a priori knowledge and on measured process input and disturbed (uncertain) output signals. The goal is to develop and continuously improve a (mathematical) model that represents the behaviour of the process as far as is feasible [Åström and Eykhoff, 1971; Eykhoff, 1974].
The choice of the type of model is influenced by a priori knowledge. One recognizes: 'white' model (i.e. a priori knowledge available through physical laws, mass balances, etc.) and 'black' model (i.e. no a priori information, but completely based on observations and data handling), as well as hybrid, inter-

mediate or 'grey' models.

The use of system identification can be traced back in early history; an example being the medical diagnosis by Chinese doctors that was practised at least two thousand years ago already; fig. 6. Based on the ethics of that time a physician was not allowed to observe a female patient. For the diagnosis of an illness he had to resort to pulse-feeling only. Even in this early example the essential elements of identification were present: observed 'output signals' served to update and correct the 'model' of the patient that was in the mind of the examining physician. This technique is attributed to **Bian Qiao**, ca. 255 BC.

So far we have met with several kinds of uncertainties: internal changes in the process, external influences on the process, an approximate model of the (complex) process. Relating these uncertainties a fundamental problem statement was given by Fel'dbaum [1960, 1961]. He formulated the concept of *'dual control'*, i.e. the necessity of combining:

- continuous identification of the process to provide a suitable model to the controller for fulfilling adequately the control (e.g. regulation) task;
- continuously controlling the process in order to eliminate as effectively as possible uncertainties working in and on the process.

This leads to a fundamental dilemma: proper control aims at counteracting all disturbances, whereas for proper identification the introduction of extra disturbances (test signals) might be needed. What additional disturbances do we have to apply in order to combat the primary uncertainties? This problem has not yet adequately been solved.

Intermezzo: Chinese and western science and engineering

In the previous sections we made some references to China. So let us digress for a moment. Due to the monumental work of **Joseph Needham** and collaborators [Needham, 1962-1998] now also the non-Chinese speaking part of the earth's population has extensive and high-quality information available on the early development of science, discoveries and inventions in China. This wealth of information has been condensed in an attractive way by **Robert Temple** [Temple, 1986]. Among other things he provides a survey of the time intervals between Chinese inventions or discoveries and their acceptance or recognition in the west. From this we select some spectacular examples:

	Chinese origin:	time interval until the use in Western Europe:
- lacquer; the first 'plastic'	13th century BC	3.200 years
- iron plough	6th - -	2.200 -
- circulation of the blood	6th - -	1.800 -
- compasses	4th - -	1.500 -
- cast iron	4th - -	1.700 -
- steel from cast iron	2nd - -	2.000 -
- paper	2nd - -	1.400 -
- quantitative cartography	2nd - AD	1.300 -
- porcelain	3rd - -	1.700 -
- gunpowder	9th - -	300 -
- printing with movable type	11th - -	400 -

These are only some examples from a long list of amazing achievements. Considering this performance so early in history, one wonders why China was scarcely involved in the development of modern science, including the concepts of automatic control. The following historical characteristics of China and the Western world might offer some base for an explanation:

China

- history until the 17th century
  Tang dynasty (618-907): bureaucratic organisation of the state; an examination system for public officers based on Confucianism, however in dialogue with Buddhism and Taoism; invention of block printing technique.
  Song dynasty (960-1279): more emphasis on the study of actual problems and political economics; invention of printing with movable types.
  Yuan dynasty (1206-1368): expansion of international exchange.
- development in the 17th and 18th century
  Qing dynasty (1644-1911): foreign (Manchu, non-Han) rulers distrust the Chinese; consequently the emphasis lies on stability and status quo; this

leads to intellectual stagnation. Examination system for public officers is based on a rigid interpretation of the nine Confucian classics; new science and technology is completely absent; 'the style was considered more important than the thinking.'

Western world

- history until the 17th century
  Christianity; military-aristocratic feudal system (king - knights - .... farmers and soldiers).
- development in the 17th and 18th century
  advent of the bourgeois entrepreneurs and capitalism; church reformation; rise of modern science: experiments, mathematical formulation, 'mathematical models'.

Apparently the differences in the developments of science in China and the West can be related to the openness of their respective societies in the 17th/18th centuries. In Chinese society many uncertainties were attributed to the degree of harmony between the Emperor, 'Son of Heaven', and Heaven. This had to be secured by performing the right rituals. In the West such uncertainties became subject of scientific approach.

Feedback in society

'No hinge or loop to hang a doubt on.'
William Shakespeare (1564-1616)
Othello, act III

Automatic control has become an important ingredient of technological change, But also the development of technological change is the result of a feedback process. That is indicated in fig. 7.

A *technological change* is effected by decisions based on various types of motives. Those decisions imply the assignment of a bigger or a smaller part of available resources: natural, human (including education), and financial

(capital and capital goods). The motives for such decisions will be based on:
- *physical and cultural needs and desires of man*, as indicated schematically in the figure. Among these needs and desires there are many aspects that are related to 'uncertainty'. Of course this list can be improved on and extended; a hierarchy of 'basic needs' of man is given by **Abraham Harold Maslow** (1908-1970) [Maslow, 1970] which range from low, basic needs to higher, more sophisticated desires:
- the physiological needs
- the safety needs
- the belongingness and love needs
- the esteem needs
- the need for self-actualization
- the desire to know and to understand
- the aesthetic needs.

A person may be confronted with uncertainty at all levels. But only if the uncertainty at more basic levels is small enough, the needs at the next sophisticated level will be of actual importance.

The resulting technological change will manifest itself and will have an impact in different ways. It gives rise to: - *new capabilities* for further development (research-push). Those capabilities can contribute to decisions to start or to continue the work on particular technological changes.

Such technological change also has an influence on the development of: - *new products*. Whether these will be successful or not depends on a type of feedback: how far do these products satisfy the wishes/demands of man that result from his physical and cultural needs and desires? The degree of acceptance by the 'consumer' (in the broadest sense of the word) will affect the decisions with respect to further development of technological changes.

A technological change can be accompanied by: - *new problems*, e.g. negative incidental effects. Those can be classified with respect to their region of impact. The smallest region is that of the individual who may meet with problems like changes in the type of work, danger to privacy due to the use of computer databases, the dangers on the road, etc. The next region of impact is related to the environment, which is affected by waste, chemicals, heat, etc. As indicated the problems can also extend to still larger regions.

Again a type of feedback will occur: to what degree will the problems be incompatible with the expectations originating from the physical and cultural needs and desires of man? The resulting public opinion will have its influence

on further technological changes too.
Apparently, in principle the feedback paths related to technological change are quite clear. Do they work adequately and are they sufficiently strong to act in an uncertainty-diminishing way? To this question probably each of us has his/her own opinion.

Conclusions

The fight against *uncertainty* is a very basic human drive. Hence the control by way of the feedback principle has been used since very early times. In the beginning man had no choice but to place himself in the control loop as the controller. The *automatic control*, an operation without direct human intervention, developed slowly and incidentally. In the acceleration of this development an important ingredient was the western recognition and use of physico-mathematical models. During part of history China has been lagging in this field.

In these notes many essential aspects of the development had to be neglected. The reader is referred to additional references like: [Åström, 1985; Bennett, 1979; Various authors, 1996].

Now the statement: *'Every good regulator must be a model of that system'* can more and more be recognized implicitly (models hidden in various optimal control schemes) or explicitly (model-based controller) as a leitmotiv.

Certainly not all problems related to uncertainty-suppression have been solved yet; there remains a challenge in incorporating partial knowledge about the uncertainty of the process-changes and about the inaccuracy of the model used, e.g. for answering industrial demands (better quality, efficiency, energy saving, waste prevention, responding to competition).

The fundamental challenge as formulated in 'dual control' still remains open: during operation -

- to reduce the uncertainty of the model through continuous identification action. For this task additional disturbances/testsignals on the process are needed;

- to reduce the uncertainty of the process by counteracting the disturbances through control action.

So some problems are still with us. However, for the time being we can live with this remaining uncertainty. This is testified by an uncountable number of engineering applications and by the recognition of numerous 'natural' types of feedback control (biology, society, economics, ...). A fascinating field of human endeavour !

Epilogue

> *'When you know something,*
> *to act as one who knows,*
> *and when you do not know something*
> *to acknowledge you do not know*
> *that is real knowledge.'*
> Kong Zi (Confucius) (551-479 BC)

A fundamental note on coping with uncertainties ...

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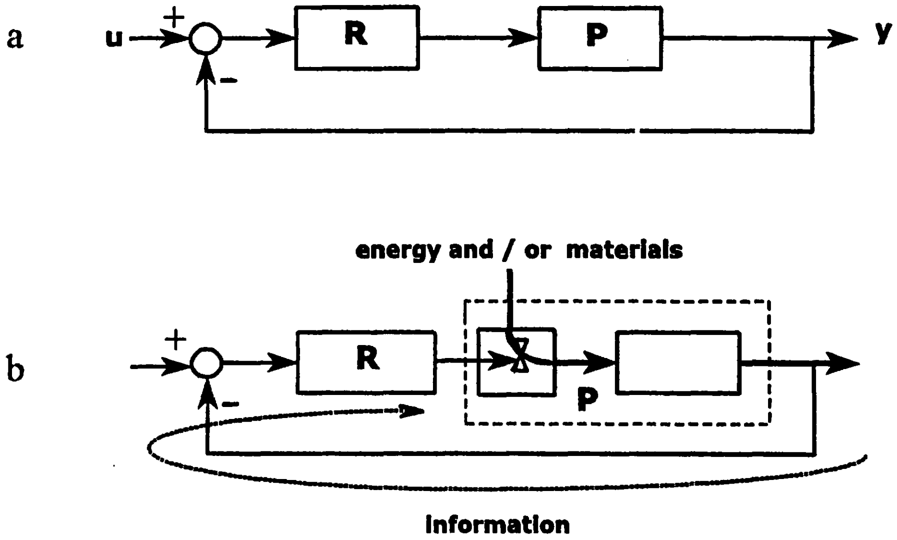
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energy and / or materials
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Fig. 1

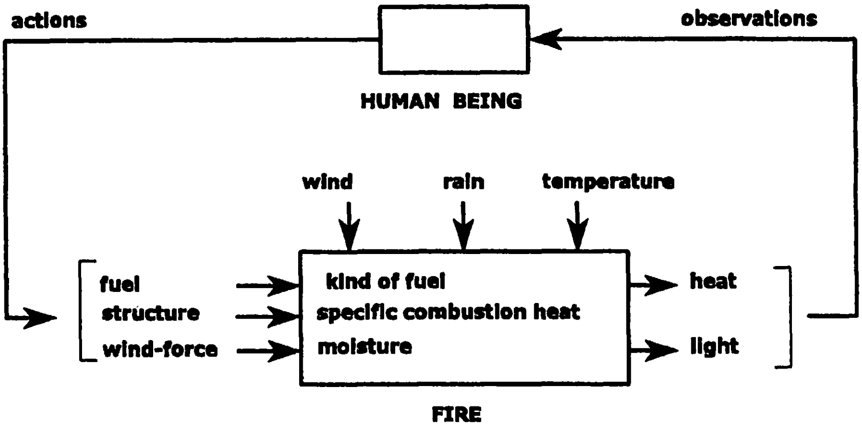

actions
observations
HUMAN BEING
wind
rain
temperature
fuel
structure
wind-force
kind of fuel
specific combustion heat
moisture
heat
light
FIRE

Fig. 2

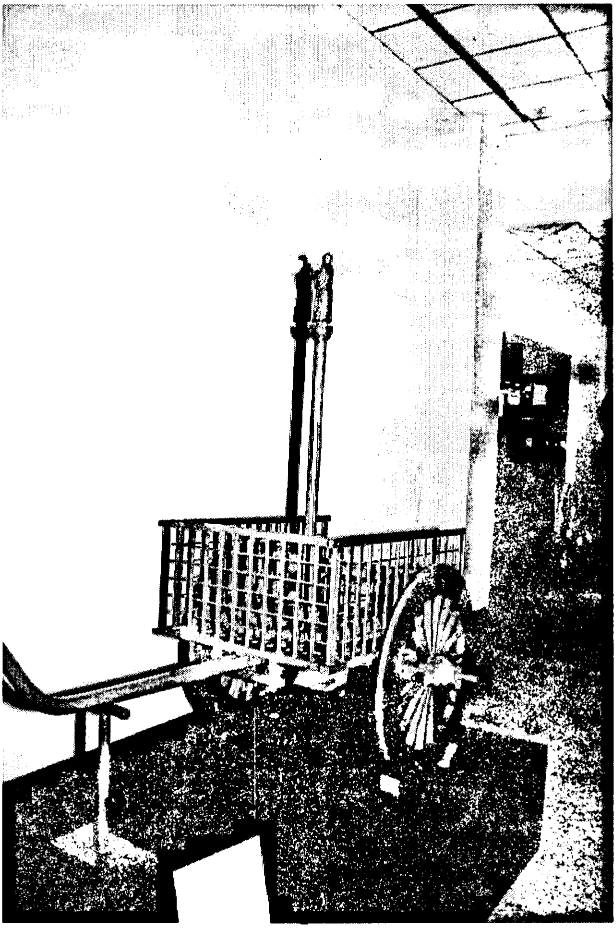


Fig. 3

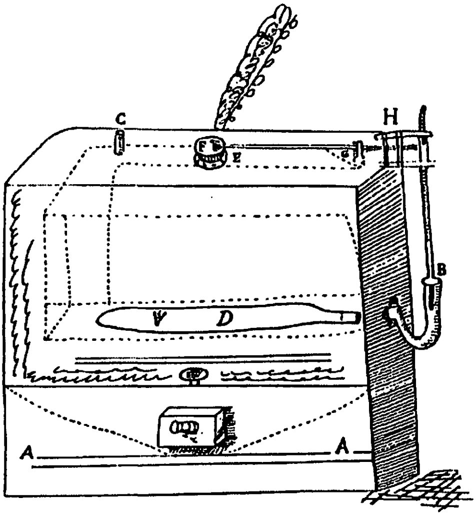


Fig. 4

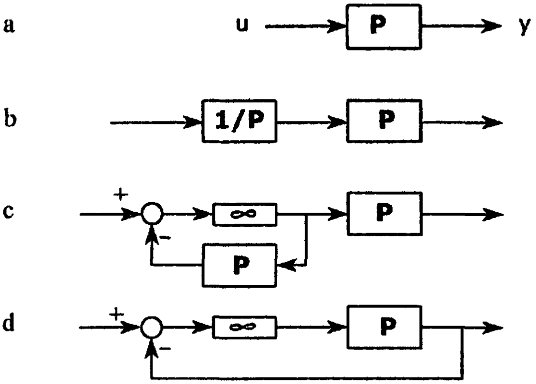
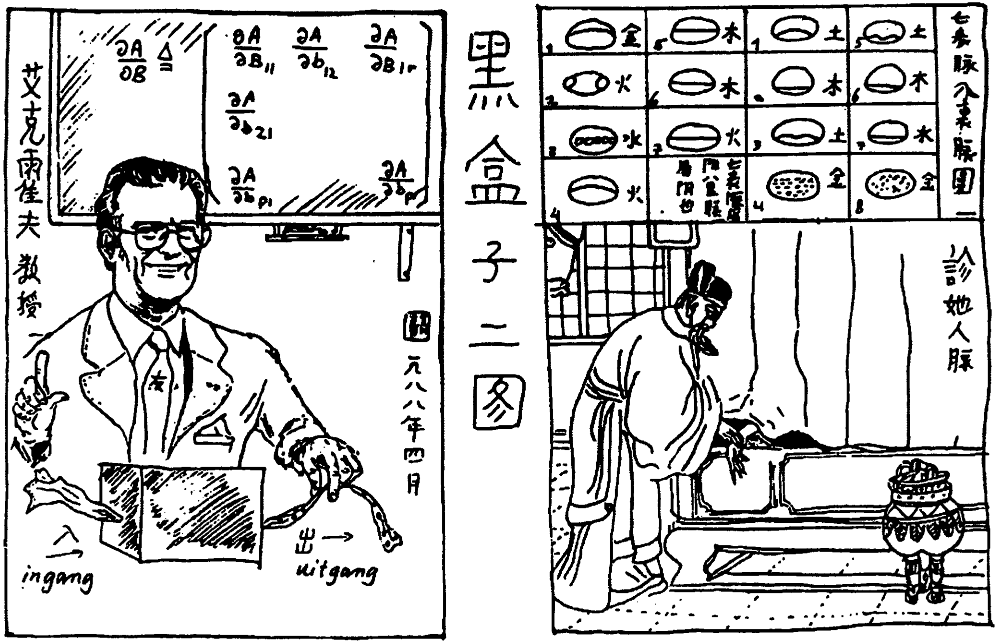


Fig. 5



Identificatie, 20e eeuw

Identificatie, 1e eeuw

Fig. 6

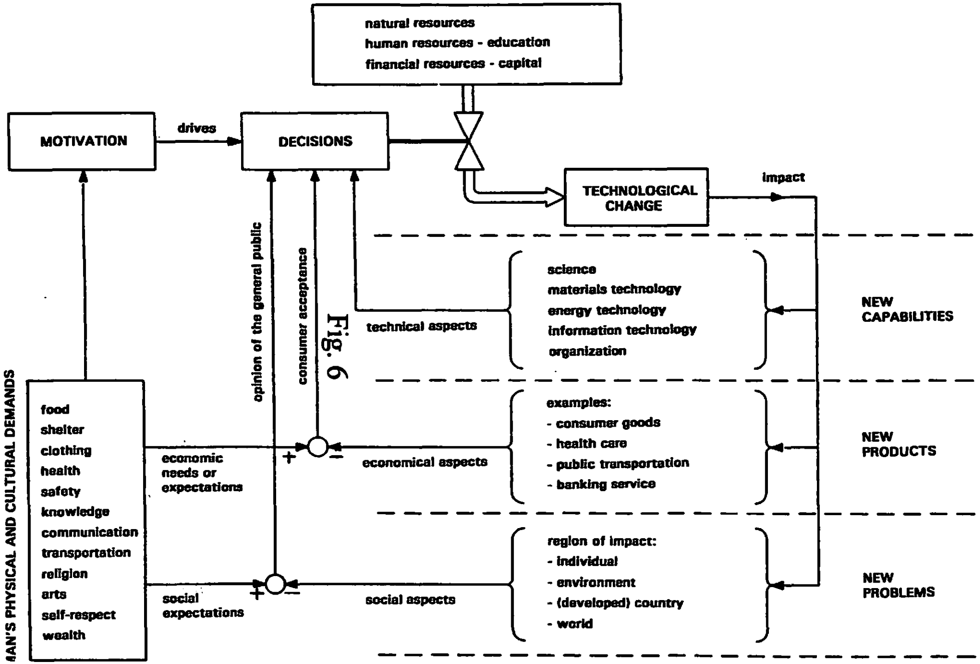

natural resources
human resources - education
financial resources - capital
MOTIVATION
drives
DECISIONS
TECHNOLOGICAL CHANGE
impact
opinion of the general public
consumer acceptance
technical aspects
science
materials technology
energy technology
information technology
organization
NEW CAPABILITIES
MAN'S PHYSICAL AND CULTURAL DEMANDS
food
shelter
clothing
health
safety
knowledge
communication
transportation
religion
arts
self-respect
wealth
economic needs or expectations
+
−
economical aspects
examples:
- consumer goods
- health care
- public transportation
- banking service
NEW PRODUCTS
social expectations
+
−
social aspects
region of impact:
- individual
- environment
- (developed) country
- world
NEW PROBLEMS

Fig. 6

Fig. 7