Cybernetics

A to Z

ИЗДАТЕЛЬСТВО • МИР •

Виктор Пекелис. Маленькая энциклопедия о большой кибернетике

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CYBERNETICS **A** to **Z**

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THE RUSSIAN ALPHABET AND ITS TRANSLITERATION

А а a	З з z	П п p	Ц ц ts
Б б b	И и i	Р р r	Ч ч ch
В в v	К к k	С с s	Ш ш sh
Г г g	Л л l	Т т t	Щ щ shch
Д д d	М м m	У у u	Ы ы y
Е е e	Н н n	Ф ф f	Э э e
Ж ж zh	О о o	Х х kh	Ю ю yu
			Я я ya

На английском языке

Foreword
to the English Edition

The appearance of the English translation of the book on cybernetics makes the author feel additional responsibility. This is because literature on cybernetics written in this language is quite voluminous. It contains books by renowned authorities on the subject such as N. Wiener, W. R. Ashby, C. Shannon, G. Walter, and numerous popular-science books, to name the works of J. Murphy, D. Fink, A. M. Andrew, A. Cote as the most noteworthy.

And still the author does not hesitate to present his book to the reader because many chapters of the book tell of Soviet achievements in cybernetics and computer technology, and they, as is well known, are formidable. People interested in the achievements of Soviet specialists following their original ways in various fields of cybernetics would do well to learn of them from this book.

The book, moreover, differs appreciably from numerous other books on this subject. It was the intention of the author to write an easily understandable popular-science book which would contain some amusing, or even humouristic, elements and, at the same time, abide by the principle of an encyclopaedia in the alphabetical arrangement and in a serious and scientifically correct exposition of the subject matter.

This, naturally, was no easy task.

Three books had to be combined in one so that one could be read, the other looked over, the third used as a manual.

The first consists of short stories about the wonderful and the unusual in cybernetics. The second—of detailed drawings. Just look at them and you'll see everything in a nut-shell. You will be amuzed, too, I hope, by the cartoons at the end of each story the ideas for which have been suggested by cartoonists from all over the world.

The third book is the encyclopaedia from A to Z. Read it as you please: in the alphabetical order, or any letter you choose first; whichever way you read it the main concepts of cybernetics will be revealed to you. For each letter is independent of the rest. Combined, they tell a concerted tale of the new science.

Only the most important "letters" of the vast "letter store" of the cybernetics "ABC" have been chosen for this book. It was absolutely impossible to include all the "letters".

The list of terms and objects described in the Automatics and Electronics Encyclopaedia for specialists alone takes 100 pages of print, the encyclopaedia itself consisting of four great volumes of 500 pages each. Even the word list for the projected small cybernetics dictionary (note the word "small") fills 30 pages of compact text.

The principal words in this encyclopaedia are chosen so as to enable you to go over its pages from the simple to the more sophisticated without destroying the order of cybernetic "letters".

Victor Pekelis

STUDY CYBERNETICS

Our century may be termed the century of cybernetics. Today science, technology, industry can hardly be imagined without electronic computers, without automata, without new methods which science of control and regulation places at the disposal of man.

The electronic machines grow in number from day to day. They are, indeed, indispensable tools for man's intellectual work. They help us to cognize nature, to control it. Each new machine made to help man contains the thought of the scientist, the talent of the designer, th skill of the worker. Yesterday clever machines were the fabulous creation of man, today they belong to everyday reality. No matter where you go—to the institute, to the factory, to the office—everywhere you are bound to meet machines helping man in his work, which demands not physical but mental exertions. Machines control automatic plants, pilot space vehicles, ontrol road traffic, carry out mathematical computations, make diagnoses, draw up plans, teach, account, calculate. It's no small burden that our electronic helpers have been made to shoulder!

It's up to you, young men, not just to master this sophisticated technology but to design and build new, even more advanced machines, develop the science which governs them, dig into unknown strata of cyhernetic knowledge.

Many are the wonderful and interesting exploits that await you. But they'll need a lot of knowledge and skill. And to attain knowledge and skill one should study long and hard.

I would like to remind you of the words of V. I. Lenin: "Study, study and study!"

Wide and deep is their meaning: you should not only study, but should always be "on the level" of advanced knowledge, be abreast of the time, see far ahead of you.

Only the competent are able to master science. If you want to rule over clever machines, to build electronic robots, to blaze new trails in cybernetics you should study the fundamentals of the science of cybernetics, should take hold of the treasures of knowledge collected for you by men of former generations, by your fathers and grandfathers.

Half a century spent in the cause of science gives me the right to say some words to you.

Firstly, I would wish you to study cybernetics. Look, even a small encyclopaedia on cybernetics contains a wealth of treasures discovered by the intellect of man. How much greater are the riches of full-scale science, of its vast domains!

So this is my advice: develop your knowledge of cybernetics.

Secondly, I would like you to love the perfect creation of man—the electronic computer. These good helpers of man haven't yet had their last word. Perhaps, some of you will be able to make them reveal their new possibilities heretofore unknown.

So learn about the electronic computer, about its history, gain skills in electronics, dream about future electronic computers.

My third wish is: remember, there's top and bottom in every job. It is enticing to be able to make one leap to the top and, having once reached it, view the boundless expanses around you. But don't forget: everything new, exciting, dazzling, if only it's the real thing, is always deeply rooted. Therefore, the knowledge of the fundamentals is an absolute must. There's nothing so dangerous in science (and in technology as well) as superficiality.

So, study fundamentals and do not forget that mathematics, information theory, physics, electronics, metallography and many other sciences are the building stones of which the foundation of the building of modern knowledge, modern technology has been built.

And lastly. Every job profits from enthusiasm, from purposefulness, from the ability to sort out the principal. Can these be attained without love for the subject, without fidelity to it?

Time will pass, and, may be, you will remember the "letter" of this cybernetics encyclopaedia which prompted you to enter full-scale science or the world of exciting technology.

A happy journey to you all, cybernetic scientists, programmists, operators to be. All the best to you!

A. BERG,

Member of the Academy of Sciences of the USSR,
Hero of Socialist Labour,
Chairman of the Scientific Council
for the Complex Problem of Cybernetics
of the Academy of Sciences of the USSR.

A

Rules for All

ALGORITHM

A rule defining the content and sequence of operations for solving a recurrent mathematical problem.

An air of excitement filled the Italian town of Bologna on the 12th of February, 1535, with mathematicians, nimble number experts and lovers of contests of all kinds flocking to it from all over Italy and even some other countries of Medieval Europe. The occasion was the opening of a mathematical tournament, one of the features of which was, it had been announced, a challenge by a mathematician by the name of Fiore to compete with him in the art of solving cubic equations. The one who solved the greater number of problems put forward by the other would be declared the winner.

Fiore's challenge was accepted by one Niccolo Tartaglia, an obscure teacher of mathematics. He won the contest, having solved all the 30 problems offered him by Fiore—who was unable to solve a single one of Tartaglia's!

How was Niccolo Tartaglia able to gain such a brilliant victory, which left none in doubt as to who was the better man? The answer to this question is to be found in events that preceded the tournament.

Ten years or so earlier Scipio del Ferro, professor of mathematics at the university of Bologna, had died. Shortly before his death he had discovered a general method of solving an extremely difficult problem, thus crowning the work of many years. The only person he had informed of this had been Anabello della Nove, his son-in-law and successor at the university. By some devious ways, however, the secret reached Fiore. With a rule for solving a problem which had defied the Arabs, Greeks, and scholars of Medieval Europe in his hands, Fiore decided that he could challenge the mathematicians of the world.

His hopes, however, were dashed when Tartaglia responded to his challenge. Tartaglia, a mathematical genius, was confident that he would easily beat Fiore, but ten days before the contest he learned that Fiore was in possession of the late Scipio Ferro's method. Undaunted, Tartaglia got down to work and within those few days came up with a better method which enabled him to triumph brilliantly at the contest.

Tartaglia's algorithm, later perfected by the Italian mathematician Girolamo Cardano, survives to this day as a general solution of cubic equations.

So what is an algorithm? What is this universal tool for solving problems?

The simplest mathematical operation is addition. It can be carried out without any understanding of how it works, simply by obeying certain rules best exemplified by the use of the abacus:

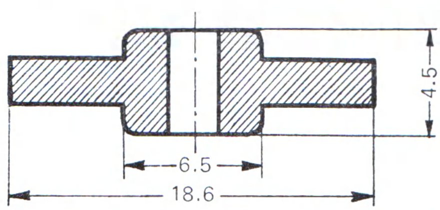
"Move to the right the number of beads corresponding to the number of units of the first figure. Then move to the right the number of beads equal to the number of units of the second figure. Count the total number of beads for the requisite sum."

Using these rules a first-former at school can add one-digit numbers with the help of an abacus. Only in mathematics instead of "rule" they say "algorithm". If a problem is likened to a lock, then the algorithm for its solution is the key.

Algorithms are needed to solve diverse problems. Mathematics cannot get along without a technology of its own—a technology of problem-solving.

A flowsheet is compiled for every part to be manufactured.

OPERATION SHEET FOR MACHINING PART No. 138						
No.	OPERATION	MACHINE TOOL	CUTTING TOOL	ATTACH-MENTS	MEASURING TOOL	CUT-OFF LENGTH
1 2 3	Face end	Turret lathe	Facing tool No. 71159	Collet Slide F–18	Snap-gauge	19



1	2	3	4	5	6	7	8	9
a	b	k	a^2	$27.5a^2$	174.2b	(5 + 6)	$\sqrt{K}$	$M = (\frac{7}{8})$
1.37	0.81	15.6	1.87	51.614	141.102	192.716	3.950	48.789
1.39	0.94	12.7	1.93	53.132	163.748	216.880	3.564	60.853

$$\mathbf{M} = \frac{27.5\,a^2 + 174.2\,b}{\sqrt{K}}$$

A computation sheet is compiled for every problem to be solved.

The solution of the most difficult problem can be broken down into a number of simple operations, a sequence of elementary steps. They are described by an algorithm.

Thus, an algorithm is a precise instruction for solving a class of problems by means of a series of simple operations. In other words, it is a manual for problem-solving. It can be drawn up as a series of concise instructions to be carried out exactly and to the dot. An algorithm is a faithful guide that shows the road to be followed to solve a problem.

A good example is Euclid's Algorithm for determining the greatest common divisor of any two numbers a and b. It consists of five instructions:

One. Inspect the two numbers a and b. Proceed to next instruction.

Two. Compare the numbers (a equals b, or a is less than b, or a is greater than b). Proceed to next instruction:

Three. If a equals b, this number is the greatest common divisor. If a is not equal to b, proceed to next instruction.

Four. If a is smaller than b, change their places. Proceed to next instruction.

Five. Subtract b from a. Inspect the subtrahend and the remainder. Proceed to instruction two.

Thus, after carrying out all the instructions, one must return to the second, then the third, fourth, and so on, until the numbers are equal. Then the job is done. Try and find the greatest common divisor of, say, 21 and 14, using these instructions.

Speaking of algorithms brings to mind a joke probably thought up by mathematicians.

One mathematician was asked whether he could cook a soup, to which he responded:

"First I must formulate the problem. Given: a pot, a gas cooker, a quart of water and a package of dehydrated soup. Required: to cook the soup. The problem can be solved by means of a certain algorithm z: pour the water into the pot; place the pot on the cooker; light the gas. When the water boils, add the dehydrated soup; ten minutes later turn off the gas."

"What if the pot is already on the cooker?"

"This introduces a complication, but the problem remains solvable. In this case the algorithm z_1 must be carried out: switch off the gas, remove the pot from the cooker; pour out the water. The new problem has thus been reduced to the old one, which I know how to solve. Hence, the new one can be solved, and I can cook the soup even if the pot is already warming on the fire."

You may well ask whether it's worth wasting one's time on such a cumbersome set of instructions to determine the greatest common divisor of two simple numbers. Perhaps not. But there are other, more complex problems, and solving them requires knowledge of an appropriate algorithm and how to use it.

As a guide to action every algorithm must meet certain requirements. Thus, it must be applicable not for the solution of just one problem, but of all problems of a given type. Its use as a guide to action would be just about nill if it could be used only for one pair of numbers such as 21 and 14.

Discovering and formulating an algorithm requires extensive knowledge and much hard creative work. But when the algorithm has been found and the problem's solution broken down into an ordered sequence of precisely defined operations, all that remains is to faithfully carry out the instructions. Anyone can do this working almost mechanically.

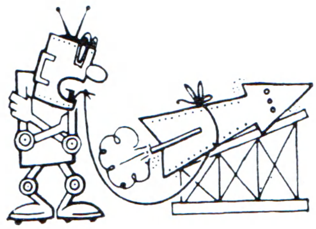
Mechanically? But if that's the case, can't the work be entrusted to a machine?

It can, and electronic computers are the answer. Nowadays scientists have learned to automate the solution of any problem for which an algorithm exists.

The long history of mathematics is essentially a quest for algorithms. Every new algorithm means new solutions of problems. The simpler and shorter an algorithm, the shorter is the road to the solution of the mathematical mysteries concealed behind many-tiered formulae and equations.

The elaboration of algorithms specifically suited for problem-solving by machine is of primary importance in our computer age. Algorithms are of prime importance in computer mathematics—in fact, they are computer mathematics.

The greater the advances of computer mathematics and the more widespread the use of computers in all spheres of life the more important is the task of discovering algorithms for solving large series of problems. With such an algorithm a computer can be programmed so that it can solve any or all of the problems of the series, as the case may require. The importance of comprehensive algorithms is enhanced by the fact that computers calculate very swiftly and in time will work even faster. It is better to discover a general method of solving a large number of similar problems, leaving the actual calculations to computers, than to work out a solution for every problem, to be calculated with or without a computer.



Extracting the root

A branch of science
and technology that deals
with the theory
and construction
of control systems capable of functioning without participation of man.

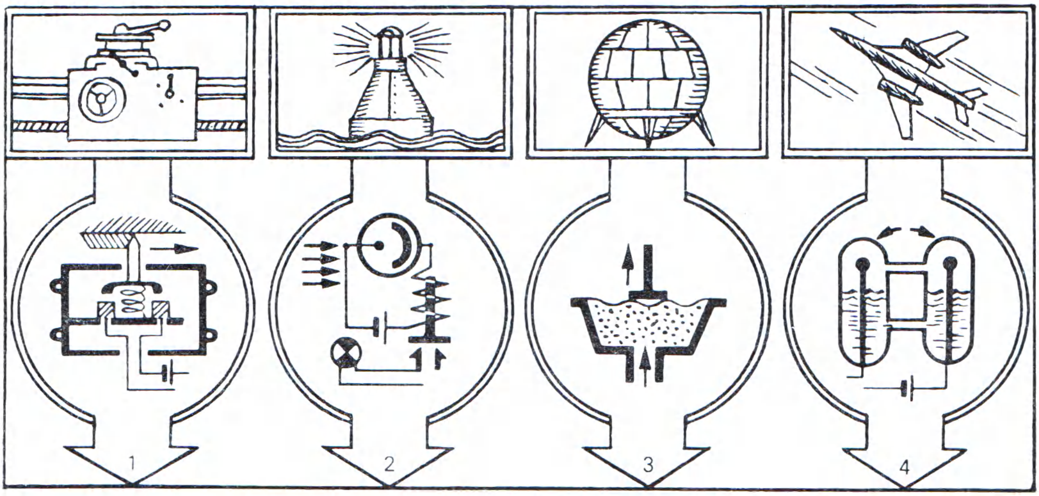
"Sense Organs" and "Muscles"

In our time a person is plunged into a world of automatics, of self-operating gadgets and devices of every size and description as soon as he wakes up in the morning. The alarm clock that woke him is one such automatic device. The water with which he washes is piped to the bathroom by an automatically operating water-works, and its temperature in the hot-water tap is automatically controlled by a thermostat. The food for his breakfast was preserved fresh by an automatic refrigerator. The bread for his toast was baked at an automatic bakery. After breakfast he reaches the ground from his tenth-floor flat in an automatic elevator. On the way to work he obeys the signals of automatic traffic lights. And so on, *ad infinitum*.

Modern technology, our whole way of life would have been impossible without automatics. We would never have been able to launch rockets into outer space, fly airplanes or descend in submarines to the ocean deeps. Iron and steel works, chemical plants, power stations and mines as we know them today would stand idle.

Men have endowed automatic systems with almost limitless capabilities. To begin with, they have provided them with "sense organs"—**sensors** which register changes in physical or chemical state and transmit their findings to the automatic device.

A **limit switch** (*1*) "feels" a workpiece and when the piece is finished stops the machine tool. A photoelectric cell (*2*) lights a river buoy when it gets dark. A sound sensor will slide open the doors of a fire department at the sound of a siren. There are sensors to indicate when the concentration of noxious gases in a mine approaches the dangerous level. There are "taste" sensors which control solution concentrations and signal if an acid or other chemical has to be added. There are also sensors which register position relative to the force of gravity (*4*) and ensure stability at rest and in motion. Other sensors determine temperature or pressure (*3*) with high accuracy, "see" invisible infrared, ultraviolet, roentgen or cosmic rays. Still others measure the intensity of electromagnetic fields, the concentration of ions, the slightest motion of the air, the impact of dust motes, the motion of electrons and many other things to which the human senses of sight, hearing, touch, taste, smell are insensitive. They are capable of penetrating virtually everywhere to relay signals carrying precise information about how a machine is functioning or how a complex technological process is proceeding.



Different kinds of sensors: (*1*) a limit switch, (*2*) an automatic "eye", (*3*) a pressure gauge, (*4*) an attitude sensor.

Sensors are elements of primary importance in all automatic systems. They are being steadily perfected and made evermore sensitive so that they can pick up the weakest signals. But then, these signals may be so weak that the devices are incapable of reacting to them.

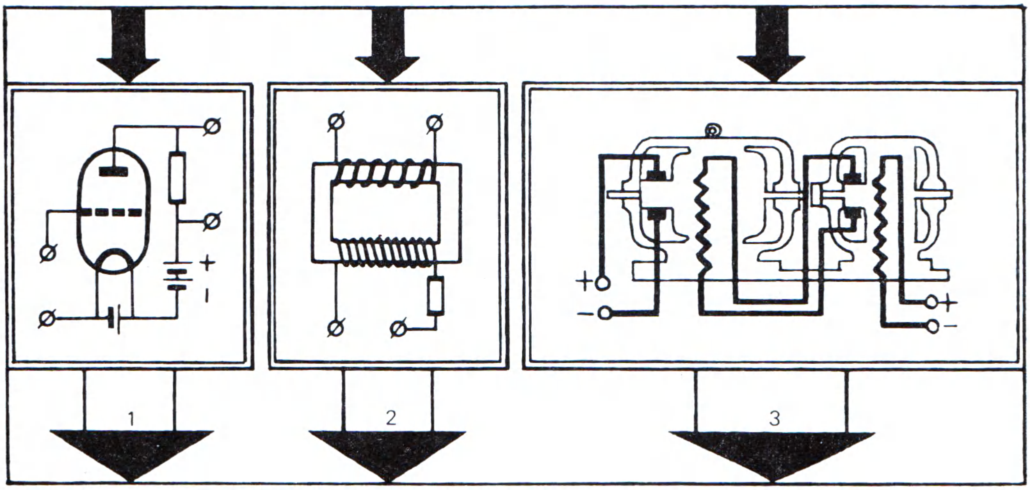
So the next element in most automatic systems is the **amplifier** or **booster**, of which there are many types: electronic (*1*), magnetic (*2*), hydraulic, pneumatic, pneumoelectric, electromechanical (*3*). Common to them all, irrespective of design is their purpose of transforming weak input signals into strong output signals. All amplifiers, as a rule, are capable of handling energies many times in excess of the control energy. Some amplifiers, electronic, for instance, are more sensitive, others are more reliable—magnetic, for example.

Amplifiers of different types may be coupled to operate together, say an electronic amplifier picks up a very weak signal, amplifies it somewhat and feeds it into an electromechanical amplifier, which converts it into a very strong signal indeed.

One note on terminology before proceeding further with some of the basic principles of automatics: the output circuit of a sensor or amplifier is known as the control circuit. It governs, regulates or controls the controlled circuit.

Often a smooth input signal is required to produce a trigger-action response in the controlled circuit. This is achieved with the help of **relays.** They can be of different types: mechanical, electronic, electromechanical, photoelectric, etc. For instance, when you drop a coin into a public telephone what you are doing is switching on the telephone line by means of a gravitational mechanical relay.

An important characteristic of any relay is its so-called response time: the time it takes to produce a change in the circuit it controls. The slowest are mechanical relays, with speeds of tenths of a second. Electromechanical relays are fas-



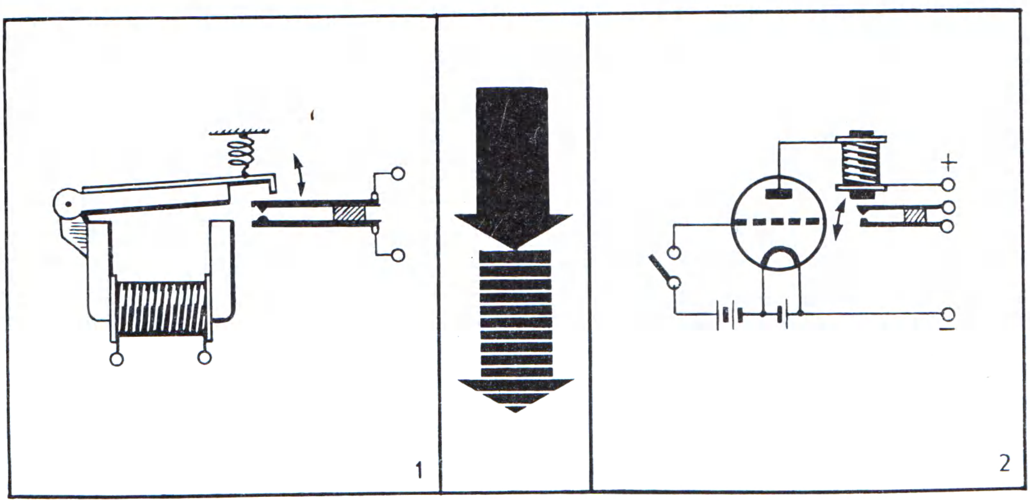
Amplifiers: (*1*) electronic, (*2*) magnetic, (*3*) electromechanical.

ter, operating at around 1/300th of a second, while electronic relays function at fantastic speed of millionths of a second.

It takes a weak current to trigger a relay, but the relay can be made to switch on a circuit through which a strong current passes. In this respect it is akin to an amplifier. Conversely, amplifiers can be made to operate relay-like, that is effecting stepped changes of some parameter instead of altering it smoothly.

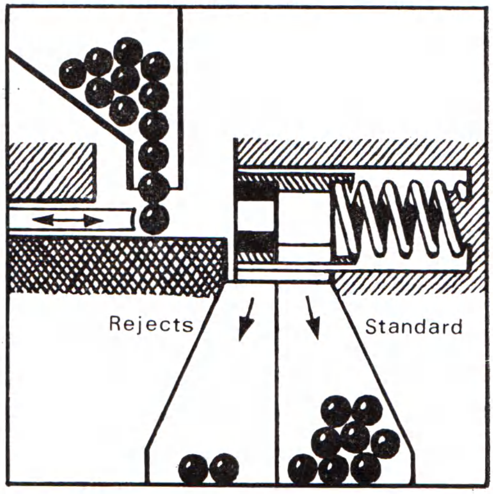
Thus, if sensors can be compared with the sense organs of a living organism,

Relays: (*1*) electromagnetic, (*2*) electronic.



amplifiers and relays can be likened to its nerve knots or ganglia.

Two more important "building blocks" of automatics are effectors and actuators—the "muscles" of automatics. Their role can best be shown by discussing some of the jobs of automatics. Essentially, they all fall within four categories: **inspection, safety, regulation** and **control.**



A simple automatic quality-checking device.

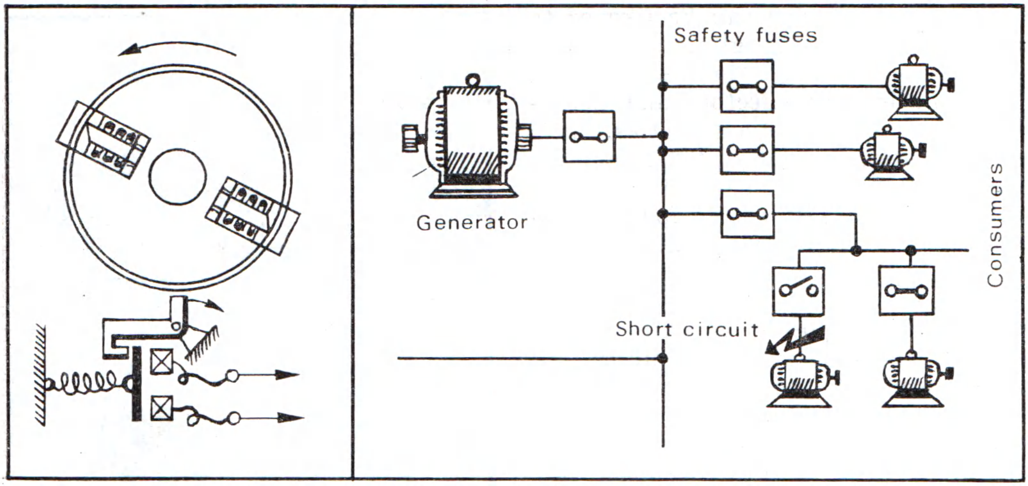
A vast number of devices have been built for the purpose of checking the dimensions and quality of workpieces, the temperature and pressure of processes, voltages and currents, the colour of fabrics, the concentration of solutions and the quantity of output. Besides, they perform a thousand and one other operations involving inspection, verification and sorting. Mechanical, electrical, electromechanical and a host of other devices have been designed and built for these purposes. Most widespread nowadays are electric and electronic instruments, because they are fast, compact and flexible in operation.

A bearing plant manufactures millions of steel balls. It would take years to sort them out by hand. A simple device with a chute with two holes in it, a latch and a suitable receptacle is capable of sorting several thousand balls per hour. Those of the required size drop through one hole, rejects roll into the spoilage bin.

An electronic thickness gauge operates with high precision and, in addition, counts the standard items and rejects, removes the rejects from the conveyer and signalizes its findings. In selecting the type of device to be employed, engineers take into account the required operation speed and accuracy, the complexity of the system, its cost and many other factors.

The simplest **automatic safety** device is a safety fuse which blows when a short circuit or overload occurs in your home, breaking the circuit and forestalling the possibility of a fire starting. Similar but much more powerful and sophisticated circuit breakers are installed on high-voltage transmission lines to keep transformers, generators and other electrical installations from breaking down in the event of a short circuit.

One clever device keeps the shafts of generators, compressors or pumps from spinning too fast. An automatic gadget protects a forging press operator from injury if he is careless. Turbines, boilers, engines, airplane systems, generators, power transmission lines, chemical installations, electric motors—all require automatic safety devices of different kinds. Without them the whole of modern industry and technology—factories, power plants, transport facilities, household appliances, every mechanical tool and system—would literally grind to a halt.

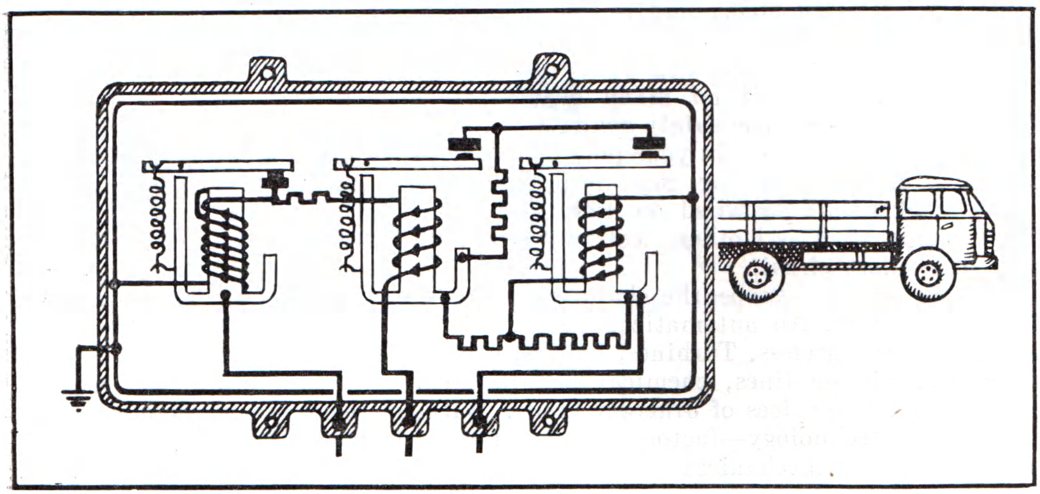


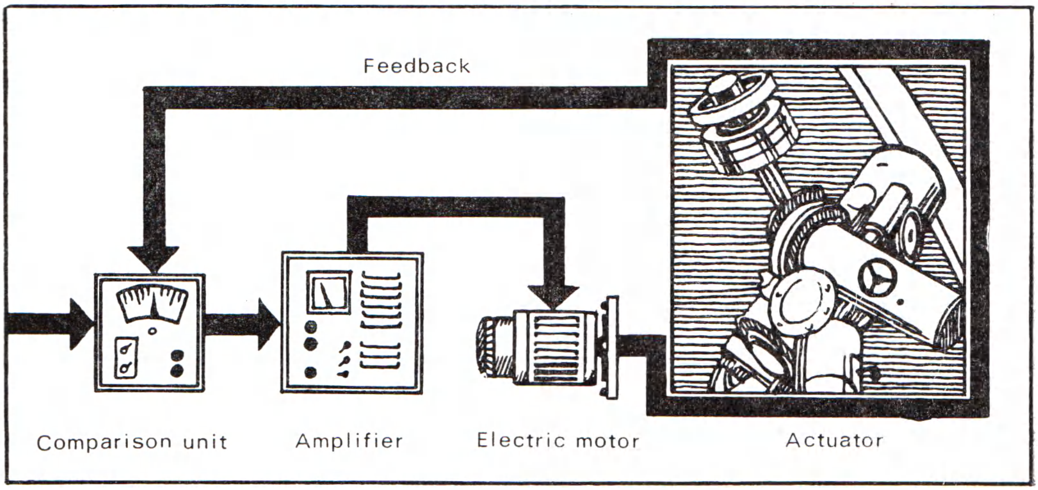
Automatic protection devices: electromechanical (left) and electrical.

The third "profession" of automatics, **regulation**, is also of tremendous importance in engineering. In most technological processes and in many machines the main thing is to maintain a certain parameter or state—temperature, pressure, humidity, speed, chemical composition, voltage, etc.—at a preset level.

This is done by regulators, governors and controllers of different kinds. A classical example is the centrifugal governor that is used to maintain a constant

An automatic voltage regulator.





A tracking system automatically turns a telescope, keeping it locked on a star.

rotation speed. A more sophisticated device is the automatic voltage regulator housed in a little black box under the bonnet of every car. An automobile generator is driven by the engine whose speed varies over a wide range. Without the regulator the generator would not recharge the storage battery at low speeds while at high speeds the voltage would soar, damaging the electrical equipment.

Today, automatic industrial installations predominantly employ electronic regulators. In these devices the controlled parameter is expressed in terms of electric current of corresponding voltage. The current is amplified and compared in a measuring unit with the voltage of the programming unit. The required adjustment is fed into the amplifier and from there to the effector unit.

A new device for regulating the temperature of overheated steam in a high-pressure boiler at a thermal electric station has considerably reduced the response time and cut fluctuation by half, keeping the temperature steady to a high degree of accuracy.

Finally, the fourth "profession" of automatics is **control.** Its importance can be shown on the example of the operation of a heavy-duty rolling mill—a giant machine for making rails, beams, strip metal and other rolled stock driven by dozens of dozens of electric motors with a total power of tens of thousands of kilowatts. The operation of all its motors, big and small, must be coordinated with split-second precision. Some five thousand switchings of the motors must be performed in the course of a single run of the rolling mill. This is done by the automatic control system.

Offshoots of automatic regulation and control are tracer **control** and **tracking.** Tracer control is employed in automatic copying machines, tracking systems are used to keep telescopes locked on to a certain star for continuous observation, and various combinations of the two are built into electronic simulators.

The crowning achievement of automatics is, beyond doubt, space technology, in which scientific and technological advances have been most spectacular.

On view in the Cosmos pavillion of Moscow's permanent Economic Achievement Exhibition is one of the wonders of automatics, an authentic spaceship with its glittering array of sophisticated gadgetry designed to provide suitable living and working conditions for men in the harsh environment of outer space.

Looking at the craft, it is hard to imagine that it embodies such a remarkable degree of organization and coordination of countless sensors, amplifiers, relays, actuators and effectors that the system, in the words of scientist-cosmonaut Konstantin Feoktistov, approximates a highly organized living creature with "sense organs", "nerves", "muscles", "limbs" and, of course, functions admirably suited for life in outer space.

The instrument systems receive and process a tremendous amount of information about the environment, the ship's position, the condition and actions of the crew, to which they respond by issuing control commands. Its automatics

register loading and vibration;

check the safety factor of structures, back-up equipment and energy reserves;

check the functioning of all systems and units;

measure temperature, solar and cosmic radiation, meteor streams;

check the airtightness and thermal insulation of modules;

control the attitude-correction systems and rocket stages;

provide power, water and oxygen supplies;

maintain the required temperature and gas composition in the crew's quarters;

carry out flight corrections during launching, orbital flight and descent;

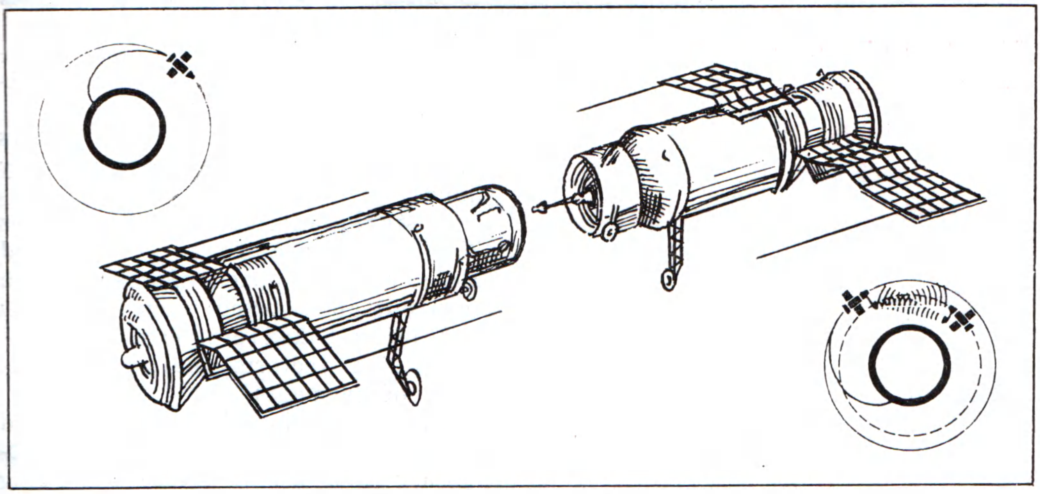
regulate on-board power supply;

and, last but not least, *coordinate* and *control* the whole complex of automatic systems continually busy picking up, measuring, indicating, recording, reading out, comparing, storing and retrieving the vast amount of information needed to ensure the spaceship's safety on all stages of its flight and to carry out all the planned investigations.

Add to this that the remote controls are remote indeed, for vehicles orbiting the Earth or flying farther out to the Moon and beyond, command and response signals, must span vast distances. This work is the function of **telemechanics**, a first cousin of automatics. One of the more popular telemechanical devices is the common dial telephone. When you dial a number what you are in fact doing is switching on an automatic system that connects you with the telephone you need on the other end of the line.

An example of the heights automatics and telemechanics have achieved is one of the technological miracles of our age: the automatic docking of two Earth satellites in space, an outstanding accomplishment of Soviet technology.

Millions of people were able to see the docking procedure on their television screens. What, regretfully, they could not see was the workings of the sophisticated cosmic cybernetic systems that guided the two satelli-



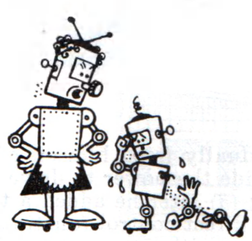
A technological miracle of our age: automatic docking of two Earth satellites in space.

tes circling the Earth at eight kilometres per second towards each other and locked them together.

Of the two vehicles, one is "active", the other is "passive". Both are provided with "sense organs" enabling them to "see", "hear" and "recognize" each other. Their antennas emit a steady stream of homing signals. When the active vehicle picks up the signal it approaches the passive one, which is beaming back response signals.

As soon as the radio link is established the automatic homing system measures the relative orbital parameters of the two vehicles and feeds the relevant data into the active one's attitude control system. Gradually the active vehicle aligns properly with the passive one and draws slowly closer. When they are 300 metres apart the low-thrust docking motors fire, nosing the active vehicle up to the passive module's docking collar. The two touch, triggering the circuit of the latching system, which clamps them tightly together.

After a while, on command from the Earth, the two vehicles separate and are brought back to Earth individually.



Lost some sensors again?

The stage of machine industry at which man is freed of responsibility for the direct control of production and this function is transferred to automatic devices.

The Only Way

Have you ever stopped to wonder how many different things are turned out throughout the country every day? Lots, of course. Billions, perhaps? Or more?

Consider several examples taken from different fields.

Soviet factories produce more than a million cogwheels a day. Even if each is not more than 10 millimetres thick, stacked one on top of another they would rise above Mt. Everest, the world's highest mountain.

An automatic screw machine turns out a hundred screws per minute.

An automatic bottle-making machine produces more than 6,000 bottles an hour.

Red October, the Moscow chocolate firm, makes 3,500 sweets a minute.

The city's meat-packing plants make 125,000 meat cutlets every hour.

A single automatic bakery bakes 30,000 loaves of bread a day—and Moscow has a dozen of them which turn out an assorted range of breads and other baked products.

Clothing factories daily sew millions of garments.

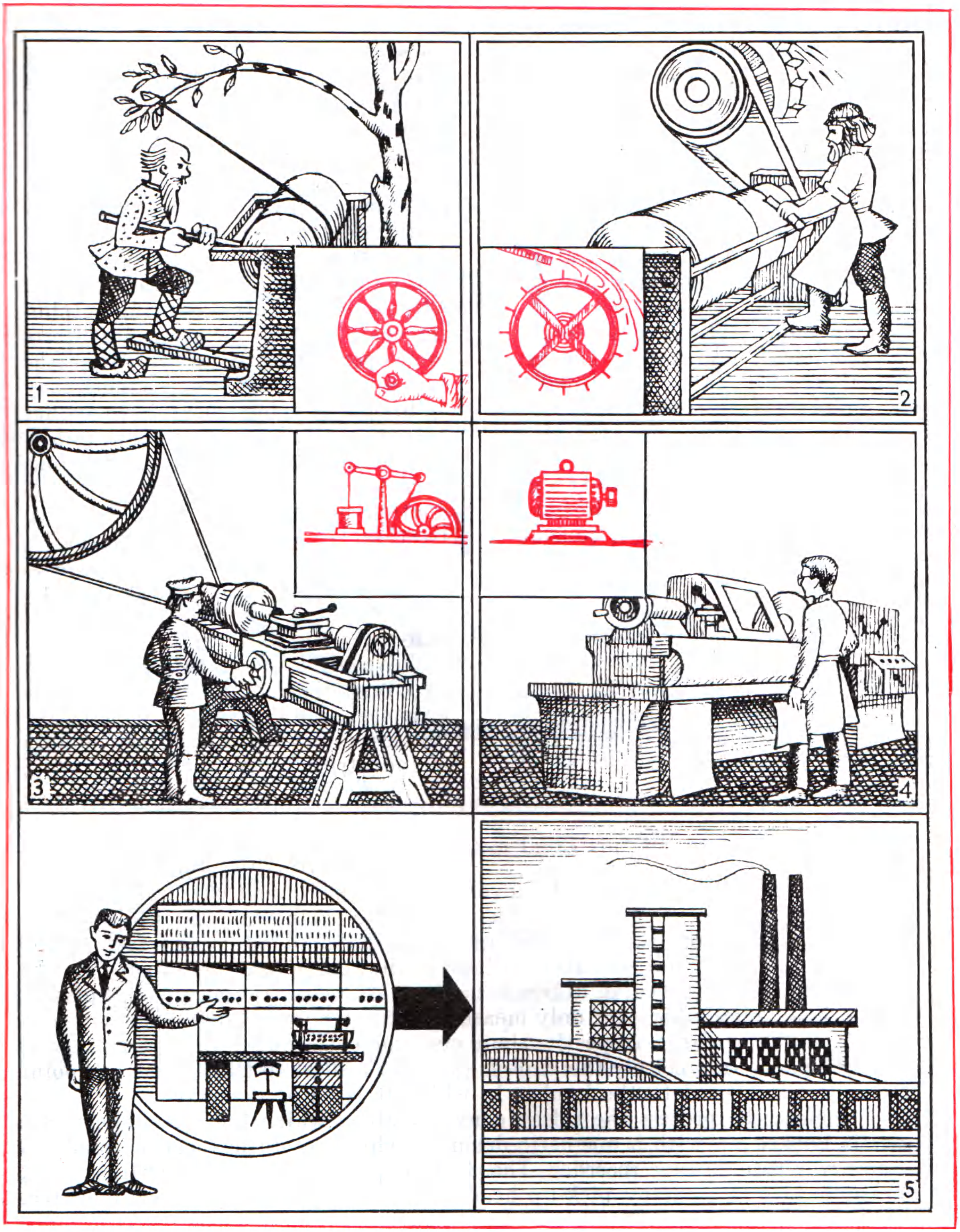
Could one imagine millions and hundreds of millions of different necessary and useful things all being made by hand? Of course, not. They are made by machines, and not just machines, but automatic ones.

Countless automatic devices (besides those that manufacture material, tangible things) and sophisticated gadgets control the operation of machines and look after production processes.

The introduction of this great arsenal of automatic machines and devices, means of control and regulation into industry is what we call automatization.

How does a worker operate a conventional machine tool? He feeds the material to it, or inserts the pieces, and removes the finished product. He watches the machine's operation, decides whether it is up to standard, controls and adjusts it as the need arises.

These pictures illustrate how man gradually freed himself of the functions of direct control: ▶ (*1*) originally the operator had to provide the power to drive his machine tool; (*2*) then he invented power drives of different kinds; (*3*) later he added a tool holder; (*4*) automatic tracer-controlled machines have freed man of direct control functions altogether; (*5*) at an automatic factory the whole production takes place without direct participation of man.


1
2
3
4
5

With automatization all this is done by machines. Moreover, automatic machines which perform different operations constituting a sequence are integrated into production lines, with automatic handling of the workpieces between operations so that a human hand never touches them.

When it is time for automatization, what are the considerations that favour it?

One we know: mass production. It is always much easier to make ten identical objects than ten different ones, for the simple reason that they involve the same operations, the same dimensions, the same sequences. And what if not tens, but tens of thousands and millions are needed? Uniformity of output is one of the main considerations in favour of automation.

There is another.

Very often, and not only in academic laboratories but in factory shops as well, it is necessary to measure, regulate and control parameters lying beyond the threshold of human sense organs. Indeed, can man detect electric field intensity or radiation? Of course, not. This has to be done by automatic devices. Thus, whenever human sense organs are incapable of accurately determining a required parameter or quantity or where human reaction is too slow to spot a change in a production sequence an automatic device is a must.

And there is a third consideration. Many industries are harmful to man. At chemical plants producing sulphuric acid, textile dyes or fertilizers some operations present health hazards and some intermediate products may be toxic or explosive. It is here that automatic machines are indispensable.

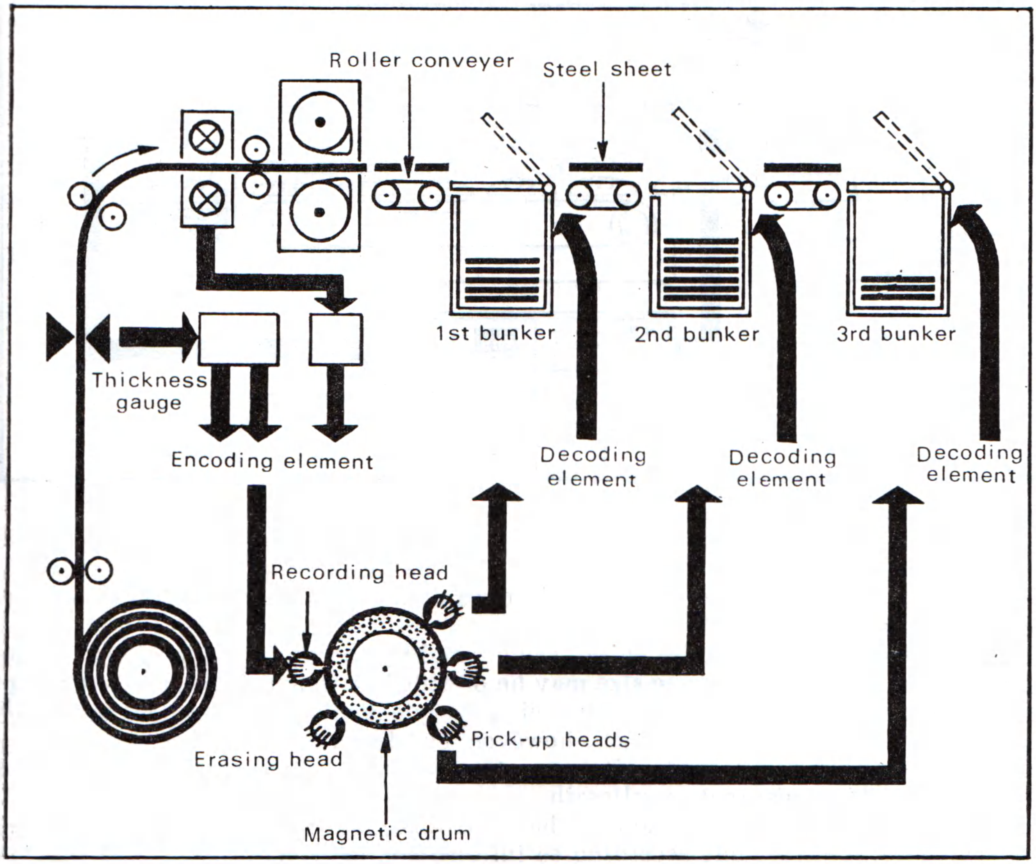
Cybernetics plays a tremendous part in the automatization of production processes. It enters automatization not only in the form of industrial electronic computers but also in the form of instruments that do not catch the eye but are, in fact, extremely sophisticated.

We shall attempt to examine how two very different devices used in the automation of certain technological processes function. This is the domain of industrial cybernetics.

First, let us see how an "artificial memory" is used in automatization.

Imagine a machine that unwinds a roll of metal strip and cuts it into sheets of a specified size and thickness. The strip varies in thickness and must therefore be measured continuously, while the cut sheets have to be graded and sorted accordingly. This may not sound very difficult, but the job is complicated by the sheets having to be stacked in different bunkers according to thickness. So what is needed is a device which not only measures the thickness of the sheets but also opens the hatches of the respective bunkers where they are to be stored—and this must be done in precisely the time it takes for a sheet to travel from the point where it was measured to the bunker in which it is to be deposited.

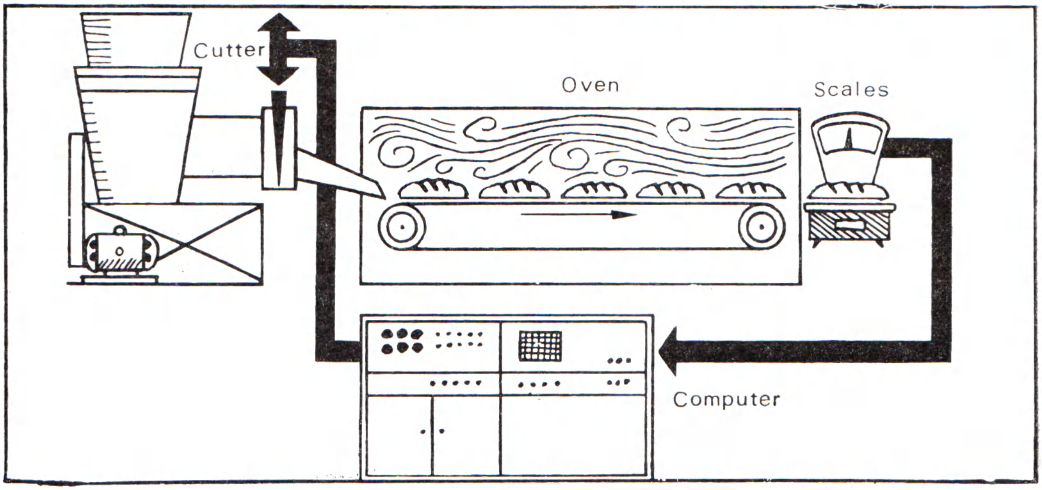
To automate the process the roller conveyer along which the metal sheets are drawn is hooked up with a magnetic drum on which recordings can be made in the same way as on a tape recorder. The drum is provided with a recording head, an erase head and as many pick-up heads as there are bunkers in the machine.



An automatic device for measuring the thickness of steel sheets, sorting and depositing them into different bunkers.

A gauge continuously measures the thickness of the metal strip. Its readings are converted into an electric signal which is duly encoded and recorded on the magnetic drum which revolves in step with the roller conveyer. The recording on the drum approaches the first pick-up head at precisely the same moment as the corresponding sheet approaches the first bunker. If the sheet passes on, it will approach the second bunker just as the recording on the drum reaches the second pick-up head, and so on.

Each pick-up head is connected with a decoding unit which responds to only one signal: the one corresponding to the sheet thickness for the given bunker. When the signal matches, the device opens the bunker hatch, and the sheet slides in.



Schematic diagram of an automatic device for weighing loaves.

Another example is one of the possible ways of automating the process of cutting dough for baking bread.

Every baked loaf must be of the same weight. But the density of the dough varies, and pieces of the same size may be of different weight. The simplest thing, it would appear, is to automatically weigh every baked loaf and control the dough cutter accordingly. This approach, however, overlooks the fact that a baked loaf must necessarily be weighed quite some time after the chunk of dough that went into its making was cut.

In other words, the cutter should be controlled not according to the weight of every individual loaf but according to information averaged over a large number of loaves. Thus even such an apparently simple job involves the use of not-so-simple statistics.

The automatic system must be provided with a special computer. As each loaf is automatically weighed the figures are fed into the computer, which keeps up a running computation, controlling the work of the dough cutter accordingly.

The mechanisms described above were examples of automation of separate processes. In recent years these ideas have been increasingly expanded into concepts of what could be called integrated and full-scale automation.

Integrated automation represents a step forward from automatic machines to the automatic transfer of materials and pieces from one machine to another within a shop or a section of a shop.

Full-scale automation envisages a system of automatic machines and measuring, handling, transfer and control units and devices which turn out an item or product from start to finish without direct human participation.

The difficulties involved in such an enterprise are enormous, what with the volume of material that must be handled and machined, the number of technological operations that must be carried out, the amount of information that must be received and processed.

Yet such an automated giant has been designed at the Automobile Industry Technological Research Institute in cooperation with the Likhachov Motor Works in Moscow. Their system involves a computer centre to which is fed all pertinent information about the manufacturing processes going on in the different shops, about the movement of workpieces from shop to shop and section to section, about the functioning of the machines and transfer lines. Each shop has its own operational control unit where all the elements of the production process are continuously controlled, from the stocks of workpieces and tools to the rate of flow of finished items to the next shop.

The tasks of the factory computer centre also include scheduling of production plans for every shop and section and continuous inventory control.

This automation system has proved its worth, and similar systems have been installed at the Moscow Compact Car Works, the Zavolzhsky Engine Works, the Yaroslavl Engine Works and other factories.

Automation of production yields an enormous growth in labour productivity. This goes without saying. But can automation be of any use to management and administration? The answer is an emphatic yes.

In fact, nowaday it is impossible to imagine the economy being run without automatization. Why? If only because in our country some years ago there were three million persons employed in the accounting services alone. A total of 10 million people are employed in administration and management. Ten million economists, planners, rate-setters, bookkeepers, accountants, designers!

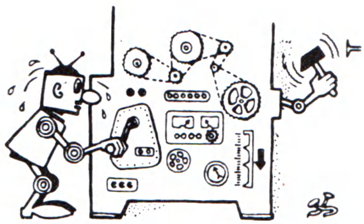
And the scale of the economy and the rates of development are expanding with each passing year. The flow of information—plans, progress reports, technical specifications, bills, invoices, and what have you—demands that it be processed in the shortest possible time.

The rise in the number of administrative and managerial personnel could well lead to a situation in which half the nation was employed in management, with a corresponding reduction in the number of people directly engaged in production. Hence, what is needed is not greater numbers but a qualitative leap. This is being achieved by the automatization of managerial processes.

Let us try and define the tasks of managerial activity. Normally these are the production, transmission, storage and processing of information. In other words, it is the job of keeping track of production, quality control, drawing up production specifications, duplicating and dispatching documents, coordination of various production sections, registration and sorting out of documents, computer work—quite a job, in short.

So one can imagine the amount of information that must be handled in running such a gigantic enterprise as the national economy of a whole country. Tens and hundreds of billions of computer operations must be performed every year. That is why in our time management and administration are well nigh impossible without electronic computers.

Hence, automatization is the Watchword.



A machine incorporating a system of mechanisms and devices (electronic, electric, pneumatic, hydraulic) capable of receiving, converting, transmitting and utilizing energy, material or information without direct human participation.

"Auto" Does It Itself

An automatic machine tool at work is a fascinating sight. Operating completely on its own, it clamps the workpiece in place, positions the cutting tool, machines the work to proper shape and dimensions and removes the finished part. In short, it performs all the operations a human operative would have carried out—but much faster, with greater precision and efficiency. How does the machine know just what to do?

The answer to this question takes us far back in time.

It is said that there once lived a Byzantine emperor who sat on his gilded throne in the shade of a golden tree with golden branches and golden leaves with golden birds among them. Two lions of pure gold on both sides of the throne watched approaching visitors. But it was not this glittering splendour that struck people most. For as a person approached the throne the golden birds sang and the golden lions roared thunderously. Not surprisingly, the awe-struck visitor fell to his knees and bowed his head to the ground. And when he lifted his eyes—lo and behold!—the throne and emperor were gone, lifted to on high, from whence the emperor gazed imperiously down at the prostrate visitor.

All these wonders—the singing birds, the roaring lions, the vanishing throne—were put into motion by hidden mechanisms of ingenious automatic devices.

Farther back in time, Heron of Alexandria, the ancient Greek mathematician and mechanic, left a description of an automatic theatre in which automata enacted several scenes suggested by the *Iliad*.

In the first scene the Greeks could be seen repairing their ships, sawing, hacking, drilling, hammering nails. When the doors of the stage opened on the next scene the Greeks were shown dragging their ships down to the sea. In the following scene the ships sailed over calm seas accompanied by dolphins diving in and out of the water. Then a tempest arose, the waves mounted higher and higher, and the ships huddled together for safety. In the forth scene Nauplius and Athena appeared on the stage. Nauplius held up a torch which lighted up in his hand. In the fifth scene the Greek ships sank into the sea, and Ajax, the sole survivor, swam for his life. Finally came a lightning bolt, a roar of thunder, and Ajax vanished. Athena vanished too.

The whole action was performed by automata; after each scene the stage doors closed automatically, the scenery changed, and the doors opened again.

In the following two thousand years ingenious mechanics designed and built clever automatic toys, mostly for no better purpose than the enjoyment of the rich.

However, there was much more to them, if only because the mechanical wonders of the past indicated the road along which automatic systems were later to develop. They were based on the achievements of technology of their time, the age of energy of running water, wind or compressed springs.

Springs were used to drive intricate systems of cogwheels, levers, connecting rods, cams, wormscrews and other parts of automata. That is why it can be said that spring-driven mechanical toys were built on the clock principle.

According to Karl Marx, clocks and watches, which rank among man's best technological creations and were the first automatic systems built for practical purposes, suggested men the idea of introducing automata in industrial manufacture. It is not accidental that the Frenchman Jacques Vaucanson, celebrated maker of mechanical toys, was the one who built a weaving loom which served as a prototype for the automatic loom designed by Antoine Jacquard.

Vaucanson's machine replaced fifty weavers. Less than twenty years later automatic looms were introduced at many silk mills in France and England. Other industries were quick to follow suit. Bigger, better and more sophisticated machines were introduced in metal-working, mining and other fields.

Of major importance was the invention of the automatic lathe scale. The Russian mechanic Andrei Nartov and then the Englishman Henry Maudslay made the cutter move automatically along the workpiece, which could now be machined without having to be directly handled by the operator.

The shrill cry of whistles heralded the advent of steam and the steam engine, which replaced draught animals—horses, oxen, mules, asses—as a convenient source of energy.

But the age of steam would not have come if the demands of the time had not driven the talented Russian mechanic Ivan Polzunov to devise a float-type controller for his "fire engine" so that "water, fire and steam could sustain themselves in motion". Steam engines would hardly have ever found such universal application as they once enjoyed if technological advance had not led the English inventor James Watt to the invention of the centrifugal speed governor.

Man became stronger than ever before. The new machines were quickly put to work and made to perform a wide range of jobs.

The governors and regulators used in the first steam engines proved to be extremely versatile. They were adapted for use in many different kinds of mechanisms. Gradually, with the advent of the age of electricity with its high power, speeds and high precision, automation spread to all technological spheres. It became the mainstream of technological advance.

Engineers classify the vast variety of automatic systems in use today according to their purpose, designation or sphere of application as technological, transport, military, computer automatics, and so on.

Lately, with the development of cybernetics, automata have come to be classified, irrespective of their purpose, according to their data-handling characteristics.

What does this mean?

Let's see how an automatic system works, a bolt-making tool, for example.

With a quick motion a lever pushes out a brass rod from which a bolt is to be machined to just the required length. A turn of the holder and the blank is brought up to the cutting tool. A golden shaving curls away from the blank. Within seconds it is machined along the whole length. The cutting tool retreats, the holder is turned again and new tools cut the thread, champfer, finish the head. A few seconds more and another cutter cuts the finished bolt from the rod. With a slight clank it drops into the metal bunker on top of a pile of other identical bolts while the machine is already busy making another one.

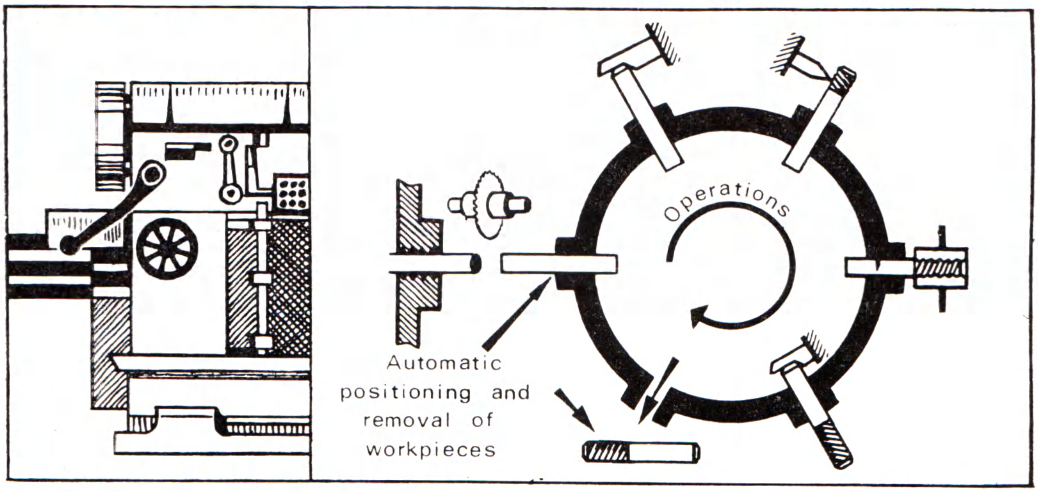
Despite the tremendous variety of modern automata, they all share in common a peculiar superficial trait: they all create an impression of intelligently performing their jobs, going about them quite independently and on their own, without any outside interference.

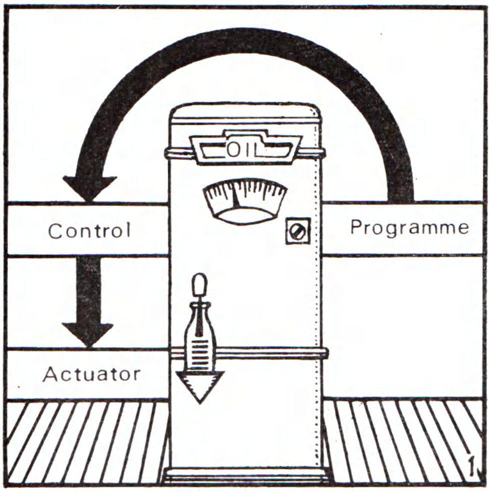
Well, you may say, this is, after all, a superficial impression. But what makes an automatic system so independent, sophisticated in its performance and self-contained in its behaviour?

One of the primary features of an automatic system is its data-handling characteristics.

Whatever an automaton does its performance is controlled by a programme prepared well in advance. In a metal-cutting tool, for example, automatic con-

This is how an automatic machine tool functions.





An automaton with an open-circuit control system.

trol can be achieved with the help of a tracer device which "feels" all the curves and hollows of a master model and feeds the necessary instructions to the cutting tool for machining the workpiece.

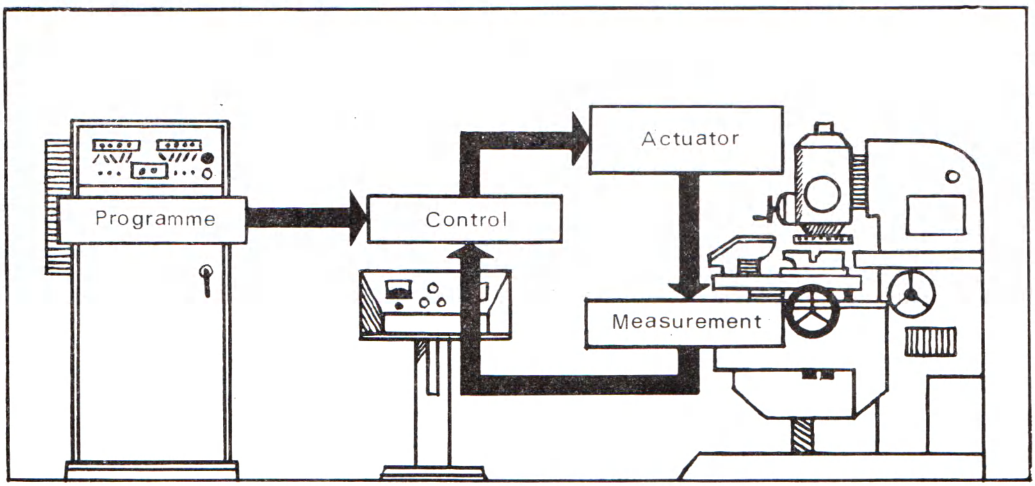
An automatic film projector, on the other hand, is controlled simply by the celluloid strip passing through the film channel.

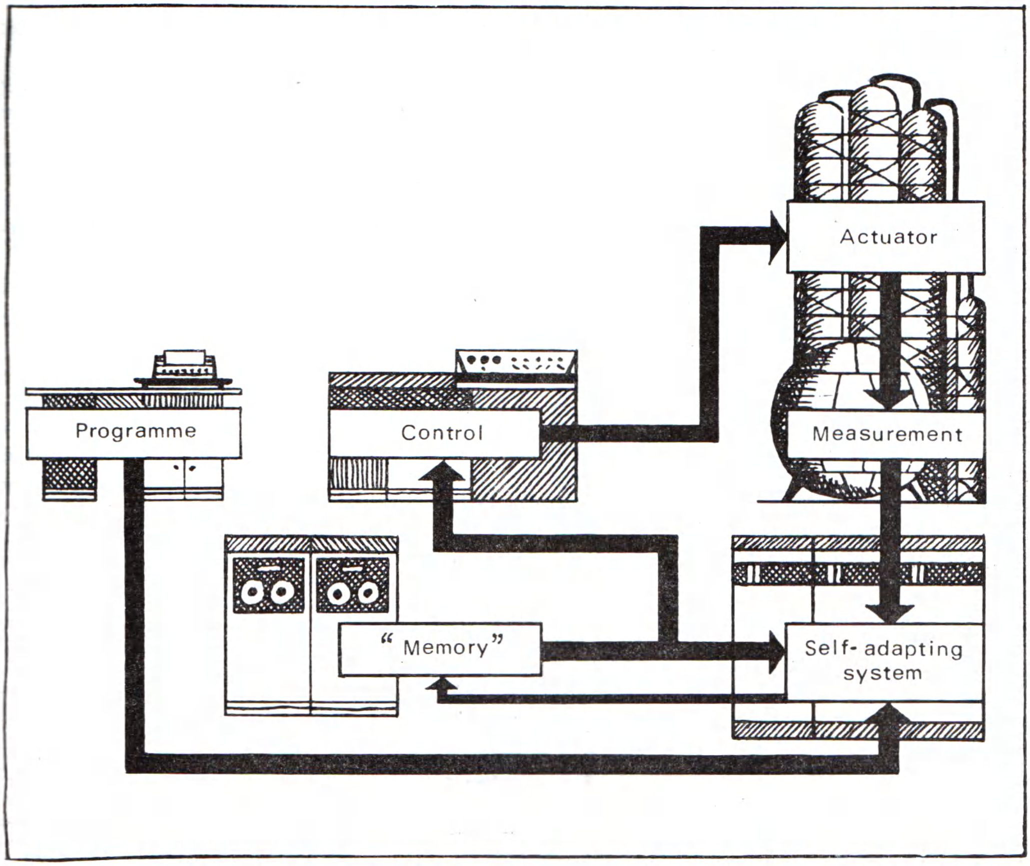
An operation programme can be fed into an automaton by means of patterns of holes punched in cards or tape, a magnetic tape-recording or any other arrangement for recording and transmitting a certain set of instructions.

Anybody who has ever received a soft drink, a package of cigarettes, a newspaper or whatever else from a vending machine or passed through a turnpike has held the simplest programme for its operation in his fingers: the coin he inserted in the slot. The data contained in any programme must travel along a certain route, as shown by the heavy black lines in the three diagrams. In the case of an automatic vending machine the information travels along a simple open-circuit system from input to output.

More complex automata require additional data inputs in the course of their operation, such as information about temperature, dimensions or voltage. This

An automaton with a closed-loop control system.





This automatic system is capable of self-regulation to meet the working requirements in the course of operation.

involves what is known as closed-loop, feedback, control system with two data input routes.

The age of cybernetics has seen the appearance of third-generation automata capable of memorizing past performance and experience, analysing previous and current operation and working out an optimum programme which can be changed and adjusted in operation to meet changing conditions. The principle of operation of such systems is shown schematically in the drawing given above.

The ultimate purpose of the operation—the expected output—is defined in the programme originally fed into the system. The relevant information is carried along the first data route. The second data route carries the working programme issued by the working memory block which controls the system's operation.

The third data route, as the diagram shows, carries the information fed back from the measurement block.

There are automatic systems with a greater number of data routes for carrying relevant information, and their performance capacity is, of course, correspondingly greater.

The world of automata is great indeed, and it is continuously expanding. This, understandably, has called for the creation of a comprehensive scientific theory to define the laws according to which it functions.

This theory rests on the firm foundation of the old classical theory of automatic control. Now it is called upon, however, to solve numerous problems of extreme complexity needed to design and build reliably functioning automatic systems.

Automation theory must, for example, show how to determine the stability of systems so as to prevent deviations in operation. It must investigate the sensitivity of automata, since the properties of a control system vary in the course of operation. There are many other complex problems which the theory of automatic control attacks and solves, thereby promoting the advance of automation.

B

Only Zeros and Ones

BINARY SYSTEM OF NOTATION

A positional notation system for representing numbers in which the base is 2.

When man first learned to count he, quite naturally, used his fingers to tick off the numbers one by one. They restricted him to ten, of course, and the decimal system of counting, as it later came to be called, proved so convenient that it has lasted to this day.

Decimal notation is the cornerstone of one of the three R's, and learning it is one of our first tasks at school. We learn the basic digital values from 0 to 9 and are later taught that every number in decimal counting is written as a linear combination of powers of ten. Not surprisingly, the system seems to us the simplest and most convenient of all possible systems of numerical notation.

This view was shared, among others, by the famous French scientist Blaise Pascal, who built the first calculating machine. His calculator employed so-called figure-wheels or counting wheels with 10 teeth around the rim. Since then many generations of calculating machines of different types have been built to replace manual doing of sums with mechanical digital manipulation. All these machines were decimal, and when electromechanical calculators were built they, too, were made to operate in the decimal system.

The first electronic computers were also based on the ten digits of the decimal system, the digits being represented by flip-flop switches. The American ENIAC computer, for example, was decimal. But it required so much costly hardware that designers

Now take the binary number 1111. The first numeral at the extreme right is 1. The next position is only two times the first, hence it represents 2; the third position is two times the second, and it represents 4; and the fourth position is, accordingly, 8.

Let us try to represent, say, the number 1017 in the binary system. For this, as in decimal notation, we count off the positions. We start with the lowest, 7. The number 7 comprises four plus two plus one: $7=4+2+1$. This can be written down as follows: $1\times2^2+1\times2^1+1\times2^0$. Accordingly, in each of the positions we write down a 1, which gives 111.

The next number is ten, which is made up of eight plus two, viz., $10=8+2=$ $=1\times2^3+0\times2^2+1\times2^1+0\times2^0$. You see that there are no ones or fours, and accordingly we write down zeros, obtaining 1010.

Continuing the operation of reducing decimal to binary, we can write down the number 1017 as $512+256+128+64+32+16+8+1=1\times2^9+1\times2^8+1\times2^7+$ $1\times2^6+1\times2^5+1\times2^4+1\times2^3+0\times2^2+0\times2^1+1\times2^0$. Expressing each position of a number correspondingly in terms of 0 or 1, we obtain the binary for 1017, viz., 1111111001.

You may wonder, of course, how one can perform the basic arithmetical operations with such unwieldy numbers.

The rules are essentially the same as in the decimal system, though with some peculiarities due to the fact that binary notation is based on only two digital values.

Thus, the rule for carrying out binary calculations can be stated as follows:

"As in binary notation there are only two numerals to denote the coefficients of corresponding powers of 2, in any position 1 added to 1 yields 0, with 1 carried to the next position to the left. When a column of 1's is added, the coefficients 0 and 1 alternate, with 1 being carried to the left for each change to 0."

Let us carry out a simple addition operation according to these rules, namely, $1+1$. In binary we have:

$$\begin{array}{r} +\begin{array}{r}0001\\0001\end{array} \\ \hline 0010 \end{array}$$

Now let us add $8+3$ in binary:

$$\begin{array}{r} +\begin{array}{r}1000\\0011\end{array} \\ \hline 1011 \end{array}$$

Tables have been compiled for basic arithmetical operations:

Addition	Multiplication
$0+0=0$	$0\times0=0$
$0+1=1$	$0\times1=0$
$1+0=1$	$1\times0=0$
$1+1=10$	$1\times1=1$

began to look for ways of reducing the number of switches.

The engineers and mathematicians who tackled the job proceeded from the two-state—binary—nature of the basic elements of computer hardware.

Take, for example, a neon lamp. It can only be in one of two states: it is either "open", and conducts electricity, or it is "closed", and carries no current. The flip-flop switch, as its very name implies, can also be only in one of two stable states. Memory elements, too, are binary.

So why not employ the binary system of numerical notation, which uses only two numerals 0 and 1, making it extremely suitable for electronic machine operation.

Accordingly, new machines were built to perform their calculating operations with only zeros and ones.

Not that binary notation is a contemporary of electronic computers. In fact, people had been dabbling in binary notation from as far back as the latter part of the 16th century to as recently as the beginning of the 19th century.

The celebrated Gottfried Wilhelm Leibnitz considered the binary system simple, convenient and beautiful. "In dyadic computation", he declared, "the rewards for its prolixity are new discoveries of fundamental value to science.... Remarkable order is achieved by the reduction of all numbers to the simplest elements of 0 and 1."

At Leibnitz's request a medal was struck to honour the "dyadic system", as it was then called. It depicted a table of numbers and simple operations with them. Around the rim ran the inscription: "Unity can suffice to derive all from minuteness."

Subsequently the binary system was all but forgotten and for almost 200 years hardly a work dealt with the subject. It was only in 1931 that several possible practical applications of binary notation were suggested.

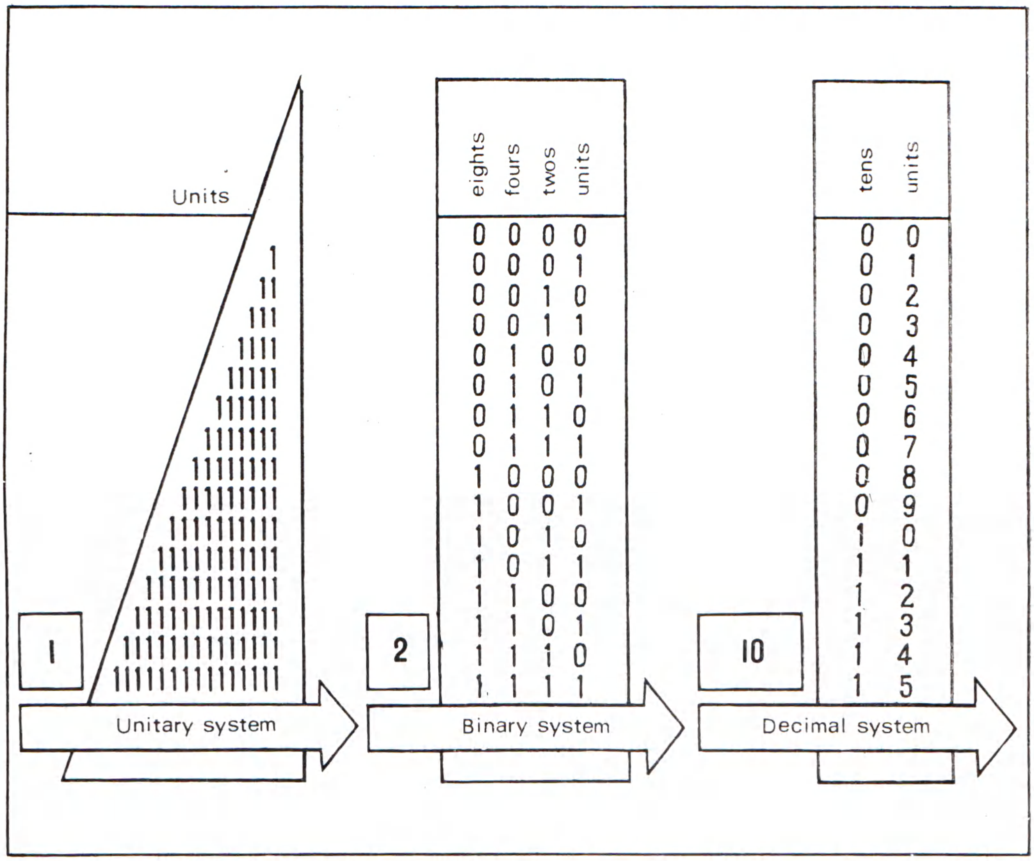
Like decimal counting, the binary system obeys rigid laws. But in the former each place of a number corresponds to a power of ten, while in the latter it corresponds to a power of two. Accordingly, in decimal notation there are ten digits from 0 to 9, while in binary there are only two, 0 and 1.

Numbers in binary notation at first seem queer indeed to the unaccustomed eye, as suggested by such a brief biographical statement:

"At school he was extremely clever with numbers. Problems which his schoolmates solved in half an hour took him no more than 101 or 110 (5 or 6) minutes to solve. Thanks to his wits and his energy he finished his college course in 11 (3) years, and he was only 1,010,000 (20) when he was placed in charge of a research laboratory."

A look at binary notation.

It can be seen from the table on p. 40 that the smaller the number of digits available to designate each digit position in a positional notation system the greater the number of positions needed to represent a given number. Take, for example, the number 8 in the decimal system. In the binary system, it takes four positions to represent it: 1000.



Comparison of number recording in unitary, binary and decimal systems.

Mathematicians claim that the arithmetical operations are much simpler in the binary than in the decimal system. Even extracting a square root is simpler. If you practise for a while in binary arithmetic you will surely agree with them. There is one stickler, though: subtraction is performed by means of addition. This is done by adding the complement of the subtrahend (i.e. the number that complements it to the next order of magnitude) to the minuend.

Suppose we want to subtract 101 from 10011 (19 — 5). First, add two 0's to the left side of the subtrahend to obtain the same number of digits as in the minuend. The complement of 00101 to 100000 is 11011. Adding this to the minuend, we obtain:

$$\begin{array}{r} + \begin{array}{r} 10011 \\ 11011 \end{array} \\ \hline 101110 \end{array}$$

Discarding the 1 on the extreme left, we obtain 01110, i.e. 14. And, as we know, in decimal notation 19—5=14.

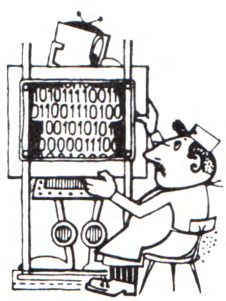
Multiplication is reduced to writing down the multiplicand in a staggered column and then adding up the column. Thus,

$$
\begin{array}{r}
\times\ \ 11011 \\
1101 \\
\hline
11011 \\
11011 \\
11011 \\
\hline
101011111
\end{array}
$$

Division is achieved by a process of consecutive subtraction, replaced, as we know, by addition.

As you see, all mathematical operations in binary are reduced to the simplest arithmetical operation of addition.

Thus, we now know the advantages of the binary system, which at first glance seems so strange because of our decimal tradition. It only remains to state the system's drawback: the binary system is used only in computers, only they reign undisputed in its domain. To be sure, they are not intimidated by the long, dreary rows and columns of zeros and ones that obey the tedious rules of binary arithmetic. Machines race through endless ranks of zeros and unities with incredible speed and easily overcome this shortcoming of the binary system.



A science that treats
of the utilization
of biological processes
and methods in solving
engineering problems.
Bionics can also be defined
as a science that investigates
methods of creating
mechanical systems
with characteristics approaching
those of living organisms.

Living Nature as a Designer of Hardware

Do you know that

... A rattlesnake can detect a temperature difference of one-thousandth of a degree?

... Some fishes can sense a one-hundred-thousand-millionth part of scent in a litre of water? This is equivalent to detecting the presence of 30 grams of such a substance in the whole Aral Sea.

... Rats feel radiation?

... Some species of microbes react to very slight changes in radiation?

... A common cockroach sees radiation?

... A stinging mosquito exerts a pressure of up to 1000 million kilograms per square centimetre? By comparison, a 16-kilogram weight with a 4-square-centimetre base exerts a pressure of 4 kilograms per square centimetre.

... Deep-sea fishes can detect a change in electric current of less than one-hundred-thousand-millionth of an ampere?

... The Nile fish mormyrus steers its way with the help of electromagnetic oscillations?

A remarkable list, isn't it? And it could be continued on and on with no less remarkable examples. It is hardly surprising that as they got to know all this, men were tempted with the idea of re-creating some of nature's achievements.

Here we must make a brief historical digression.

The human race has been around for about one hundred thousand years.

What did the first man see? Rushing waters, flying birds, running animals, blowing winds. In the early stages of man's creative life it was only natural for him to learn from nature. Animals, fish, birds suggested ways and means of tackling the "engineering problems" facing him.

And the modern man?

Having surrounded himself with numerous intricate machines in a world of high speeds he has again turned to nature for guidance. Why? Because he still sees the superiority of many of nature's creations over his own. Because the materials, devices and technological processes of nature are more complex than anything known to science.

It was man's desire to learn from nature that gave birth to the new science of bionics.

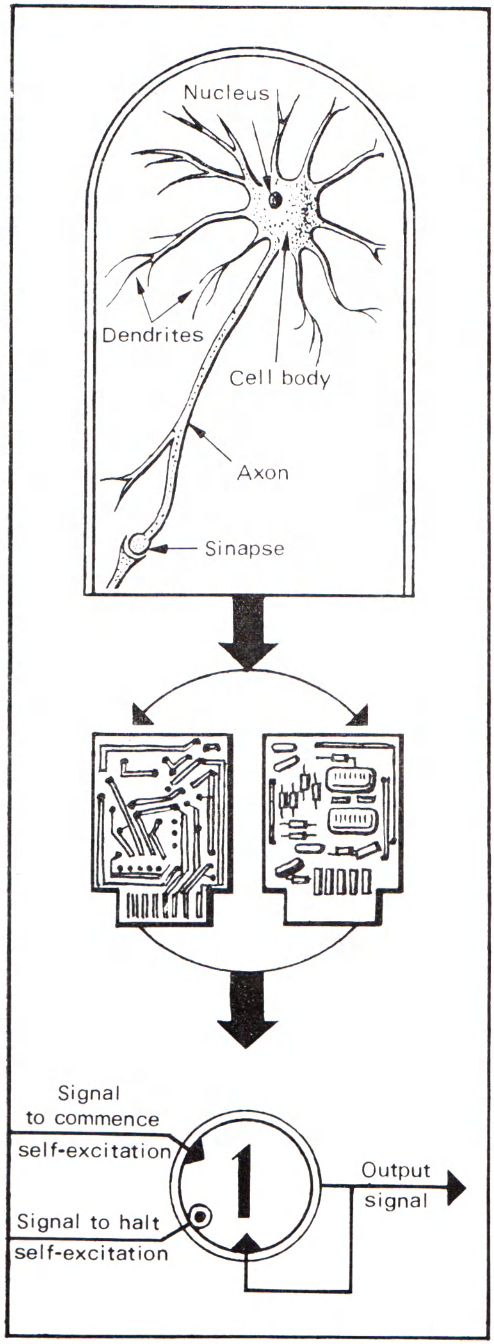
Bionics derives its name from the Greek word "bios", which means "life cell". And it studies biological systems and processes with the aim of applying the knowledge acquired for solving engineering problems.

Among the results of bionic research were the remarkable items cited at the beginning of the chapter. Such careful, exacting, refined observation is extremely important to science and technology, to teach them how to build inanimate things like living entities.

Have you ever reflected that the more complex a structure the less its stability? Most probably, yes. Nor does one have to go far for examples. It is obvious to anyone that it is simpler to build a one-storey house than, say, the Atomium that was one of the central attractions of the Brussels World Fair. One will also hardly dispute that a single brick in a building is more stable than the whole gigantic building built of countless bricks.

And in living nature? An organism as a whole is more stable than any one of its "bricks" taken alone. That is one of the secrets of survival of living systems. What is the explanation? As yet scientists do not know. But now bionics is increasingly and ever more successfully attacking that old invincible bastion—the unit of life—from every side.

The objective in this consorted attack is not thoughtless imitation, not copying of all the characteristics of biological entities, but a critical, strict selection of technologically useful properties. Proceeding from a biological "prototype" bionics elaborates models for concrete practical ap-



The nerve cell—neuron—is quite unlike its man-made counterparts—tiny electronic devices that simulate some of its simplest functions.

plication. It is interesting and useful to simulate only those functions, the specialists say, which enhance the flexibility, reliability, efficiency of a system or a process.

The nervous system has long been recognized as the most complex biological system capable of performing an extremely wide range of seemingly unlike functions of control and data processing. All through the history of biology as a science researchers have been probing the nervous system from every conceivable aspect. As a result they discovered that it owes many of its features to the structural peculiarities of nervous cells, or neurons, as they are called.

Why shouldn't bionics try to create a technical control system which would model the nervous system? What is needed for this? First of all—to simulate its fundamental "building block", the neuron. Such neuron models were instrumental in establishing many interesting points.

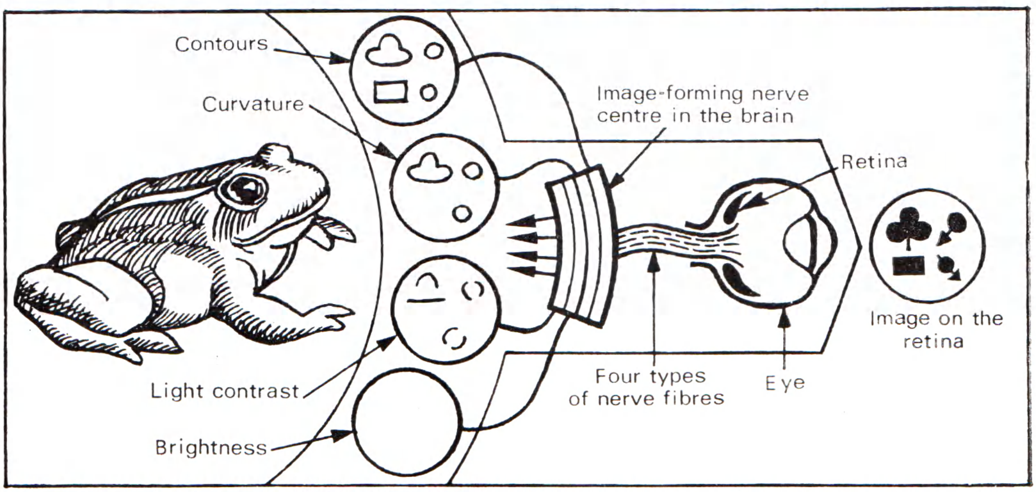
This is a schematic representation of a neuron and its electronic model.

In a living organism a neuron is usually in one of two states: quiescent (inhibition) or excited (excitation). Experts say that in simplified terms these neuron functions can be compared to a two-position electronic element operating in an "on-off" regime. It can be an electron tube, relay, transistor.

From neurons extend nerves, the "wiring" of the body which links its organs and various sections into an integrated whole and also connects the organism with the environment.

Both the living neuron and its electronic model are so-called threshold elements, which means that they "turn on" or "trigger" only when the input signal exceeds

Visual perception: the frog's eye perceiving the object takes in its various qualitative features separately: contours, curvature, brightness.



a certain level, the threshold. The process involves accumulation and build-up of signals in time and in space. The number of signals a neuron can receive may vary over a wide range from only a few to several thousand.

The simulated neuron has told researchers many things. To begin with, the engineer in building a control system will like to have the flexibility, reliability and efficiency of a neuron. But, on the other hand, an engineering system has no use for such a property of the neuron as its need for a relatively prolonged "rest period" to "restore its strength". A technological system does not need it, and this is its advantage.

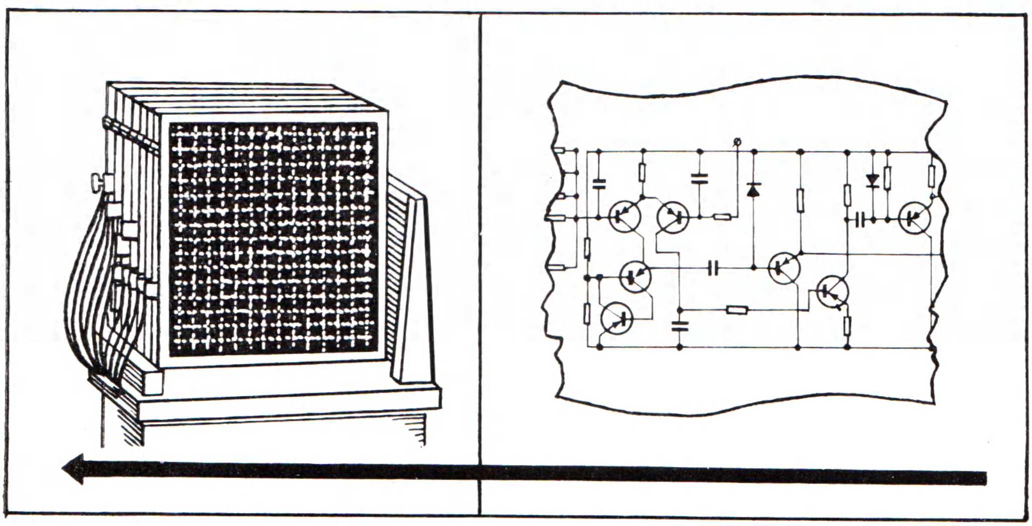
What practical results has bionics yielded, what are its contributions to technology?

Bionics experts are amazed, for example, at the remarkable navigational abilities of birds. A common carrier pigeon, for example, returns home from practically any place. It has been shown that the unassuming little bird golden plover can cross the Atlantic from New Scotland to South America (a distance of some 4000 kilometres) without a single stop-over. And every year they follow the same routes.

How do they take their bearings in space? How do they find their invisible routes in the sky? What are the highly accurate and sensitive "navigational instruments" that function inside these champion navigators?

So far scientists are unable to explain how this highly sophisticated orientation system operates. However, we are entitled to expect that

Electronic model of a frog's eye—one of the first bionic circuits.



the question will not remain unanswered. This is confirmed by the initial results of some extremely interesting experiments being conducted with birds.

On the other hand, the remarkable ability of bats to find their way about the darkest caves or flit among tree branches on moonless nights is no longer a secret to bionics experts. They know that the apparently random, helter-skelter flitting of a bat out foraging for food is in fact an extremely accurate method of sonar (sound navigation and range finding), enabling the animal to measure the distance to its prey with utmost precision. When hunting, bats are extremely "garulous" "shooting" bursts of ultrasonic radiation at insects and picking up the reflected waves.

The study of sonar techniques of animals, notably bats, has been useful in investigating the direction-finding system blind people develop in themselves. It has been found that a blind man can use the sound of his voice to take his bearings, find his way without the help of a stick and even distinguish wood, metal or fabrics "by ear".

For many years bionics experts have been studying the speed with which various prairie animals, birds, insects, fish and marine animals travel. As is known, man has long since surpassed the speed records of the blue shark, which can swim at 70 km per hour, and the most fleetfooted grasshoppers which leap at speeds of 10 to 60 km per hour.

It's the problems of manoeuvrability and flexible steering which birds, fishes and insects handle automatically with the greatest of ease, which interest the transport engineers.

Japanese engineers and biologists established after many experiments that whales had a better shape than the best-designed modern ship, and used their newly found knowledge to build a "whale-like" vessel. The advantages of the new design were readily apparent: with the same speed and load capacity as its conventional equivalent it required only three-quarters of the engine power.

Bionics principles have been incorporated in the design of the "Penguin" Soviet snowmobile. Its name is fully justified. How does a penguin travel over soft snow? Sliding on its belly and propelling itself with its flippers much like a skier uses sticks. The mechanical Penguin also slides on its belly, pushing off with spoked wheels. Weighing 1300 kilograms, the machine can travel at 50 km per hour.

Bionics is helping chemists. Organic chemists studying and creating polymer materials are interested in the "technologies" employed by nature in producing complex chemical compounds.

The symbol of bionics is a crossed scalpel, soldering iron and an integral sign. This alliance of biologist, technician and mathematician offers hope that the science of bionics will prove capable of penetrating where none have penetrated before and of discovering what none has ever seen before.

The time is not far off when the advances of bionics will cause many remarkable changes in the field of technology. We can look forward to new breakthroughs in methods and tools for detecting and extracting minerals and manufacturing materials. In engineering, control systems will incorporate what could be called biological machines.

Looking farther ahead, scientists predict the advent of the age of bionics. Its contours can be surmised from the first advances of this discipline. One book describing the new science declares that in the future, following the example of living nature, men will design and build ornithopters, fast submarine liners, vehicles for negotiating the rugged terrains of the Moon, Mars, Venus and other planets, sparkling cities of dendroid dwellings and communities of fabulous beauty on the sea bottom. Men will learn to orientate as freely in outer space as birds do in the air, to forecast the weather, earthquakes and volcanic eruptions, to literally grow various electronic devices, remarkable biomechanisms and artificial neurons, to build protein computers.... The book envisages direct transformation of sunlight into clothes and food along the lines of photosynthesis that takes place in every green leaf.... Artificial muscles instead of cumbersome machines.... Aircraft, machines, automobiles, rockets guided by will-power alone, without steering wheels or levers....

An object of investigation whose internal structure is ignored or unknown.

A Thing in Itself

It is hard to overestimate the importance of the "black box" concept in cybernetics. It is not often that the name of a concept conveys its meaning and content so aptly and at the same time picturesquely as that of "black box". In fact, it is one of its basic concepts.

Fundamental for the "black box" are the concepts of its "input" and "output". "Input" is the combination of all possible influences (physical, chemical, etc.) to which the "box" is subjected. "Output" is the reaction of the "box" to these influences in terms of some observable values. The "black boxes" we usually deal with are not "absolutely black"—we know what kind of influences (out of infinite number of possible combinations) they should be subjected to, and what results to expect.

Man encounters "black box" problems literally from his first steps in life. To be sure, in life he generally copes with them successfully, without attempting to classify the problem or even knowing that he is, in fact, dealing with a typical black box.

As soon as a child pulls itself to its feet and starts walking about its crib, it experiences the urge to get out into the "big world". But there is the net that doesn't let him out. To the child the net is a typical "black box": he knows nothing about its structure, how it is fastened. He pulls it at random here and there. In the language of cybernetics, what he is doing is manipulating the input leads in the hope of producing a result at the output end: the lowering of the net.

A clockwork toy is also a black box. Children don't know how it works. All they know is that it runs when you turn the key. We can say that at the input end there is the key which should be turned, at the output end there is the running of the wheels.

A TV or wireless set is a black box to the owner who knows nothing of how it works, except that he must apply electric current at the input in order to obtain image and/or sound at the output.

It is no exaggeration to say that every thing, every object, every phenomenon, in fact every knowable thing is initially a "black box".

In the examples cited the "boxes" don't remain "black" for long. As experience builds up the "blackness" gradually disperses.

But is it always as simple as all that? Let us take some other examples. "Black boxes" are fairly common in electronics, sometimes in the quite literal sense.

An engineer stands in front of an electronic apparatus. He cannot disassemble it. But he must decide whether it should be returned for repairs or simply thrown out.

A similar task confronts a telephone engineer whose installations are out of order but cannot be disassembled without good reason.

Or take a physician, who in his practice is confronted with only the external manifestations of a disease and knows nothing of the actual state of the patient's organism. He has before him a "black-box" problem.

Specialists studying "black-box" theory claim that its application can be useful in coping with the tremendous diversity of problems involved in industrial planning. For even an enterprise with only ten production processes has a choice of almost ten million different plans.

As you see, the "black box" is a problem of electrical engineering and electronics, of automatic control, medicine and economics, and the list could be continued. True, the English scientist Walter Ashby, who investigated the "black box" concept, declares that the purpose of his theory is merely to investigate the relationship between the experimenter and the environment with special attention to the flow of information.

Thus, we know that a "black box" is a system of the internal structure of which we are ignorant. How then can it be discussed, studied, investigated? The "black box" method investigates a system from only one aspect: the relationship or connection between its input and output. The purpose is to comprehend the system's behaviour. Only its behaviour: structure and material are not taken into account.

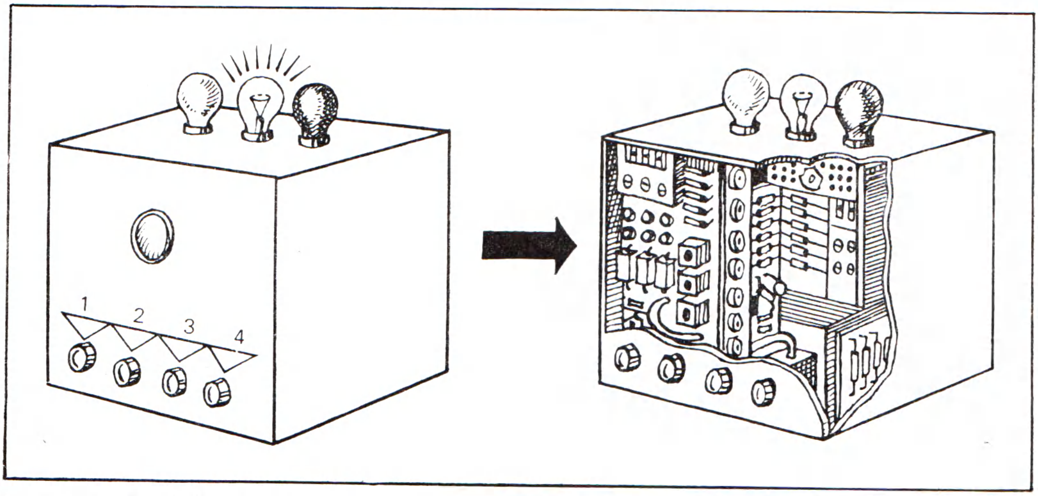
William Ashby describes "black box" investigations as follows:

A person cannot enter the same stream twice; similarly, he cannot perform the same experiment twice. All he can do is to perform another experiment differing from the first in elements which can, by general agreement, be ignored.

The same is true of "black box" investigation. The basic data about the observed states of different parts of the "box" (its "input" and "output") are tabulated in chronological order. Thus, suppose you are studying a "box" that has fallen from an unidentified flying object. You could write down:

Time (hours)	State
11.18	Did nothing—box emitted steady buzzing noise at 240 hertz frequency
11.19	Pushed button marked "K"—buzzing rose to 480 hertz and continued at that level
11.20	Accidentally pushed button marked "!"—temperature of the box rose by 20 °C

Thus, every system is investigated by chronologically tabulating the observed sequences of the states of the "input" and "output". The record tells what input leads the experimenter manipulated with and what happened as a result at the "output". By gradually expanding the "input"-"output" scope the experimenter gets to know the behaviour of the object. And as he gets to know more and more of its behaviour he attempts to reveal the inner connections of the "box", its structure.



This is a "black box". By repeatedly pressing the buttons the lamps on top can be made to flash on in different combinations, making it possible to establish the laws of "input"-"output" relationships without knowing what goes on inside the box.

Ashby notes on this score that the experimenter is like an engineer sitting in a ship's deck-house in front of an array of levers and telegraph systems with which he manipulates the machines observing the results of this manipulation as readings on a row of dials.

The explanations about what a "black box" is were sufficiently long and sufficiently convincing. What they have failed to reveal, however, is why the "black box" is one of the fundamental concepts of cybernetics. The answer is: because in cybernetics people deal with systems which cannot be described in detail, very big systems, as they are commonly called.

Let us try and see what this means. Once again some examples will be helpful.

Here is one: the human nervous system. It is like a huge electric circuit, like that of an electronic apparatus. But the difference is tremendous, the quantitative differences are beyond all comparison. A radio device incorporates several hundred different kinds of switches. An electronic machine has as many as 100 000 switching elements. But the number of neurons in the human brain is of the order of 14 000 million.

Imagine a biologist who has undertaken to establish all the switchings that take place in a thought process. Let us assume further that the biologist can master the switching circuit of the nervous system just as fast as a radio engineer masters the circuit of a radio device. It is known from experience that a good specialist needs five hours to analyse a circuit of 200 switchings. Let us assume that a biologist analyses the switching circuit of the human nervous system with the same speed. A simple calculation shows that this would take 40 000 years! Detailed investigation of a very big system is impossible.

Another example. Automation is being carried out at a chemical works in shops where health hazards are present. For a while everything is in order: the operator pushes the necessary buttons, the automatic machines function flawlessly, the processes run normally. But here is a hitch: the operator is human and it is dangerous for him to be in the shop! He, too, has to be replaced and his duties handed over to an automatic device.

In the dry language of cybernetics this problem is defined as "the need to replace one system by another, similarly functioning one".

This is where the "black box" comes in. We know that some as yet undesigned system must perform the functions of the human operator. We ignore how a human being performs his actions, concentrating only on what he does (input) and what comes out of it (output). We regard the human operator as a "black box" and build its model. The important thing is that both the box and its electronic replica can be described by the same mathematical formulae.

Here, as you can see, we again have a very big system. Such systems may be so complex that even when complete information concerning the state of individual elements is available, the number of elements is so great that it is very hard to synthesize this information, to bring it together, so as to judge of the behaviour of the whole system. A human investigator is incapable of coping with it, he is swamped by the incoming information and cannot grasp it all.

What is the conclusion? There are several. One of them is vividly stated by the cybernetician Ashby. If an engineer building a bridge had to consider every atom of the building materials his job would be impractical, if only because of its scope. Therefore, a builder ignores the fact that beams and panels are made up of atoms. He considers them as indivisible units, because their nature allows of such a simplification, and the engineer's task becomes implementable.

But are simplifications always possible? Not by a long shot.

A psychiatrist trying to determine what is going on in a disordered brain has to deal with a very big system. Moreover, this is a system which demands a very cautious approach to simplifications. They are not always permissible and can grossly distort the overall picture of the disease.

When an economist engages in his complex calculations at an enterprise, the raw materials prices, manpower requirements, finished goods prices, expenditure of labour, demand and other indices are buried in an ocean of minor things which must be taken into account. He must approach simplifications with the utmost care, and weigh them in his calculations with the greatest precision. Such examples are literally countless.

Therefore, the "black box" is indispensable in studying very big systems. It is the magic key of a practical method which can be employed for controlling the enormous diversity of very big systems.

In such cases a complex system is represented as a "black box". Then a simplified model is built and its investigation commences. Next the behaviour of the system and of its model is compared and analysed.

If the model doesn't behave like the system, the experimenter is entitled to conclude that the principles incorporated in the model are at variance with those of the system. Hence, a new hypothesis about the system's structure is required, and new experiments must be carried out.

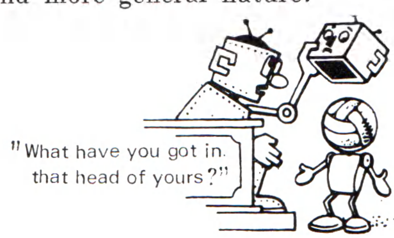
Finally, the lengthy investigations yield success. The principles on which the model was built tally with the hypothesized principles of the system confirming the experimenter's initial conclusions.

Let us see how such theoretical reasoning bodies forth in practice on the initial stages of the work of the Central Automation Laboratory in creating reliable automatic steel-making equipment.

Today steel is produced mainly in two ways: in open-hearth furnaces and in Bessemer converters. The open-hearth furnace has earned affection and respect of the steel-maker, but the converter.... The converter demands truly creative skill on the part of him. Unlike the open-hearth method, in which he is assisted by precise laboratory analyses, Bessemer steel is produced largely by rule of thumb. Converter operators are like huntsmen aiming at difficult targets. Even the experienced hit the bull's eye with difficulty, and the best register only 40 per cent direct "hits".

So the cyberneticians decided to represent the converter as a "black box". The "input" is the initial charge for the melt, the "output" is the finished steel. What goes on inside the "box" is for the time being neglected. The next thing is to write a series of simultaneous equations describing the heat balance, the required carbon and oxygen, their amounts before and after the melt. The equations tell what is needed for the best "input" to obtain the best "output". Today producing Bessemer steel is no longer a question of "shooting in the dark". The process is carried out according to a calculated method, and the percentage of precision "hits" has almost doubled.

To what conclusion have we arrived as a result of our acquaintance with the problem of very big systems and the "black box"? After due reflection we can, evidently, agree with the cyberneticians' view that the discoveries of science are displaying ever growing diversity which is pushing back its frontiers and revealing ever more important details. At the same time, as a result of the discoveries of science, wide classes of phenomena are being reduced to an ever smaller class of principles of more and more general nature.



C

From Plum Stones to Computers

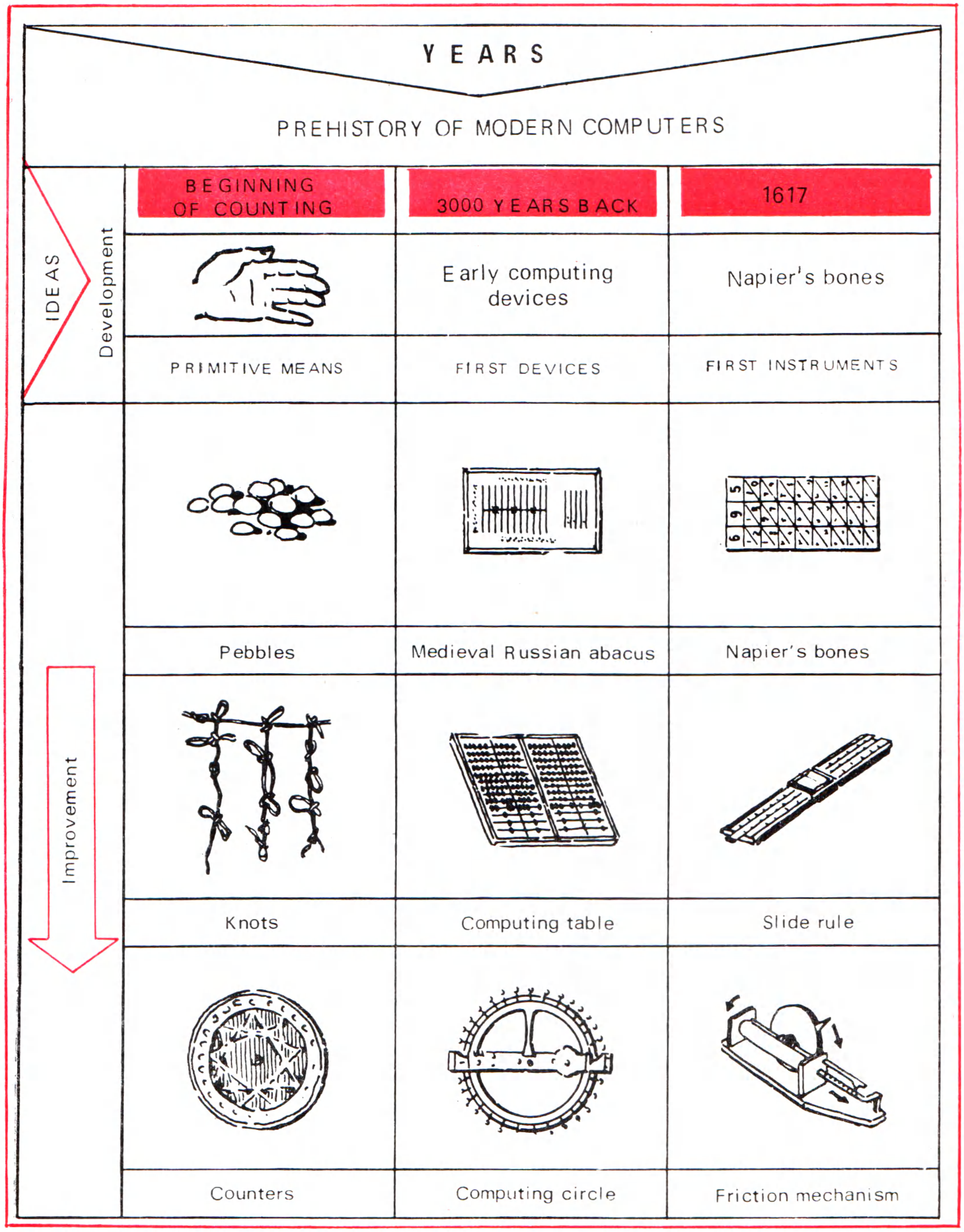
CALCULATING HARDWARE

Machines and devices for speeding up calculation procedures through partial or total automation.

A foreigner visiting Russia some 400 years ago during the reign of Ivan the Terrible noticed that scribes in government offices had little bags containing plum and cherry stones. In his diary he wrote down: "In the land of Russians counting is done with the aid of plum stones."

The history of counting devices is thousands of years old. The first "calculator" was provided by nature herself: the human hand, "the ten fingers with which men learned to count, that is, perform the first arithmetical operation", as Engels wrote. It is not accidental that the first numerals from 0 to 9 are called digits, which means fingers.

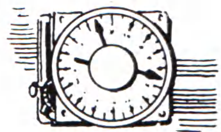
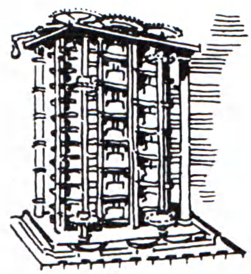
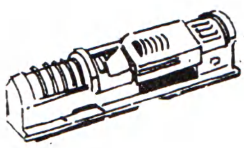
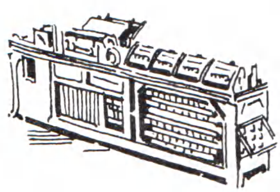
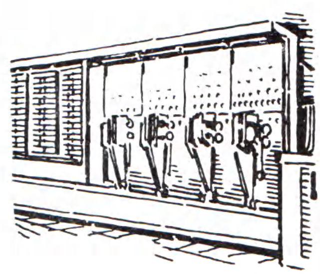
The earliest calculating device was the abacus, which evolved through a series of types, many of which are on view in museums, notably at the Hermitage Museum in Leningrad. Two shallow boxes hinged together open up like a book. An exquisite richly ornamented casket made of ivory pieces joined by silver pins and locked with a silver hook is actually an old Russian counting board. Red and black glass marbles serve as counters. A genuine work of art, it probably belonged to a wealthy person. But this doesn't mean that only rich people used counting boards. According to a 17th century manuscript, they were in wide use "for mercantile accounts, and counting and calculating weights, measures and moneys". Also on view at the Hermitage is a counting board made of crude pinewood hammered together



From the history of the development of calculating machines (pp. 54-57).

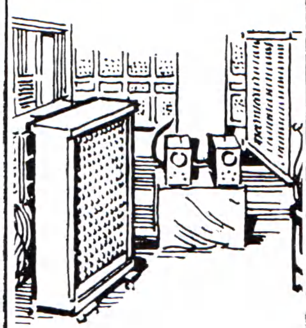
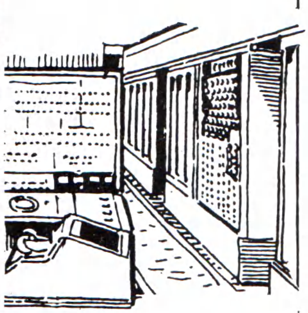
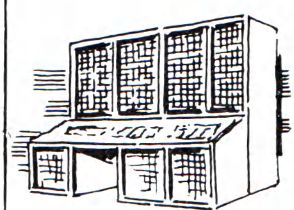
YEARS

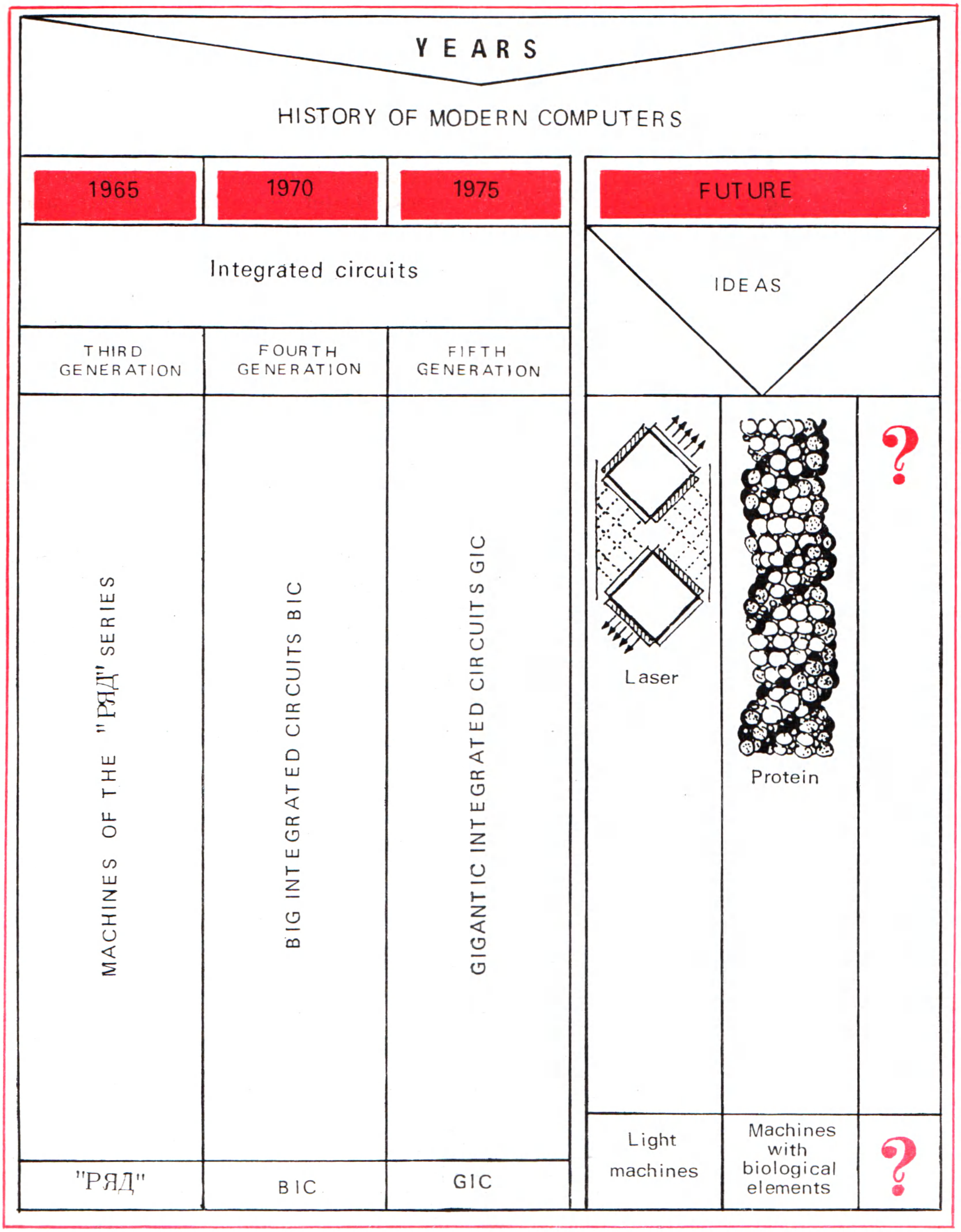
PREHISTORY OF MODERN COMPUTERS

1642	1801	1834
Counting wheel	Punched cards	Division of "duties" in the machine
FIRST MACHINES	FIRST PRINCIPLES OF CONTROL	PRINCIPLES OF OPERATION OF CALCULATING AUTOMATON
 Pascal's machine	 Hollerith's machine	 Babbage's analytical engine
 Chebyshev's arithmometer	 Tabulating machine	 "Mark-I"
 Keyboard computer		

YEARS

HISTORY OF MODERN COMPUTERS

IDEAS / Development	1945	1950	1960
	Flip-flop type electronic circuits	Valves	Semiconductors
	BEGINNING OF THE DESIGN WORK ON MODERN COMPUTERS	FIRST GENERATION	SECOND GENERATION
Improvement	 Uniac 1946		
	 Machine of the early 1950s	БЭСМ 1953	 БЭСМ—6


YEARS
HISTORY OF MODERN COMPUTERS
1965
1970
1975
FUTURE
Integrated circuits
IDEAS
THIRD GENERATION
FOURTH GENERATION
FIFTH GENERATION
MACHINES OF THE "РЯД" SERIES
BIG INTEGRATED CIRCUITS BIC
GIGANTIC INTEGRATED CIRCUITS GIC
Laser
Protein
?
"РЯД"
BIC
GIC
Light machines
Machines with biological elements
?

with plain nails. The use of counting boards was obviously widespread in Russia. Special instructions were even printed, such as "Convenient Calculations for Use by Buyers and Sellers" printed in Moscow in 1682, which contained a table of products of whole numbers from 1 to 100.

The abacus is still used in some countries, having hardly changed since ancient times. A high degree of skill can be attained in using the abacus, so much so that some accountants can compete with a simple desk calculator.

With the development of the productive forces the importance of calculation grew apace. Mechanical calculators were built. Man made them count faster, gradually reducing the degree of his own participation in the work. Later he added motors and "taught" the machines to "read", "memorize" numbers and "record" intermediate results.

It is only natural that in the age of automation calculating machines have also gone automatic. Nowadays they control and regulate the whole computing procedure operating at tremendous speeds. Their spheres of application have expanded enormously.

Great is the arsenal of modern calculating machines, numerous are the ways of mechanizing calculations. From the desk calculator to the high-speed electronic computer. From the simplest planimeter to the most complex electronic analogue computer. From a small accounting office to a huge computer centre.

All this has been placed at man's service, enabling him to perform mathematical operations with huge numbers with great speed, accuracy and reliability, to solve the most complex problems of higher mathematics, to study very fast processes.

Today a vast range of calculating machines of all conceivable sizes and types are manufactured, but they all fall into several distinct classes.

The oldest and simplest calculating appliances gave rise to the **adding machine.** The evolution of this branch led to the appearance of all kinds of **desk keyboard machines** of the type that can be found in book-keeping departments, planning departments, etc.

Another branch in calculating technology includes **punched card machines.** They employ oblong cards with holes punched in them. A complete set of such machines forms a computer flow line employing punched cards at all stages of the process. Punched card machines are capable of handling tens of thousands of cards per hour.

Complete sets of punched card machines are the basic equipment of computer stations and bureaus. They are used at factories, offices, institutes, collective farms.

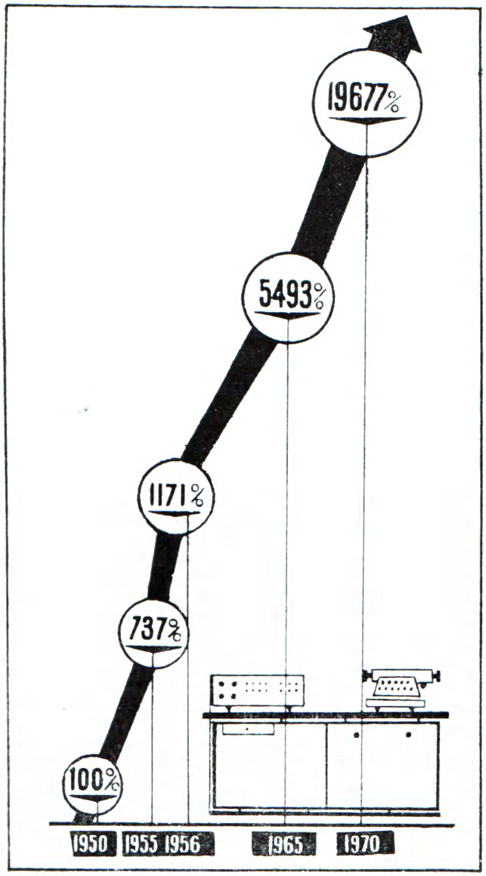
Our designers are continuously striving to improve designs of punched card machines, supplementing and complementing them with new types and systems. Sorting, tabulating and multiplying systems have been built which incorporate electronic elements, all the efforts are aimed at expanding the data-handling capacity of computer flow lines and increasing their productivity.

Another branch of computer hardware is **analogue machines and systems** in which mathematical quantities are represented not as numbers, not as concrete data changing in discrete steps, but as physical quantities presented in a certain scale: a change in angle of turn, voltage or liquid level. The advantage of such machines is that they can operate with quantities fed in a continuous stream, like a flow of water. The replies also come out continuously.

Many of you have seen devices of this type, the slide rule and various variations of it, and mathematical instruments, such as planimeters, pantographs, tangential mechanisms, etc.

Electronics has worked a revolution in this sphere too, having produced a wide range of electronic analogue installations and simulators: continuous-action analogue computers capable of solving complex systems of simultaneous equations to accuracies of several per cent. These machines are simple in operation, reliable, and require a minimum of preparatory work prior to solving a problem.

An example of a machine of this kind is an electronic simulator (analogue computer) of the EI (electronic integrator) class. It is an impressive installation capable of calculating 70 to 80 variants needed for positioning 50 extraction and 250 pressurization wells in a matter of two or three days. Formerly it took 200 man-months for calculators to solve the problem for only 100 wells.



Computer manufacture is soaring in the Soviet Union.

Another machine is the "MH-14". The initial data are fed in automatically and the result is recorded by an electric typewriter. When necessary, the whole course of the solution can be followed on the screen of a cathode-ray tube. The machine is serviced by one engineer and one technician.

Soviet industry manufactures a wide range of analogue computers. They are all classified into three groups: integrators, machines for solving differential equations, and specialized analogue computers, such as the "МПТ-9", "МН-8", "МН-10", "Integral-1", "МН-14", "ЭМСС-7", "УСМ-1", to name but a few.

But, of course, the "elite" of the world of electronics is the **high-speed electronic computers.** The first of the family appeared in the 40s, but already by 1955 the manufacture of electronic computers was running ahead of the rest of the manufactured goods by 546 per cent in West Germany, 505 per cent in Italy, and 303 per cent in Great Britain. Only three computers were built in Japan in 1957, by 1970 their number rose to over four thousand. In 1960 there were some five thousand computers throughout the world. By the end of 1967 their number rose to forty thousand. By the end of 1975 their number in the largest capitalist country, the USA, is expected to reach 200 thousand, the forecast for 1980 being 355 thousand.

The same situation exists in other industrial countries. In 1959 France had 20 electronic computers, and by 1969 the number was five thousand. Japan had only three computers in 1957, nowadays it has thousands.

The total number of computers in 1949 could be counted with the aid of fingers; by 1966 it reached 30 thousand, by 1969—75 thousand, and now it is presumed to go into hundreds of thousands.

In the Soviet Union the manufacture of mathematical machines is soaring. Taking the production for the year 1950 as 100, five years later the figure was 737, and only one year after that, 1171. By 1965, the output had increased 4.7-fold over 1956, and in 1970 it exceeded that of 1965 by 4.8 times. In the next seven or ten years the USSR will reach one of the first places in the world by the production of electronic computers.

Several major computer families have appeared in our country. One is the "Ural" type, ranging from "Ural-1", "Ural-2", "Ural-3", through "Ural-10" and on to "Ural-16". Although belonging to the same family they serve different purposes and can solve a wide circle of mathematical and logical problems.

Not long ago a new series of universal digital computers appeared: "Minsk", "Minsk-1", "Minsk-2" ... "Minsk-22" ... "Minsk-32". This is a family of small machines designed mainly for solving scientific and engineering problems and also for production planning and control. The "Minsk-22" is a semiconductor unit intended mainly for data processing in handling economic planning problems. What can it do? Calculate wages, keep warehouse tabs, compile balance sheets, process statistical data, draw up finished products specifications and do many other things listed in the accompanying instructions as "other economic problems". Furthermore, the computer can solve simultaneous algebraic equations and perform multiple arithmetical operations "and other mathematical operations involved in solving scientific and complex engineering problems".

As you see, this isn't just a machine, but an all-purpose mathematical combine, a jack-of-all-trades capable of performing any task.

The "Minsk-32" is another step forward beyond its brother 22. It calculates five or six times faster and can handle eight times more information. Furthermore, it can function with 136 external appliances. It is operated by one person with the aid of a typewriter.

Our review of small machines would be incomplete without the universal "Nairi" designed for scientific research organizations and design offices, without the "Promin", a small desk with the control console on the top and the hardware underneath capable of solving engineering problems of average complexity and performing small computations. Another interesting machine is the "Setun" which is housed in two cabinets. Special mention should be made of the "Mir" which, in spite of its small size, is capable of solving many types of simultaneous equations, linear programming problems, of calculating time-tables and of performing a wide range of complex mathematical operations, including analytical transformations of formulae and solving equations in letter form.

Academician V. Glushkov, Hero of Socialist Labour, head of the team which built the "Mir", lists the characteristics of his offspring as follows. It is capable of memorizing 12 000 symbols—six or seven pages of text. Innate to it are all the main formulae we were taught at school plus some items from the college course. Called the "electronic engineer", it is an indispensable tool in the hands of specialists employing mathematics in their investigations.

Alas, so many mathematical machines are produced in our country that it is impossible to tell of them all.

Before we forget, we should note one more quality of the "Mir" family of computers: the problems are fed into them with the help of conventional mathematical signs, symbols and numbers. No translation into a machine language is required, which is extremely convenient.

Now let us proceed to the most important family of machines, the "generals" of Soviet computer hardware, the "БЭСМ" family. They are large installations, extremely reliable, fast, with a vast data-handling capacity, tremendous universality, and capable of solving the most complex mathematical problems.

The first-born of this family was the "БЭСМ-1" created by a team of scientists and engineers under Academician S. Lebedev, Hero of Socialist Labour. Originally it was the best in Europe, capable of performing 8 000 and, after some improvement, 10 000 operations per second. It also possessed an excellent memory with swift retrieval.

Today this machine is a great-great-grandfather. It was replaced by a new generation, the "БЭСМ-2" and "БЭСМ-3", capable of performing 20 000 operations per second and with a vast memory of four million words.

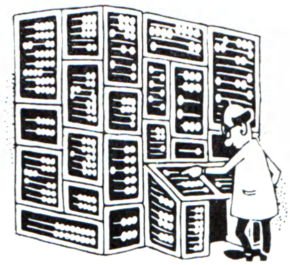
The next generation was represented by the "БЭСМ-4", awarded a diploma of the International Exhibition of Engineering, Administration and Management Mechanization held in Moscow in 1966.

Life goes on, and we became witnesses of the creation of "БЭСМ-6". This was a veritable giant—not in size but in capabilities. Though several times smaller than its great-great-grandfather, the "БЭСМ-1", it performs a million operations per second. It is designed for solving a wide range of complex scientific, technological and economic problems requiring a vast amount of calculations.

The machine incorporates all of the latest achievements of computer technology. Its designers were awarded the 1969 State Prize. The "БЭСМ-6" is capable of carrying out several operations and solving several problems simultaneously. Input information can be fed to it by means of punched cards or tape, magnetic drums or tape, and even by telegraph. A very high-speed memory device additionally enhances the machine's already high productivity. It can be run by several operators simultaneously working from several control panels, which need not be in the same room.

One of the flag-ships of Soviet computer electronics has already assumed its duties at the head of the electronic machines of the sophisticated computer complex at the Joint Nuclear Research Institute at Dubna, north of Moscow. The "БЭСМ-6" is employed in solving the most difficult mathematical problems of modern physics, which entail the processing of numerous experimental data in the shortest possible time.

As you see, many excellent computing machines have been created in this country. Their rate of production is such that specialists confidently declare: "In the near future we'll move to one of the first places."



Computer

The amount of information (numbers and instructions) that can be simultaneously stored in the memory block.

"*An Impress on a Wax Surface*"

The famous philosopher of ancient Greece Socrates compared the process of memorizing an idea with the action of a seal-ring leaving its impress on a soft wax surface.

How deep can this trace be? What is the strength and the capacity of memory, how great can its intake be? In general, what's memory?

Some wonderful tales are told about our memory. In one of his lectures Professor V. Solodovnikov cited an example of six brick-layers answering under the influence of hypnosis a question about the form of the crack in the sixteenth brick in the fifth row of the eastern wall of a particular house on a particular street. And that after six months have lapsed since the wall was laid!

The famous Russian scientist Academician S. Chaplygin could unerringly name a telephone number he used only once some five years ago.

It's rumoured that the cashier of the "Gurnik" football club by name of Leopold Held remembers all the results and all the details of the club's games. Once in the course of a televized programme the commentator asked Held: "What was the result of the match between 'Gurnik' and 'Odra' (Opole) four years ago?" The answer came instantly: "We won 4 : 0, the game was played on the 18th of August in the presence of 27 000 fans. The all-round profit was 235 thousand zlotys. Three goals were scored by Pol and one by Zsolliseck."

And yet these starting examples do not represent the limit of man's abilities.

There is the case of the reporter of one of Moscow's papers by name of Shereshevsky, who was initially examined by specialists in 1926. His memory was practically boundless. He memorized rows and tables of over a hundred numbers, enormous combinations of words from texts unfamiliar to him in an unfamiliar language, even ultra-long chains made up of two concepts "red" and "blue" in an arbitrary order. The durability of this man's memory, too, was limitless. He could repeat unerringly a table of numbers that he happened to have heard once 20 years ago.

Professor A. Luria, who had Shereshevsky under observation for 30 years, tells how he answered questions when examined: "He closed his eyes and slowly drew circles in the air with his finger.... 'Wait a moment ... you wore a grey suit ... I sat vis-á-vis to you at the table ... got it!' And not a single mistake!"

Where is this wonderful treasure-store of intelligence, what are the mechanisms of its operation? Unhappily, we do not know it for certain.

If we define memory as the ability of the brain to store information accumulated in the past and produce it on request, in our century of electricity we unwittingly tend to assume that memory is a combination of pulses travelling along a circuit in the same way as does electric current. But, alas, as yet no "memory currents" have been found in the brain.

The question looms large in the minds of scientists: how does the brain hold the fantastic amount of information accumulated by man during his lifetime? Scientists are labouring unceasingly to solve the problem of the origin of memory.

The opinion holds that our brain is made up of 12-14 billion neurons. It can be presumed that each neuron is capable of storing more than one unit of information. The presumption that this minute particle of the brain is able to assume ten or hundred states to record information seems less justified. Even if this was the case, it would be impossible to imagine how the brain is able to hold the gigantic reserve of intelligence. We cannot but presume that memories are recorded on the molecular level, that molecules of memory are active in the brain. Those are enormous, very complicated molecules, which look like rope ladders with cross-beams of two types. These molecules, placed in a definite order, like the dots and dashes in the Morse code, constitute a peculiar atomic and molecular ABC.

How much can be recorded with the aid of it? Let's make some calculations. Each molecule has 10 000 cross-beams of two types. The chromosomes of human cells contain some 100 000 genes. This means that the number of elementary signs will be $100\,000 \times 10\,000 = 10$ billion. This is equivalent to 50 000 pages of the Grand Encyclopaedia.

But this is not the final word. If we go on, it will become clear to us that with an "ideal" code the text written with the aid of the two signs of our chromosomes would amount to hundreds of thousands or even millions of encyclopaedia pages. And what if nature managed to produce some special signs by making small shifts in the molecules? Then the information capacity will defy all imagination. That's what can be done with the aid of atomic and molecular ABC. Experiments have shown that not everything and not always is retained in man's memory for a long time. Frequently information is kept stored in his head only "until tomorrow". This leads us to suppose that man's memory is of several types.

Information reaching the brain connects its neurons into electric circuits and circulates in these circuits. This is the short-time memory.

The currents circulating in the neuron circuits act upon the molecules of the nerve cells, and this leads to proteins being synthesized in them. When the signal is repeated, the protein reacts to it and admits information to the long-time memory—the brain. If the signal is not repeated, the circuits will fall apart, the short-time memory will be switched off. It is presumed that there is also a working memory. Just watch a typist. When typing a text, she keeps in her memory only short pieces of it for a very short time until she finishes typing them.

People were quick to see that all

records in the brain are short-lived, and that extraordinary memory is, unhappily, the gift of very few persons. Practically, to memorize man had to seek the aid of artificial means of memory, capable of supplementing the natural memory of the human brain.

The oldest practical method is the use of inscriptions and signs. It dates back to rock-wall pictures. Then came the turn of characters, and after them of the letters of ABC's.

The invention of book-printing has increased human memory to the dimensions capable of engulfing all sciences, all intellectual heritage of mankind.

Later photography came to the aid of graphics, and it was followed by cinematography. This enabled events to be memorized in action, in time. People learned to memorize, not only what they have seen, but also what they have heard—due to the appearance of sound recording of the mechanical, photographic and magnetic types.

A method of recording various commands has been devised as far back as the Middle Ages. Plates were "sensed" by pins fixed onto drums—bells rang, musical boxes played.

Information was also memorized by holes of perforated drums of looms in the middle of the 18th century.

Great prolification of artificial memory aids is characteristic of our time. Electromechanical and electron-tube recording devices employing two stable states (on-off) were succeeded by novel devices using magnets (magnetized-demagnetized), semiconductors, etc.

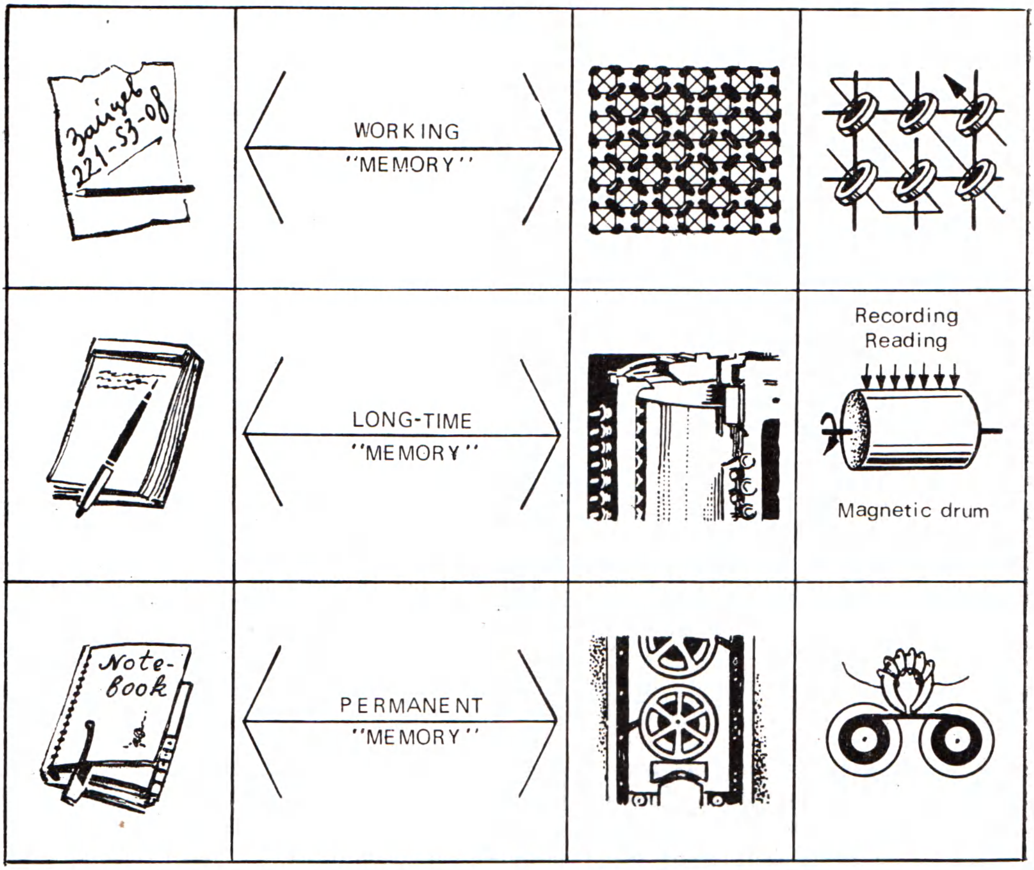
Let's take a look at the computer memory. Its electronic "memory" is used as a depot to store numbers and instructions. From this depot they are sent for processing to the "mathematical mill". The results obtained are returned to the "memory". An absolute order must be maintained here to facilitate the extraction of the necessary numbers or of a definite result.

The computer "memory", its recording device, can be compared to the headgear wardrobe. It's full of hats, but each occupies its own section. Each section has its number. Produce your check and take your hat (yours, and nobody else's). The sections of the wardrobe, its cells, all have their addresses—their numbers. Take, for instance, the instruction +475. It means that the number occupying cell 475 should be added.

The computer, like man, has "memories" of different kinds.

You'll smile recalling how you say aloud, when multiplying: "Seven times five is thirty five. We'll write five and keep three". The computer has to do the same. It, too, writes five and keeps three in its mind—memorizes.

Sometimes an address or a telephone number is needed only once. In this case it is written down on any scrap of paper that comes handy. Having telephoned, you throw it away. If you expect to use the address or the telephone once or twice more, you'll, probably, copy it into your note-book or address book. This contains data the need for which will arise in due time. This is a fundamental, long-time "memory".



Types of machine "memory".

The computer, too, has all these kinds of "memory". You'll find here the "scrap of paper", together with the "address book" of long-time "memory" and the note-book.

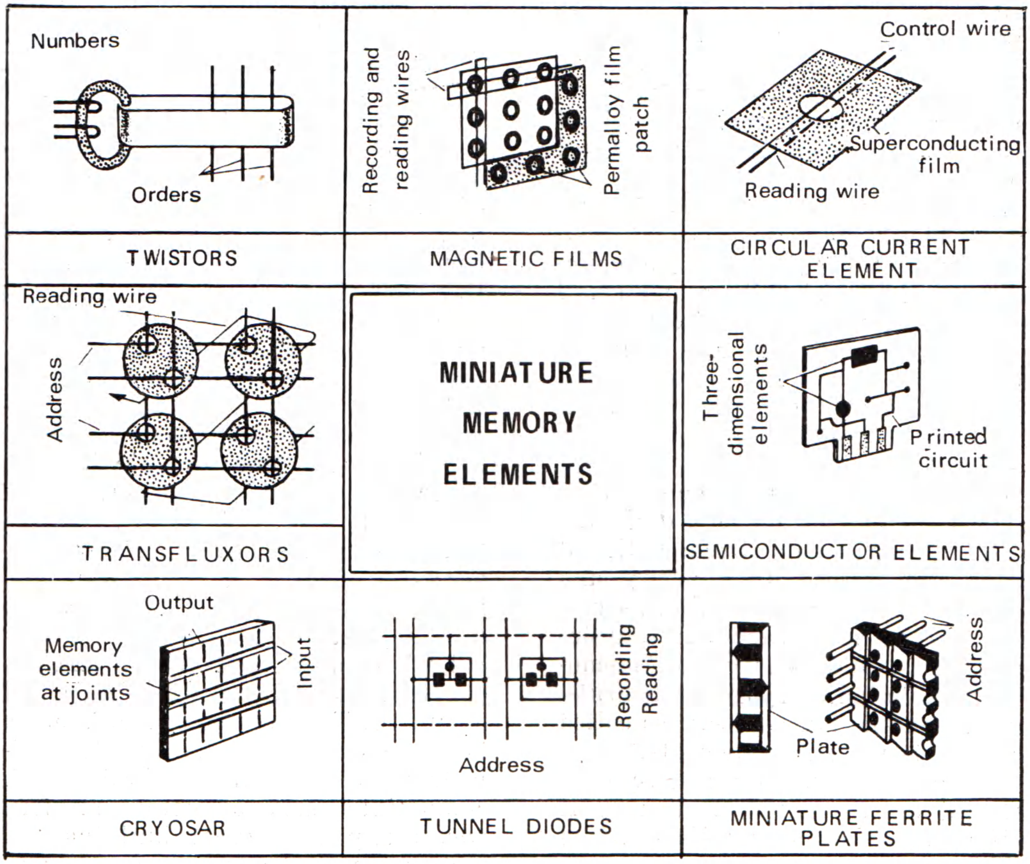
The "scrap of paper" is the working "memory" directly connected with the arithmetical blocks of the computer. The "note-book" is the long-time recording devices. They serve to memorize all information introduced into the computer that is needed in the course of solving the problem. The "address book" of the computer contains constant reference data, tables, coefficients—all that, like the multiplication table, may be needed in calculations. Hence, its name—the permanent recording block.

The capacity and operation speed of the computer "memory" are determined by its construction. It is interesting to note that these two characteristics are closely interrelated. The simplest type of "memory" is the magnetic tape. It's easy to increase its capacity just by increasing its length. But simultaneously the time needed to find a number on this tape will be increased, too. Tens or even hundreds of metres of tape must be turned over to find the required data.

Therefore, the device was adopted of increasing the capacity of the "memory" while at the same time decreasing the time needed to produce data, the so-called circulation time.

Magnetic tape drums enable recording blocks of practically limitless capacity to be built. With the recording density of one number per millimetre, 500 metres of tape can record 500 000 numbers; one hundred tapes of this length will hold $5 \cdot 10^7$ numbers. Compare this number with the number of signs in L. Tolstoy's novel *War and Peace*, which is only several millions. But in this case it will take

Designers endeavour to build reliable miniature high-speed memory elements.



several minutes to find the necessary cells with numbers. Most ingenious contraptions enabled this time to be reduced to half a second. However, this time is eternity for modern high-speed computers.

So magnetic drums were invented. The magnetic drum is, in essence, a very wide magnetic tape closed to form a loop. It contains many—up to eighty—recording paths. This requires a corresponding number of recording and reading heads.

The drum holds up to 30 thousand numbers, which are recorded, as on the tape, by magnetizing small areas of the surface.

The drum revolves at a high speed that sometimes reaches 12 thousand revolutions per minute. The necessary number, or group of numbers, is read or recorded in the time of one revolution.

It will not be an exaggeration to state that the history of progress in high-speed computers coincides with the history of the improvement of their "memory". Quite recently electron-tube "memory", as in a television set, was considered high-speed "memory".

Next ferrite-core "memory" was produced. Its speed of over 300 thousand circulations per second is coupled with high reliability and small space requirements: 1 cm^3 can "house" a thousand information elements (bits).

The working "memory" of most up-to-date computers holds up to ten million bits.

However, even such "memory" characteristics can no longer satisfy the designers, and they strive with all means to increase its capacity and data production speed. For this reason most recent advances in physics are being used to construct "memory": tunnel diodes, cryogenic elements, thin magnetic films—these so-called microminiaturization elements.

But despite such impressive qualities of the computer "memory", it still in many respects falls short of human memory.

The capacity of our memory, as has been assessed above, is enormous. Here is one more example to make the matter obvious. The total number of all electron tubes and transistors manufactured throughout the world is comparable to the total number of neurons in the brain of one man, the capacity of his memory being equal to up to one million billions of bits! And its reliability, too, is much higher than that of computer "memory". The more elements the memory blocks contain, the higher is the probability of their failure. If a complex "memory" aggregate contains millions of elements, it will not function properly because of frequent faults. The brain, on the other hand, despite the fact that it contains billions of neurons, works "without fatigue", the memory, practically, never stops and does not need repair.

Let's compare now the volume occupied by the memories of man and computer. The volume of man's brain is some one and a half cubic decimetres; and electronic brain with compatible semiconductor memory would require a great building 100 metres high. The brain's power consumption does not exceed ten watts; a hydro-electric station would be needed to power a corresponding computer "memory". However, much better results are now being obtained with integrated circuits (IC).

And, of course, there remains the paramount advantage that every one of us feels every minute. During our lifetime we register millions of events and impressions which accumulate to make our intellectual wealth boundless. This wealth is a powerful source of supply for man's emotional life. Man retains intact in his memory the colours of the setting sun of some evening in his youth, as well as hardly perceptible events from his private life.

We are tempted at this place to cite some examples from a book on bionics of how man memorizes impressions once received. The French graphic Gustave Doré (the author of well-known illustrations of François Rabelais' book *Gargantua and Pantagruel*) once received an order from his publisher for a copy of a photograph of an Alpine landscape. Doré went home and forgot to take the photograph with him. On the following day he brought an exact copy of the photograph. It's an established fact that the best portrait of President Lincoln was made by his provincial admirer who saw him only once.

The contemporaries of Julius Caesar and Alexander the Great credit them with knowing all their soldiers by name and by sight though they numbered as great as 30 000. It's rumoured that Mozart managed to write down accurately a long intricate symphony which he heard only once. The composer Glazunov had no difficulty in reproducing lost scores of long musical compositions. The brilliant pianist Rachmaninov had to listen to a piano concert only once to reproduce it correctly. The prominent chess-player A. Alekhine held in his memory all the chess games played and could simultaneously play with 30-40 partners without looking at the chess-boards.

Our memory is defined as associative.

Reminiscences follow each other in a logical process that guards the brain against excessive work by providing it with necessary information at the right moment, imparting to it a wonderful inventiveness.

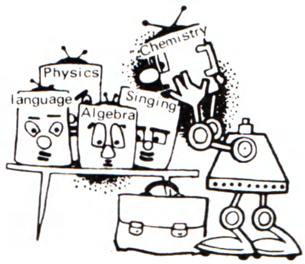
The "memory" of the electronic brain looks quite humble alongside this wonder of nature. Inferior capacity (as compared to the capacity of our brain) is not the main drawback of the computer "memory". Its tragedy is its impotence in searching for information on the "shelves" of the electronic or magnetic "depots".

To find a definite "reminiscence" the computer has to look through tens of thousands of information bits, just as a negligent store-keeper would look through his store to find a lost item.

True, scientists foresee the possibility of increasing the compactness of computer "memory" to that of the brain. If this materialized, the computer would be able to store in a volume of 1 cu m all information accumulated by mankind in all its history! This is equivalent to 100 000 billion bits of information. This gives us reason to hope for a practically unlimited working memory in the computers of the future.

It's a firm belief of modern science that progress in many branches of knowledge depends to a great extent on the solution of the problem of human memory and on the level of development of artificial computer memory.

That's why so much attention in this encyclopaedia is focused on this apparently narrow question.



"We've got chemistry today."

A plant equipped
with electronic computers.
Designed to carry out
complicated and labour-consuming
calculations.

The Factory of Numbers

This is a perfectly new type of plant. It's a factory that receives and processes raw materials quite extraordinary from the usual point of view and turns out quite extraordinary products—numbers. For this reason the name—the factory of numbers—has stuck to the computer centre.

Everything and in every way is calculated here! Mathematical, engineering and economic problems are solved, the so-called routine calculations are carried out, methods of numerical solution, methods of programming and methods of mathematical and technical servicing of electronic computers are developed, census results are worked out, pay is calculated, etc., etc. The task performed depends on the type of the computer centre.

Let's enter this CC, as it's termed briefly.

Without a guide we won't be able to find our way among numerous machines, sectors and services. Let's ask an expert from the sector of mathematical preparation to tell us about the work of the CC.

There are three main sectors in the computer centre. The first is the sector for mathematical preparation and for programming of problems. Programmists work here. They compile programmes—lists of rules in compliance with which the machines solve various problems. This is one of the main departments. It decides upon the manner in which the computers are going to "mill" mountains of numbers, and foresees what will come out of it.

To guarantee normal working of the "mathematical grindstones" there is another department—the maintenance sector. Highly qualified engineers watch computer operation, their condition, and provide for timely repairs.

Electronic computers are no simple units. They consume much power, their temperature rises. The premises where they are installed require ventilation.

Therefore, a sector of auxiliary equipment is needed whose employees watch electrical equipment and ventilation.

"Let's calculate something," proposes the guide.

He goes to the control panel and types on the keys like those of a typewriter: "January 29, 1970, the excursion of sixth-grade pupils from school No. 341 of the Bauman district of Moscow."

We take a long time to agree upon the problem to be solved. Meanwhile holes are being punched in the cards, and we are told: this is a problem being solved in accordance with the plan.

We will learn how it's being solved as we go through the shops of the "counting factory".

First we come to the key-board counting machines department. It reminds one of a big typing office. There are automatic arithmometers on special tables. They look like typewriters. The fingers of the operator run fluently over multi-coloured keys. He types numbers—items, multiplicants, dividends and devisors. By pressing definite keys the operator makes the machine automatically perform some arithmetical operation. A short buzz of the electric motor, a light clatter of the gearwheels, and the result is there, on the counter of the arithmometer. The operator enters the result on a blank. And his fingers are on the keys again.

We are told that it is no easy job to prepare for computing operations. There are some very complicated cases. For example, there are numerous factors that have to be taken into account in constructing a space rocket. It must be controlled from the Earth. The rocket has liquid-propellant rocket engines which enable it to rise to a great height. Its body houses extremely sophisticated devices, control system equipment, fuel and oxidizer tanks.

Before starting the design work, many calculations have to be made. It must be taken into account that such a rocket is launched vertically and at the start, during the first period of its flight, it passes through the densest layers of the atmosphere. The main part of its trajectory, however, passes in vacuum. The Earth's air jacket intensively decelerates the rocket. As a result of air friction the rocket's body is intensively heated. This, too, has to be taken into account.

Trajectories should not be computed with the aid of simple equations without taking into account the aforesaid factors. Otherwise a situation may arise of the sort in which the personages of Jules Verne found themselves when they failed to reach the Moon.

Of course, computations of this kind were not made in our presence. We saw only some auxiliary work—the checks of operation stages, of computation accuracy. The mathematicians can be said to follow the long path leading from the equations and formulae to tables and numbers. The flow-line production of all this gigantic mass will be done by powerful electronic computers.

They occupy the main shop of the computer centre. One wonders a little seeing such vast work being done so silently and unostentatiously. Only the light hum of the computer and the rattle of the typing device filling in long paper tapes with columns of numbers tell of the untiring work of the "mathematical mill".

The computer centre may be connected by special communications channels with the organizations it serves: with plants and factories, institutes and offices. This is the more economical and advantageous method that provides for continuity of work and for standardization of maintenance.

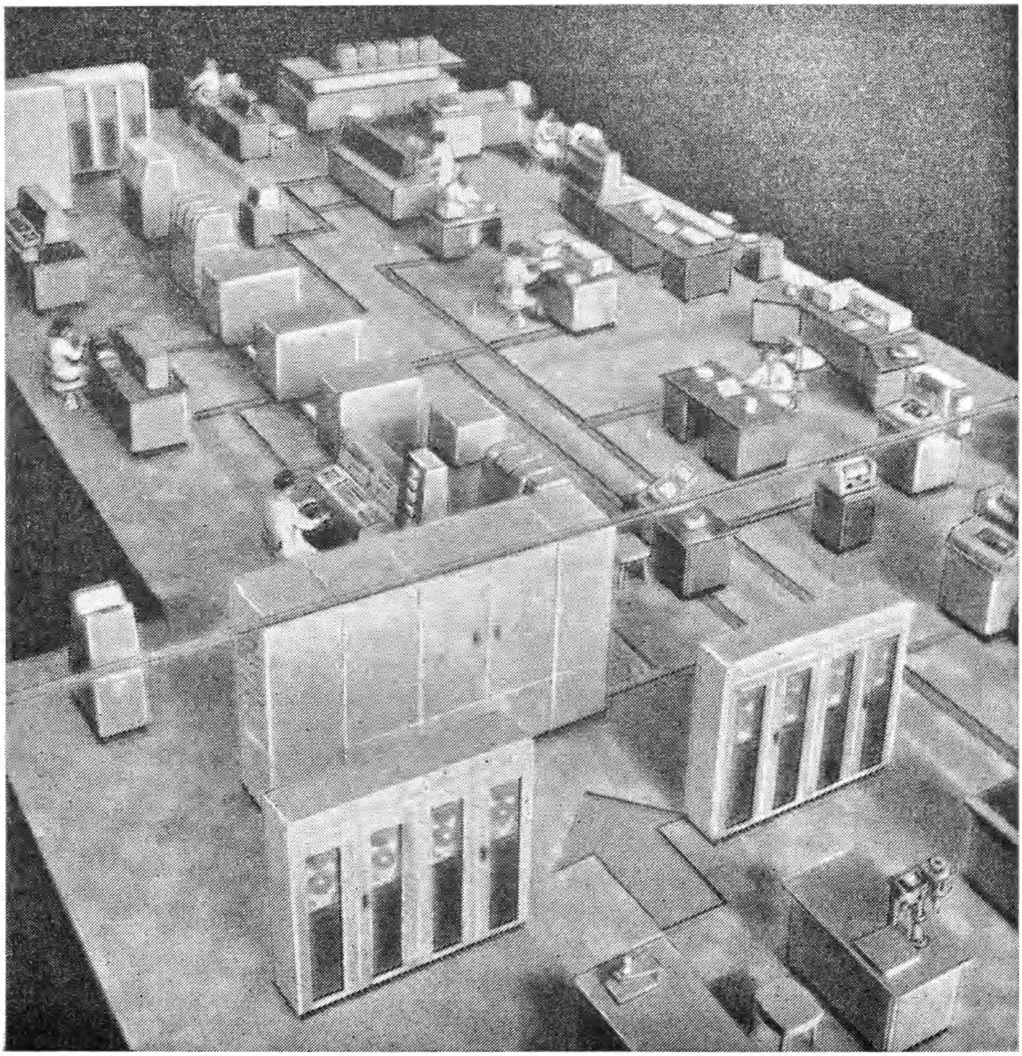
One computer centre can do the work of an army of calculators tens of thousands strong. Computation with the aid of computers saves millions of roubles. Even a small computer, say, "Minsk-22", brings 50 thousand roubles profit per year. Formerly, a computation requiring one year's work of calculators was unacceptable to many design bureaus. And now? Now a problem requiring a hundred years of calculators' work is considered simple. A common CC does it inside 24 hours.

Twenty-four hours instead of a hundred years!

Such a reduction in time needed for computation work opened up great possibilities in science, technology, in the control of national economy.

So you see what great feats are accomplished by computers assembled under the roof of a building the signboard of which bears the letters CC.

A computer centre.



Here's a first-class computer centre. The area of its premises amounts to 4000 m^2. Some 500 people work here, of them 150 are highly qualified mathematicians.

The centre has several big electronic digital computers. One of them works at a rate of up to a million operations per second. There are, as well, several sets of automatic calculating machines of simpler types and up to a hundred table key-board calculating machines.

The CC, like a big plant, works in three shifts. Computers are expensive. It is unprofitable to let such valuable equipment stand idle. Once a week "the number factory" stands still: there is no rattle of the typing devices, no monotonous hum of the computers. Expert engineers test, tune and carry out maintenance repairs—the computers must always be in a working condition. Should anything go wrong, and there will be a flood of mistakes on the tapes where the computation results are printed. The computers demand precision.

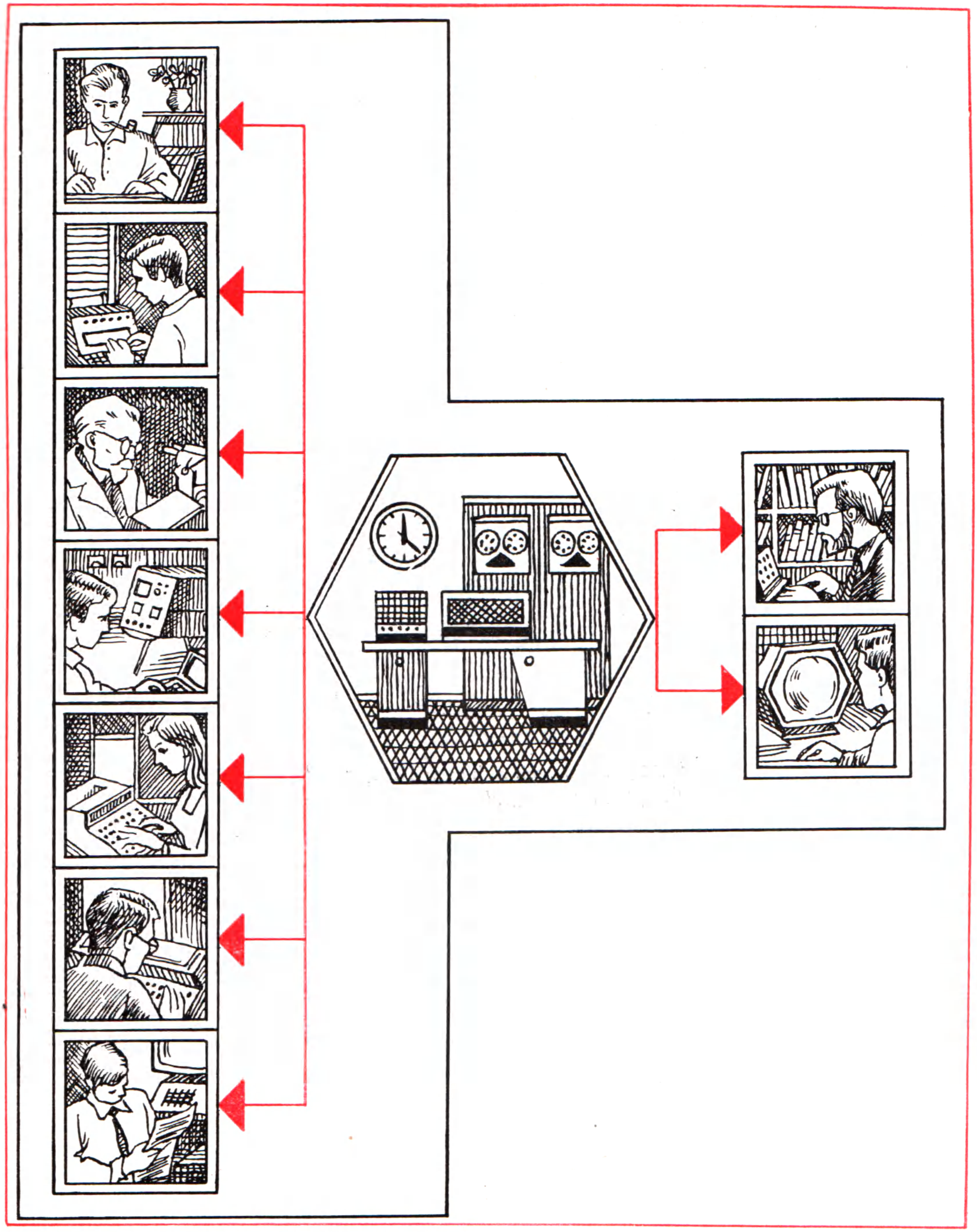
There are hundreds of computer centres in this country. Some of them are the so-called principal centres, for instance, the Computer Centre of the Academy of Sciences of the USSR, the Principal Computer Centre of the State Planning Committee of the USSR. There are computer centres working at the Academy of Sciences of the Ukraine, of Byelorussia, of Georgia, of other Union Republics of the USSR, in many of the larger cities. Nowadays powerful factories for the processing of numbers ceased to be a rarity.

Computer centres may serve various purposes: the general-purpose CC, CC for computations of plans and for economic studies, CC for branches of industry.

In the drawing you saw a general-purpose computer centre. Specialized CC are somewhat different. They may have a smaller number of low-power machines. Research work of a general nature, such as the principal problems of computer mathematics, is not done at a branch or a specialized computer centre, general methods of solving scientific problems are not developed here either. These centres carry out concrete computations in the field of planning of national economy, in economics. There is a lot of accounting and statistical work to be done here and of calculations for administrative purposes.

Recently a new trend in the use of electronic computers and of computer centres has developed. A tendency may be observed to "collectivize" them, to unite them into computer systems for collective use. These will be permanent systems to which several subscribers would be able to apply at any time for any reference, for any computation, because they

Computer employed in the divided time mode to serve multiple subscribers. This makes a dialogue between the subscriber and the computer possible. This faculty of information exchange exists for several subscribers as well. Tens of distant subscribers, too, may be connected to the computer. ▶
Several types of such connections are shown: a scientist in his flat, an engineer in a design office, a research worker in his laboratory, a scientist at an institute, a secretary preparing matter for print, a mathematician, a newspaper editor, an historian, a physicist.
The automatic distribution of computer time is much more efficient than the usual mode of employing computers; it saves time and money.



will be operating in the so-called divided time mode.

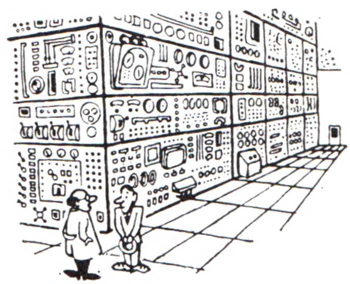
This is already a communal-purpose CC.

It can be used in the same way as we use water, gas, electricity, telephone.

Since the computers will be equipped with universal input and output devices which can read normal type, typed messages, produce visual data, record oral messages and receive oral commands, the communications with them will be by means of telephone or television.

In other words, electronic computers, their immense "memory" reserves, the centres of information and computation centres will be freely accessible, without go-betweens, irrespective of time and distance.

In the near future it will be as difficult to find "individual" computers (serving one plant), as it is now difficult to find a plant with a private power station. It is much more economical and profitable to draw power from a single nation-wide power system.



"Did you ever work with such a computer?"
"No, but I'll manage."

A computer employed for automatic control of a complex object.

Where Man Is Inadequate

For a better understanding of the importance of control computers for modern industry let's start the story about them from the very beginning. Let's together with engineering specialists make a historical survey and assess the role of the machine in human life, to be precise, in industry.

As is well known, even primitive machines imitated the faculties of man. For example, first machines increased man's strength. Objects could be transported, moved and lifted with the aid of a lever or a block.

After machines used to transform and increase force came the turn of machines that effected mechanical motion.

Let's take another faculty—precision. The invention of vice for fixing objects led to the precision of their working being improved. This, if you like, already constituted a step from the transformation of force and of motion to control.

Later another problem sprang up: how to effect control of a sequence of operations, how to go over from one product to another.

Man does it easily—he's got a special "control device", the brain. When first computers were built, it became possible for the first time to devise artificial systems for such complex control operations.

But there are different types of control—there is a true hierarchy of them, depending on the level of control. In modern conditions with the aid of modern technology it is not difficult to make a lathe work properly. But to make the lathe work efficiently, as well, a higher level of control is needed. To this end a more advanced faculty of man should be copied—that of acting rationally.

And now let's make another step up the hierarchy of control—we're ready for it.

Let's take a whole factory with numerous machine tools. You'll have to agree that its control is of a higher order, since in this case the bounds of man's abilities to do without specialized electronic assistants are exceeded. People nowadays can make plans for the operation of a factory, and get some results. But because of a large amount of initial data they are unable without some kind of assistance to arrive at a correct plan for the complex utilization of all tools, that would take account of raw materials reserves, orders, and other conditions.

Let's take this example. The old Putilov plant at the dawn of the 20th century produced machines made exclusively of metal. Nothing but coal, coke and pig iron was transported to this plant from other plants.

Now the same plant has hundreds

of subcontractors, because its products are much more intricate. Some of its machines even have electronic devices and blocks installed in them. Tens of thousands of parts made by other plants are needed to make these new products. Try to synchronize, to combine everything into a single complex—the operation of the tools, the work of the employees, the arrival of raw materials, the completion of products—so that there is no interruptions or delays, so that the whole plant functions like a well-tuned engine.

It's in such cases that intricate control devices are needed.

See how useful was this short excursion into history—step by step we covered the distance from simple machines capable of increasing man's strength, of aiding his muscles, to intricate machines designed to increase man's control abilities, to automatic systems capable of supplementing the human nervous system, the brain.

Scientists have calculated that in modern industry the power of one worker equivalent, on the average, to 0.1 hp is increased by his mechanical assistants to the mean value of 1000 hp. An analogous degree of amplification of intellectual abilities could be obtained, too. Control computers are now playing the part of such magic amplifiers.

What are the properties peculiar to them?

First and foremost, they are principally different from other machines. It's an absolutely new class of man's assistants—not machine tools, or engines. Control computers transform information into control processes. And this, as a rule, involves calculations.

The task of control computers is to maintain normal or maximum (but always efficient) operating conditions, maximum productivity, high product quality, minimum costs of labóur, raw materials and power. Those tasks are difficult tasks, as you see.

Here is the Soviet "Dnieper" control system.

It can do the job of an accountant, of a steel-maker, of an economist, or of a pilot. All depends upon the programme which has been introduced into it. "Dnieper" has been used with success in the steel and shipbuilding industries. It's also been used to process the data of complicated physical experiments.

The system consists of two parts: a central device—an electronic computer, and a control complex. In accordance with its programme the operating computer "interrogates" several hundred gauges installed on objects under control. Next, it processes the information received and sends instructions to the objects.

Let's watch the control device controlling a powerful rolling mill.

Red-hot 20-ton steel slabs over half a metre thick radiating unbearable heat leave the furnace and pass through the 12-roll stands of the rolling mill to turn gradually into thin steel sheet. This is an enormously difficult job to roll a steel slab into thin sheet, and an extremely exacting one—the deviation in the thickness of the sheet from the standard value must not exceed several hundredths of a millimetre.

Elongating as it is being rolled the steel moves between the rolls of the last stand at a speed of 900 metres per minute or nearly 60 kilometres per hour. And despite this speed, control gauges installed along the rolling path manage to report to the control device the thickness and the stress of steel at various stages of the rolling process. Zonal regulators will measure the temperature in the furnace and correct it, special gauges will mark the changes in metal.

The cybernetic commander will re-arrange all incoming data, compare it with the standard recorded in its "memory" and instantly decide what corrections are needed in the speed and pressure of individual rolls to ensure the required thickness of the rolled sheet.

A deviation of 0.13 mm from the specified thickness of the sheet is considered normal. The controlling device managed to reduce it to 0.076 mm—nearly twofold!

It was not overnight that experts in automation succeeded in building such perfect computers for the control of technological processes. During the first experiments in the use of computers operators introduced into them data they read off the instruments. On the basis of this information the electronic computer evolved directions for the tuning of control devices. Naturally, the operator retarded the control process. Moreover, he was not a very reliable part of such a system. Then it was decided to connect the instruments directly to the computer. Now it could itself read off data needed for computations. But still the operator had to tune the control devices in accordance with computer directions.

Only the third stage of control improvement resulted in full automation. It involved the direct connection of measuring and control instruments and control mechanisms with the computer. And what did this lead to?

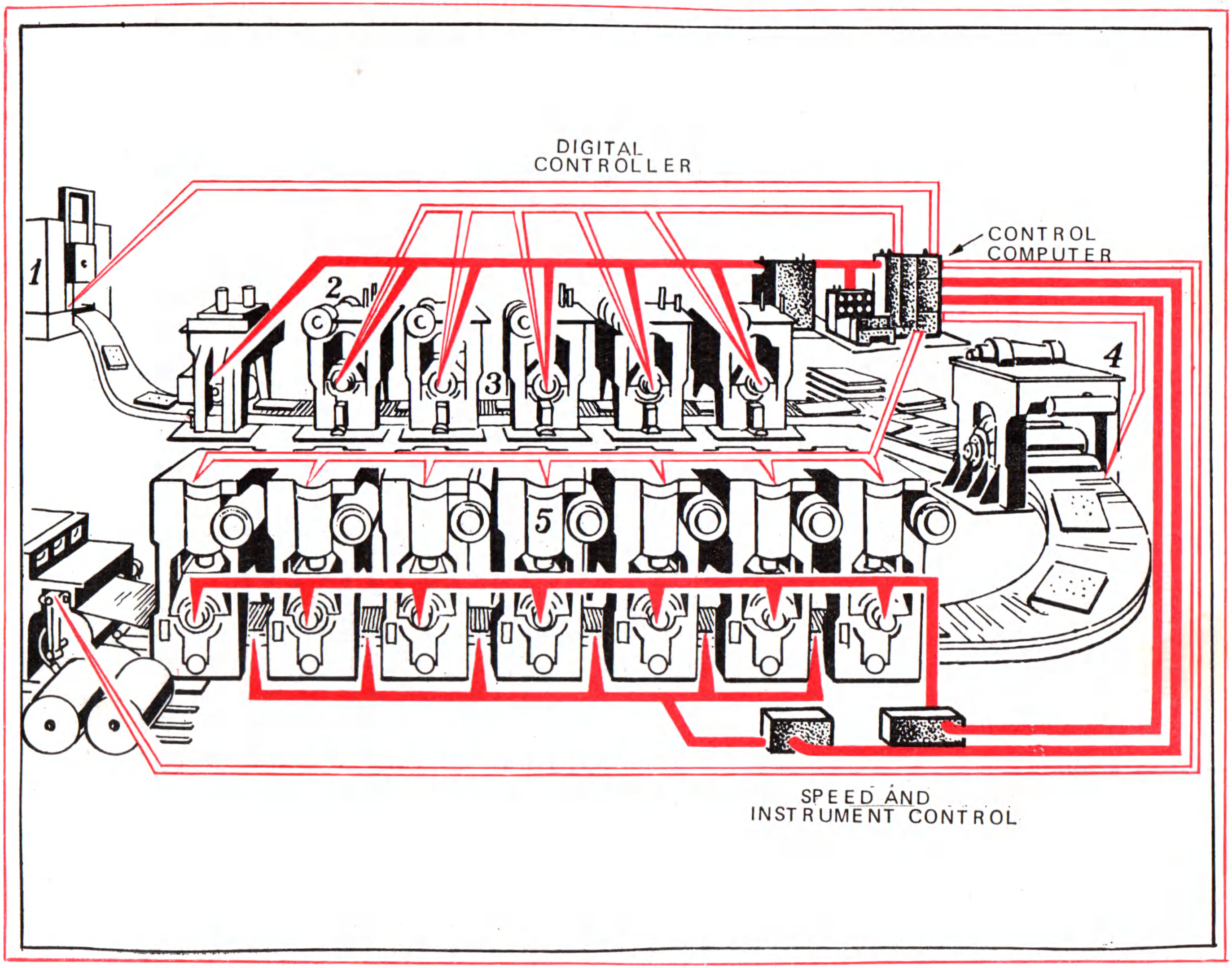
Let's take a specialized paper on the subject: "The computer connected with hundreds of gauges through its own communication system quickly collects information about deviations from the standard technological process and analyses these data. It can find out with fantastic speed what takes place, say, in a rolling mill or in a chemical plant, where accurate determination of the course of the process involves thousands of calculations. Having analysed the situation the computer decides quickly how valves, injectors, rollers and sundry mechanisms should be regulated. Then it takes appropriate action. Through the communications line it sends instructions to organs controlling individual mechanisms of the aggregate, ordering them to carry out the necessary tuning.

"Literally without the slightest interference by man the computer can repeat the operation several hundred times a day, week after week, using free minutes to type concise reports of its work."

First results of computer application were the most impressive in four major industries: power, metallurgical, oil-processing and chemical. Why? They all belong to the so-called mass production type with numerous control parameters.

To automate power production the readings of thousands of control instruments must be taken into account.

The control system must carry out some 1000 control operations in sequence only to put a thermal power


DIGITAL CONTROLLER
CONTROL COMPUTER
SPEED AND INSTRUMENT CONTROL
1
2
3
4
5

station turbine into full operation: it must watch the cooling, the water level in the boilers, the flame, etc.

But this turns out to be only the beginning of a difficult work. Having put the aggregate into operation, the computer must control the temperature and the pressure of the steam, and the speed of the turbine according to the readings of 1560 instruments.

And this is its everyday work. It has also to be on a look-out for emergency situations—everything can happen in a power-station. Should gas (the usual fuel) be cut off the computer will carry out fifty operations to change the burner over from gas to oil (the reserve fuel). Even when a turbine bearing fails, the computer commander is not terrified. It is capable of switching off the colossal power plant in the spell of several minutes.

In addition, the computer simultaneously calculates technical and economic data, sums up report data, calculates the efficiency coefficient of the plant.

There is one more property left to complete the description of the control computer—it makes no mistakes.

Now is the time to revert to the hierarchy of control, to the higher and lower levels of it. One of the initiators of control systems development in the USSR, Academician V. Glushkov, defines their tasks in these words:

"For the lower control level comparatively simple highly reliable computers are usually chosen. Their task is to work with the object of control on the real time scale. Each of the lower-level computers can do the job of several tens or even hundreds of automatic regulators. A higher-level computer is a much more intricate machine with a much more complicated structure. Such a computer works with up to several tens of lower-level computers, and is engaged, as a rule, in optimizing calculations, planning and organizing the work of the system as a whole."

Now you see that the step-by-step, hierarchical structure of control systems automatically leads to a natural change over to systems controlling entire factories, firms and even industries.

This to a greater degree obviates the need for continuous inspection of the automata by man. All control and regulating functions are concentrated in one block.

Man ruling over the production process plays the part of a strategist, because now he is free from the necessity of solving minor problems of operation, from the routine everyday factory work.

Meet the control system of the Lvov television receiver plant. Its name is "Lvov". It's a system typical of mass production plants. It can be connected to the country-wide system of economics control. In one year "Lvov" helped to achieve a 20-per cent increase in production

◀ The control computer in control of a rolling mill. Steel slabs pass through the furnace (*1*), pass at great speed through a row of mills: cutting-off (*2*), rolling (*3*), grinding mill (*5*), and finally leave the rollers of the coiler in the shape of thin sheets. The dashed line shows the route of input data to the control computer; the solid line shows the route of instructions to control centres and thence to individual instruments.

due to a more efficient utilization of materials, a better adherence to the time-table, an improved technology and advanced organizational and technical control.

It really is an unheard-of thing—an increase in television sets production by nearly 20 thousand without any increase in production equipment.

The main part in the "Lvov" control system is played by the electronic computer "Minsk-22". It receives information about the progress in the work from the technological production scheme as well as from the product counters installed on the assembly line and in the product control department. The control is aided by a whole complex of means of traffic control: television sets, telephones, signalling system, light boards of different sorts. Rapid printing devices make out summary reports. All documentation in the plant is transacted so as to facilitate its feeding into the computer.

The industry of the USSR already employs several control systems. In addition to "Dnieper" and "Lvov" there is, for instance, the "Complex". It's an expert at controlling large thermal power stations. The "Cascade" has no rivals in the art of controlling ammonia plants. The "Taiga" is a real commonwealth of sixteen "Angara" electronic computers and two "Baikal" computers. Such a powerful system proved necessary to control the gigantic paper-chemical mill—the Bratsk wood-processing complex in the Irkutsk area.

The science of the general
principles of control,
means of control
and their utilization
in engineering, living organisms
and human society.

What's Common to Oranges and Kings?

A little over a hundred years ago André Marie Ampère, the French physicist and mathematician, completed a voluminous work *Essai sur la philosophie des sciences (Essays on the Philosophy of Science)*, in which he sought to systematize the human knowledge of his day. In it he classified all the known sciences of his day under different numbers, leaving a few numbers for conjectural sciences. Under number 83 he listed a science that was to deal with the methods of regulating society. Ampère termed this science "Cybernetics", from the Greek word "kybernetes", meaning "steersman", "helmsman". In fact, in Ancient Greece cybernetics was the science of ship navigation.

In his classification of sciences Ampère placed cybernetics under the general heading of "Politics" which he defined as a science of "the first order". As such, he subdivided it into sciences of the second order (among which, incidentally, he included the science of coexistence), and of the third order, to which he relegated cybernetics, the science of control.

Ampère also provided each science with a versed motto in Latin. For cybernetics he provided the highly symbolic motto: "... *et secura cives ut pacè fruantur*" ("... and secures for citizens the possibility of enjoying peace").

After Ampère, however, the term "cybernetics" was forgotten until it reappeared again in 1948 in a book by the well-known American mathematician Norbert Wiener entitled *Cybernetics or Control and Communication in the Animal and the Machine*. Although the laws invoked by Wiener as the basis of cybernetics had been discovered and investigated long before he had written his book, it evoked widespread interest among scientists of many specialities.

The cornerstones of cybernetics are information theory, the theory of algorithms, and the theory of automatic systems which investigates the methods of building data-processing systems. Its mathematical apparatus is extremely extensive and includes the theory of probability, the theory of functions, mathematical logic, to name but a few.

Among the major contributors to the advancement of cybernetics have been the biological sciences which study control processes in living nature. But the decisive factor in the new science's emergence was the swift development of electronic automation and especially the appearance of high-speed computers which opened up literally boundless vistas in data processing and the modelling of control systems.

Just as the composer seeks to express all human emotions and moods in terms of musical notation, so cybernetics seeks to express all situations and processes in nature and in human conscience in terms of digits.

The foundations of cybernetics were laid and its basic principles formulated over centuries by the work of mathematicians, physicists, physicians and engineers. Of outstanding importance were the works of American scientists Claude Shannon and John von Neumann and the ideas of the world famous Russian physiologist Ivan Pavlov. Historians note the important contributions of such outstanding engineers and mathematicians as I. Vyshnegradsky, A. Lyapunov, and A. Kolmogorov.

It would, in fact, be more correct to say that 1948 saw, not the birth but the christening of cybernetics as the science of control. By then the problem of improving the quality of control in our complex technological world had become especially acute. It was cybernetics that blazed the way for applying precise scientific analysis in solving problems of control of modern technological hardware.

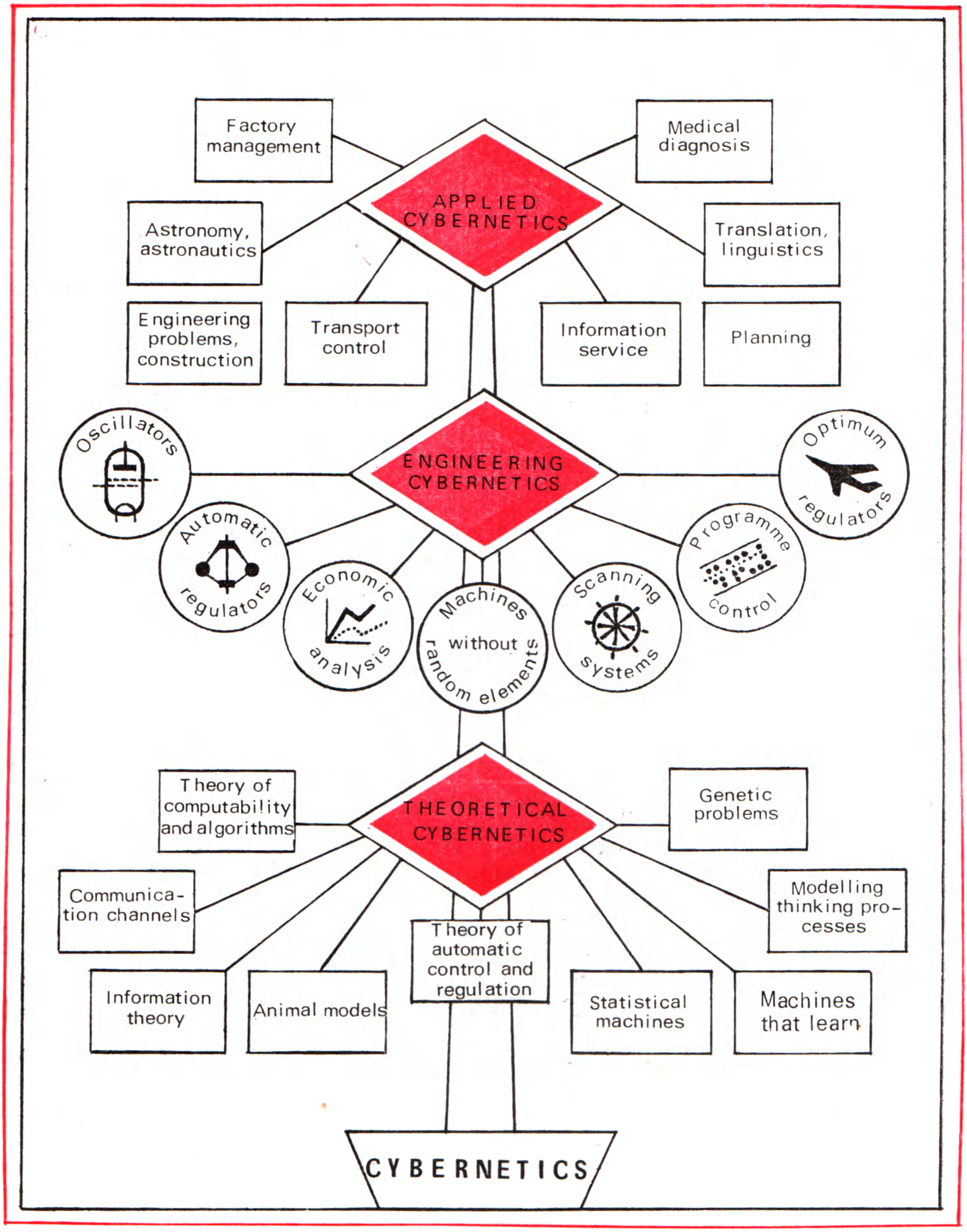
Nowadays cybernetics is a fashionable word bandied about in sundry engineering, scientific and popular journals. Cybernetics is the subject of books and lectures, scientific seminars and international conferences with the participation of mathematicians and physicists, biologists, physiologists and psychiatrists, economists and philosophers, engineers of various specialities. They are all united by the common goal of achieving maximum automation of control processes in various spheres of human activity and of enhancing labour productivity. And this requires a deep and comprehensive study of controlled and controllable systems, knowledge of the laws governing control processes, and determination of the principles governing the organization and structure of control systems. Inevitably, the living organism became the object of the closest scrutiny and thorough investigation: man himself represents a control system of the highest order whose functions engineers and scientists would like to reproduce in automatic gadgetry.

Cybernetics studies the common properties of different control systems, properties which are quite independent of their material basis. They can equally be manifested in living nature, in the organic world, in human collectives.

These common properties manifest themselves in many ways, and primarily in the structure of complex dynamic control systems. There is a continuous exchange of information between the controlled object—whether a machine or transfer line, an industrial enterprise or military unit, a living protein-synthesizing cell or a muscle, a written text for translation or a set of symbols to be made into a work of art—and the control unit—the brain and nerve tissue of a living organism or an automatic regulator.

The control process always and everywhere involves the transmission, accumulation, storage and processing

The tree of cybernetics. ▶


Factory management
Medical diagnosis
APPLIED CYBERNETICS
Astronomy, astronautics
Translation, linguistics
Engineering problems, construction
Transport control
Information service
Planning
ENGINEERING CYBERNETICS
Oscillators
Optimum regulators
Automatic regulators
Programme control
Economic analysis
Machines without random elements
Scanning systems
Theory of computability and algorithms
Genetic problems
THEORETICAL CYBERNETICS
Communication channels
Modelling thinking processes
Theory of automatic control and regulation
Information theory
Animal models
Statistical machines
Machines that learn
CYBERNETICS

of information about the controlled object, process, environmental conditions, work programme, etc.

Obviously, the nature of the information carriers may vary widely from system to system: sound, light, mechanical, electrical or chemical signals, punched or magnetic tape, master patterns, etc., may be employed. The important thing is, as mentioned before, that, irrespective of the material carrier of information, the processes of transmitting it obey certain common quantitative laws.

A characteristic feature of the whole diversity of such systems is the feedback. Through it they receive information on the effects or results of their control operations.

Finally, the control systems—living and man-made—incorporate elements performing similar jobs: the receiving, classification, memorization, etc., of information.

On page 84 is represented the "genealogical tree" of cybernetics which offers vivid illustration of the scope of its applications.

Cybernetics can be subdivided into theoretical (mathematical and logical basis and philosophical problems), technological (design and operation of control and computer hardware) and applied (use of theoretical and technological cybernetics for solving specific control tasks in industry, power supply, transport, communications, etc.).

The remarkable similarity of control processes in systems of entirely different nature provided the basis for the development of cybernetics, which uses mathematical methods to study control systems and processes.

This definition of cybernetics reminds us that its subject of investigation is, primarily, quantitative laws, quantitative relationships in control processes.

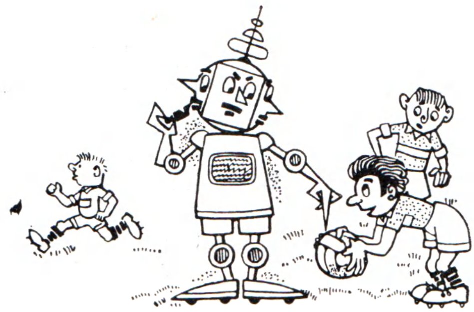
It should be noted that cybernetics does not identify processes which take place in the living organism or society with processes in automatic systems. Nor is it interested in specifically biophysical or biochemical processes which characterize living nature. It restricts itself to investigating how a living organism or machine processes the information relevant to the control process. The same holds for society.

Cybernetics seeks to discover common features of the two control systems. It studies human thinking to create algorithms more or less faithfully describing the operation of this living control system. It also studies the automata design principles and investigates the possibilities of using them to mechanize human mental processes. Thus cybernetics enriches engineers engaged in creating complex automatic systems with the experience of nature which over millions of years has evolved the most complex system in the world, the human organism.

Cybernetics also helps physiologists and psychiatrists in their investigations of this organism, in discovering the quantitative laws governing the functioning of living control systems.

Cybernetics helps to discover various laws in economics and sociology.

That is why the theoretical and practical importance of cybernetics is so great and diversified. And that is why an ever increasing number of scientists are devoting their creative efforts to the advance of this most promising and exciting of sciences.



Application of the methods and means of cybernetics to the study of living organisms, to building models of their functions and to the creation of devices for maintaining normal body functioning.

Living Matter under the "Microscope" of Numbers

We shall begin our discussion of the applications of cybernetics in biology with a confession made by the celebrated cybernetician and physiologist, Walter R. Ashby: "The second peculiar virtue of cybernetics is that it offers a method for the scientific treatment of the system in which complexity is outstanding and too important to be ignored. Such systems are, as we well know, only too common in the biological world."

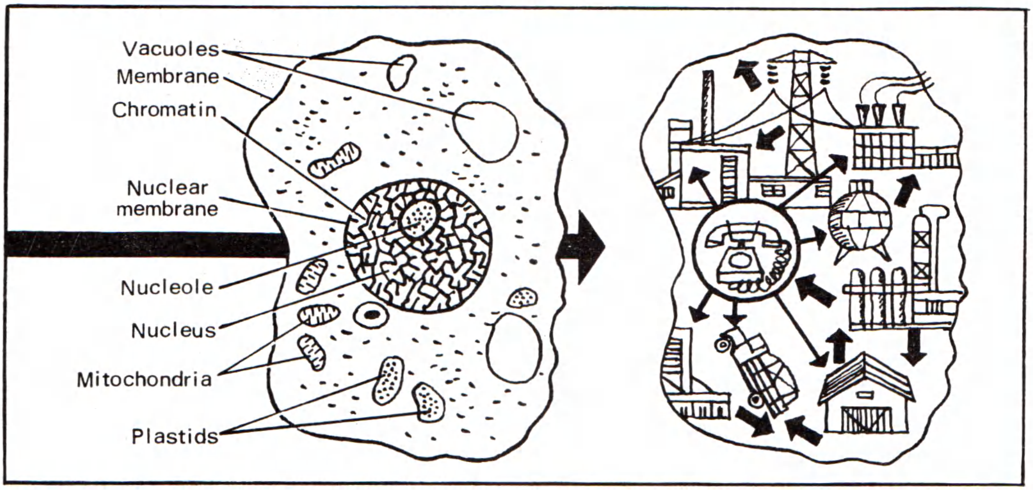
One doesn't have to go too far to find confirmation of the Complexity of Biological Systems: take the human brain. Not so long ago it was thought to be made up of some 14 000 million neurons intricately interlinked and connected by nerve fibres with all body organs and tissues. And the newest data indicate that the brain's complexity is in fact much greater. The cerebellum — the controller of the central nervous system — has some 100 000 million cells.

Nor is the cell itself a simple structure. It is a diversified enterprise with different "shops" and "workplaces", with its "power supply", "time service" and "transport means".

The complexity of the biological world is acknowledged universally. But it is additionally compounded by the enormous changeability of biological phenomena. Take the leaves of a tree. Can you find two absolutely identical ones in size and shape? Or, when a scientist takes a mouse or a frog for an experiment, can he ever expect to find all the animals' organs in exactly the same state even if the animals are precisely of the same age and weight? Take another example. A man's height is considered a relatively simple characteristic. But how it varies! The smallest known height of an adult is 38 centimetres, the greatest is 283 centimetres.

Besides being extremely complex and changeable the biological world possesses another important characteristic: dynamics, eternal motion, continuous work. A never-ending process of coordination of the work of different organs goes in every living organism; there is a continuous stream of information on the state of its systems; conditions of the environment, temperature and pressure are always maintained constant.

Complexity, changeability and dynamics present the greatest difficulties in the study of living organisms. Biologists view with envy the charts and diagrams



The living cell can be likened to an integrated industrial plant.

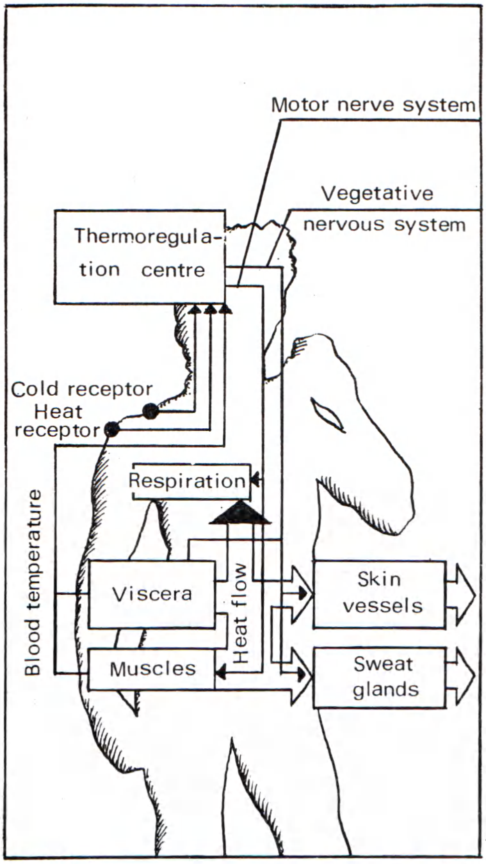
of physicists, chemists, engineers. The data obtained in experiments can be represented on them in consecutive series of dots which reveal to the specialist the laws governing the phenomenon under consideration.

It is extremely difficult to grasp, describe and represent graphically the complexity of living systems. This is the complex, tangled world which cybernetics is invading through two main gates at the termini of its two main directions, theoretical and applied.

This subdivision as it were delineates the spheres of activity of cybernetics in biology: the purpose of theoretical research is to elaborate problems connected with the investigation and description of various control functions, control "motions" in the body. This is "internal" cybernetics. It seeks to understand how various control and controlled systems function within the organism, what communication channels transmit the signals about various actions.

Scientists study with great interest the processes of self-regulation and feedback in living organisms. Their role was underscored by one biologist, who declared that life originated with the origination of the first feedback and control process; in fact, self-regulation is recognized as a universal law of life.

Cybernetics provides biologists with the invaluable method of mathematical analogues. It is employed by workers of the USSR Academy of Sciences Biophysical Institute and the Ukrainian Academy's Cybernetics Institute to study the role of feedback in biochemical processes at molecular level. Latvian scientists, for their part, decided to probe the secrets of protein synthesis in the living cell. The cell functions as a fully automated protein "factory" performing a



The human body's ability to maintain a constant body temperature is a result of complex regulation processes.

most complex biological process. For this they devised several programmes which they fed into a computer. In other words, they constructed an electronic model of the cell. Thanks to this approach they were able not only to answer the questions they had set themselves originally, but they also attempted to use the machine model to study the cell's responses to viral action and the introduction of various drugs.

The cyberneticians have built a veritable electronic zoo with "tortoises", "mice" and "dogs". The purpose is to use the machines to study animal reflexes, how they appear, how they are reinforced.

Let us meet some of the "old timers" of this "zoo".

Here are the famous "tortoises" of the English engineer and psychiatrist, Grey Walter. Their names are Cora, Elmer and Elsie. They were built with the specific purpose of providing a mechanical model of one of the primary properties of living creatures: the ability to carry on an exchange of energy with the environment and alter that exchange in accordance with changes in the environment.

What can the "tortoises" do? They can sense and skirt obstacles. They can meet and part. They can even dance.

How do they operate?

The idea of the "electronic tortoise" is clever and exquisite, says the researcher. Imagine a photoelectric cell that generates electricity used to charge a small storage battery. If a lamp burns too long before the photoelectric cell a moment may come when further charging can damage the system.

It becomes necessary to switch something off, either the lamp or the cell. This is the system's natural property, a condition for its faultless operation.

Now let us place the system on wheels, provide it with a motor and an automatic control unit which, working jointly and powered by the battery, will steer the system away from the light at the right time. And conversely, when the battery's charge drops to a dangerous low level the control unit must steer the system to the light source to replenish its energy reserves.

The most significant thing is that such a system does not require external guidance and all its actions derive solely from its internal state.

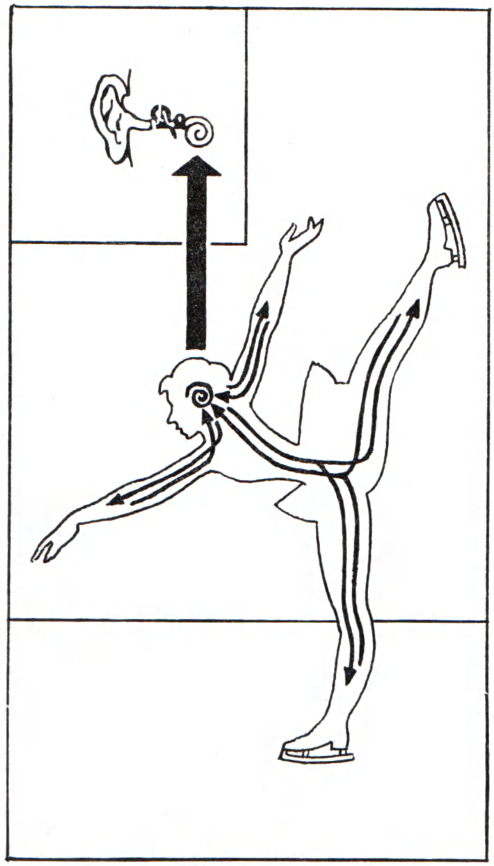
Mechanical rivals of Walter's "tortoises" are the "mice" built by the American scientist Claude Shannon.

... A changeable aluminium maze made up of 25 cubicles: five rows of five. At one end is a "bait" in the shape of a metal rod. The model is activated, and the "mouse" starts crawling through the maze in quest of the bait. It encounters walls, turns from one cubicle into another, changes its direction, trying to reach the "titbit" prepared for it by the researcher. And finally it reaches its goal.

Now the "mouse" is let into the same maze for a second time. This time it doesn't grope its way, blundering into walls, but easily, quicker than a live mouse, finds its way from one end of the maze to the other.

When the "mouse" is placed in the part of the maze it hasn't visited before it again bumps into walls in search of the way. But as soon as it reaches the "familiar" road it quickly reaches its goal.

A relay control system under the maze directs the "mouse" to make the right turns. The "mouse" is equipped with a pair of metal "whiskers" with which it "feels" its way along the walls. It also uses a "memory" device to mark the passages along the route and to "block" entrances to corridors through which it had already passed. When the whiskers finally contact the "bait" they

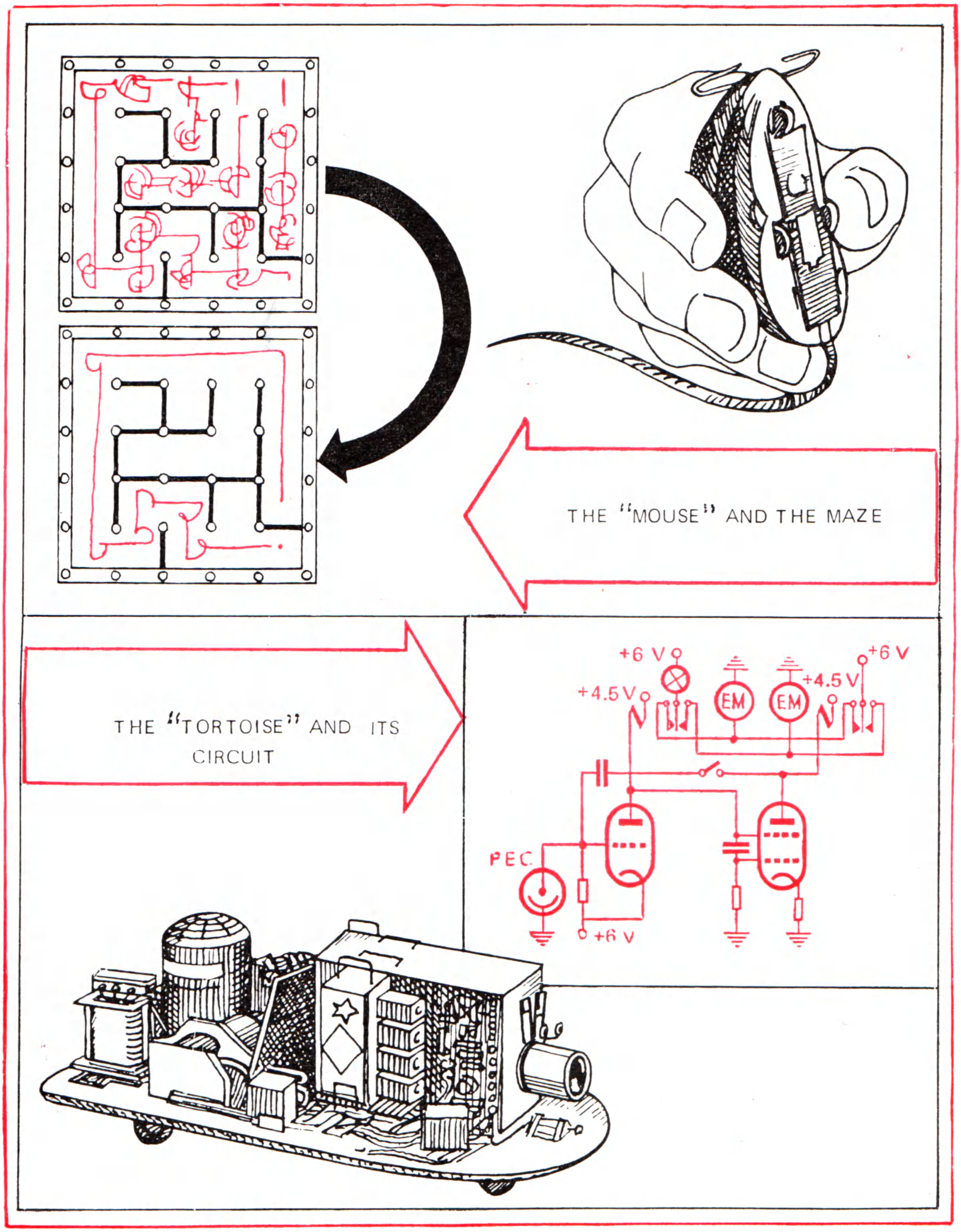


The vestibular mechanism is an example of feedback in the organism.

halt the mechanism. Thus, the memory unit traces the shortest route, enabling the "mouse" to pass quickly through the maze on its second run.

Obviously, the operation algorithm of the mechanical mouse is as different from the algorithm of a conditioned reflex as the feet of a real mouse are from the wheels which carry the piece of hardware through the maze.

Workers in our country have also


THE "MOUSE" AND THE MAZE
THE "TORTOISE" AND ITS CIRCUIT
+6 V
+4.5 V
EM
EM
+4.5 V
+6 V
PEC
+6 V

built a "mouse in the maze" device. Plastic lamina on the cover of a black valise form a fanciful pattern like leafless branches and twigs. A similar pattern can be observed on the glowing wall panel of an automatic blocking system at which a railway dispatcher works.

The plastic strips represent the tracks, the lights between them are the stations. There are 25 of them. Each one has its own switch. When it is flipped over one of the station lights flicks on.

Now the thirteenth flicks on. We press a button and the strips representing tracks flash on one after another. This is the light signal, which passes along the sidings on its way to the destination.

Try and press the button a second time. All the lights on the panel go out, then the beam of light, bypassing the now unnecessary sidings and spare tracks, takes the shortest route to the thirteenth station.

A red light glows at the left-hand corner of the panel. This is the memory indicator. It measures the time it takes the unit to memorize the route.

Here is another representative of this unusual "zoo": an electronic "squirrel". It rides a platform driven by a motor and is provided with two sensitive photoelectric cells, a filter that can distinguish between direct and alternating current, and other gadgets.

The "squirrel" has two paws which it can cup together. It also has a little tongue with which it can "lick" its cupped paws, and a metal tail which drags over the floor behind it.

Here is how this little "animal" operates. Electric lights are burning in a big room. White beads are scattered over the floor. In one corner is a metal sheet lit by a daylight lamp, the "squirrel's nest". It is brought in and placed on the floor. The "squirrel" begins to move about the room until it spots—with the help of its photoelectric cells—one of the white beads. It turns to the bead, scoops it up, "tastes" it with its "tongue" and then turns to look for its "nest". The electric filter enables it to steer towards the daylight lamp.

When the "squirrel" mounts the metal sheet its tail closes a circuit, it opens its paws and drops the bead into its "nest", after which it is free to continue its search for food.

To be sure, all these "tortoises", "mice", "squirrels" and other "animals" are very approximate models of conditioned reflex formation. But they have helped men approach a new stage in studying nature: investigating organisms by the method of models.

In biology not only organisms, but processes, too, are simulated. By building analogues of biological processes we can verify in practice the correctness of our theoretical constructions and postulate hypotheses for experimental verification.

Imagine a colony of living organisms living in favourable conditions. Their numbers will change depending on their birth and death rate. But

◀ Electronic "animals" are used in the search for methods of studying organisms with the help of models.

how, according to what law? The birth rate is affected by the available food supply, suppression by other species, life expectancy and many other factors. Scientists have built so-called abstract models and used them to establish the precise laws of development of organisms in circumstances of unlimited food supply and living space, in the absence of harmful species, and in conditions of hunger, limited living space and harassment by predators.

Such a model was used, for example, to help in growing penicillin fungi. They were fed abundantly, provided with ample space for growth and sheltered from predatory species. And the future harvest was predicted accurately by means of a special formula.

Interesting facts are provided by a model of the stabilization of the number of two species, one of which is a predator with respect to the other. Running ahead, we can say that the "prey-predator" model offers mathematical proof of the usefulness of predators.

Suppose we decide to destroy all the wolves so as to increase the number of their prey—herbivorous animals. The model revealed that annihilation of the predators may result in a brief burgeoning of the population of their prey, followed by a sharp drop and almost total extinction. And in fact biologists have observed a marked deterioration of herbivorous stock wherever wolves have been eliminated: ailing animals abounded, the offspring grew smaller. The wolves, it was found, performed a very useful function by destroying unviable animals.

As you see, simulation of biological processes helps men gain an understanding of the complex system of links between species and forecast the consequences of human interference in the affairs of nature.

Nowadays biology, one of the oldest sciences which originated as a descriptive and experimental science, is boldly appropriating all of the latest from the arsenal of scientific means: cybernetics, mathematics, computers, methods of abstract analysis, speculative reasoning and, at the same time, precise calculation.

It can be said that we now witness the emergence of a new biology, swiftly advancing thanks to numerous highly promising discoveries in molecular biology, biochemistry, biophysics, cytology and genetics, thanks to the appearance of new and unexpected branches such as biostatistics, biomathematics and systems theory.

Besides theoretical investigations, cybernetics in biology engages in immediate practical work. This is the other—applied—branch, which abuts on cybernetics in medicine.

Naturally, it is hard to cover all the spheres of applied cybernetics in biology and we shall have to single out the principal targets of the "cybernetic attack", the main directions of the "offensive".

Let us return once again to mathematical simulation. With the help of special equations one can describe the process of photosynthesis—the absorption of solar energy—in plants. Scientists are working on mathematical models of such processes as the evolution of species, blood circulation, and others.

There is another approach to mathematical simulation. With the help of a suitable analogue of the biological subject an experiment which could result in the death of an animal or be hazardous to human health can be replaced by a computer calculation. Need we list the advantages of such an approach? They are obvious. And the result? Superb, for a mathematical model takes minutes to show how a disease may develop in a patient, how a medicine may affect the body.

As stated elsewhere, the basis of cybernetics is the collection and processing of information. Therefore, for the biological applications of cybernetics it is important to build electronic devices for assembling information about processes going on in the organism. Some remarkable supersensitive, extremely delicate instruments capable of penetrating to the farthest nooks of the body have been invented for this: the electrocardiograph for studying the functioning of the heart; the electroencephalograph which probes the mysteries of cerebral activity; the electromyograph which records muscle activity; tiny radio capsules for investigating the stomach and intenstines; electron microscopes; television microscopes; colour television in medicine, and so on, and so forth.

In the course of an experiment the investigator is assailed by an avalanche of data, figures, graphs. Many workers declare that the main difficulty is not in staging an experiment but in the subsequent analysis of the information gleaned from the numerous devices in which modern biology and medicine abound. This is what makes automatic processing and analysis of assembled data so important.

Interesting research in this field is being carried out by workers of the Cybernetics Laboratory at the Vishnevsky Surgical Institute, under Academician A. Vishnevsky and Professor M. Bykhovsky. Work at the laboratory they say, has underscored the enormous difficulties encountered by a physician confronted with the data supplied by various instruments. How can he assess the progress of a disease if the patient's state is recorded in terms of several hundred characteristics? He can hardly encompass, much less analyse them.

Here is where the physician can be assisted by a machine capable of "diagnostic reasoning" on the basis of the data obtained and duly processed. The "Ural" computer, for example, is capable of compiling 200 diagnoses of congenital heart disease a year. Moreover, the computer is more reliable than a physician, and on several occasions, when its findings differed from those of the physician, during the operation the machine was shown to be right.

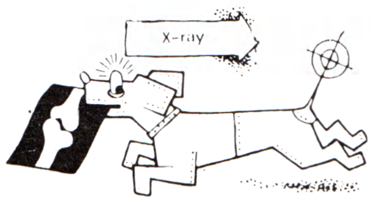
With the progress in theory medical diagnosing systems have been built capable of diagnosing not only heart defects but also diseases of the liver, stomach, some infectious diseases, and tumours, including tumours of the brain.

An important advance in medicine will be the development of an information system for amassing all pertinent data, processing them mathematically and swiftly retrieving relevant information about analogous disease cases. It would represent a vast medical "memory" storing the experience not of one or a dozen clinics, but of all the clinics of the country or even several countries. Any doctor in any country could then consult this central medical "memory".

Cybernetics has entered the surgical operating room. It participates directly in operations and controls vital functions of the organism: looks after the work of the heart, regulates arterial blood pressure, controls anaesthetic sleep.

Cybernetics is confidently invading biology and medicine. In time its pace will become even firmer, its stride longer, its accomplishments greater. It is well to recall here the words of our celebrated physiologist, Ivan Pavlov: "The time will come—even though it may be a long way off—when mathematical analysis in combination with natural science will illumine all these equilibria [life from the simplest to the most complex mechanisms—*V.P.*] with the majestic formulae of equations."

This time has now come.



D

DATA HANDLING

A branch of science that deals with the problems of automation of information accumulation, storage and retrieval processes.

How to Find a Needle in a Haystack

Mass documentation storage has only recently developed as a technical system following the introduction of the ideas and methods of cybernetics into the field of data handling. It developed as a result of the pressure generated by the avalanche of printed matter that followed in the wake of the scientific and technological revolution. Information is contained in scientific monographs, historical archives, libraries, museums, patent offices, in fact in every office. It is recorded in books, newspapers, magazines, photographs, films, magnetic tapes, phonograph records, catalogues, advertisements, business reports, letters, files, etc.

The storage, processing, retrieval and transmission of information have become a formidable task in our time. Little wonder that a veritable information industry, based on electronic computers and a wide range of other business machines, has appeared and has become a concept.

Look What Is Happening. In forty years the All-Union Book Chamber has registered 22 million of all types of Soviet printed matter—almost one per every ten inhabitants, including babies.

We have literally been flooded with printed matter. Annual output amounts to some 7000 million pages, about one-tenth of which is devoted to scientific information.

In 1800 there were 100 scientific journals, and in 1950 there were almost 100 000. Today the figure is in excess of 200 000.

Take a look at the field of chemistry. There are more than 6000 journals on chemistry in the world, and every day one or two new ones appear. In the 20 years, from 1926 to 1946, the number of works on zinc alone was three times more than the total figure for such publications in the preceding 200 years.

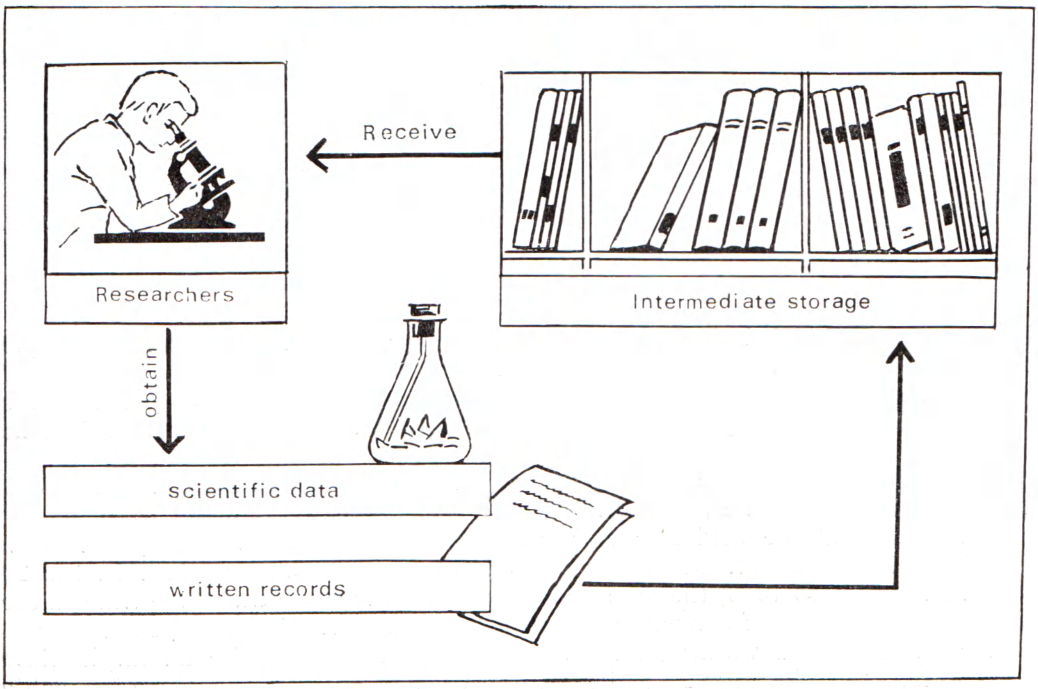
A chemist with a working knowledge of 30 languages (quite an implausible supposition) "swallowing" 20 articles a day without holidays would be incapable of familiarizing himself with one-tenth of the publications appearing in periodicals on his specific field. And "swallowing" is not enough: one must also "digest" what one has read.

The situation is hardly any better in mathematics, physics, biology and other major spheres of scientific progress. Experts have calculated that in the near future computers will be handling such a quantity of information that it will be equivalent to 7000 pages of reading matter per head for every man, woman and child in Europe.

As for fiction, some are thinking of adopting the American way out: novels by Tolstoy, Stendahl and Dickens are compressed into 20- or 30-page digests that can be carried around in a coat pocket and read in two instalments when there is nothing better to do. How convenient, it would seem, yet ....

Here is what Stephan Zweig had to say on this score: "Try and read a Dostoyevsky novel in an abridged French edition. Everything seems to be there: the sequence of events unfolds faster, the figures seem more mobile, integral, impassioned. Yet they are somehow emasculated: their souls lack the same finish, the specific sparkle radiating all the colours of the rainbow, the atmosphere of glittering electricity, the oppressiveness of intensity which only a discharge makes so terrible and so salutary. Something is irretrievably destroyed, the magic cir-

Schematic diagram of the "recycling" of scientific data among researchers.



cle has been broken. In these experiments in abridgement one realizes the meaning of Dostoyevsky's breadth and the necessity for his apparent long-windedness."

It is better to read a thousand novels in the original or a good translation than to gain a distorted idea of a hundred thousand. But in science and technology the condensation of information into digests, abstracts or extracts is a must.

In our country in 1952 an Institute of Scientific Information was set up under the Academy of Sciences. It has now expanded into a vast "concentration" mill for processing and enriching scientific and technical literature.

The All-Union Institute of Scientific and Technological Information began publishing its journal of abstracts in 1953. It presents brief synopses of articles appearing in 100 countries on all the main branches of learning (mathematics, physics, chemistry, etc.) and thereby substantially facilitates the work of not only Soviet scientists, but of foreign scholars as well. It receives publications put out by 450 foreign academies and scientific societies. Parcels arrive here from the British Museum, the United States Congress Library, the Sorbonne and a score of other major book repositories of the world. The Institute receives books and magazines on science and technology published by all the publishing houses of the Soviet Union. In the course of a year more than 100 000 sources of information in 65 languages are processed. In 1960, for example, a total of 700 000 sources were condensed into reviews, digests, abstracts and bibliographical notes.

The Institute has a staff of over one thousand workers supplemented by 20 000 part-time collaborators. Obviously, the reviewers must not only know one or more foreign languages, they must also be specialists in some field of science.

It would seem that with so many eyes keenly scrutinizing the press and so many highly qualified translators, not a single discovery or invention could escape the vigilance of probing researchers. Alas, this is by no means the case.

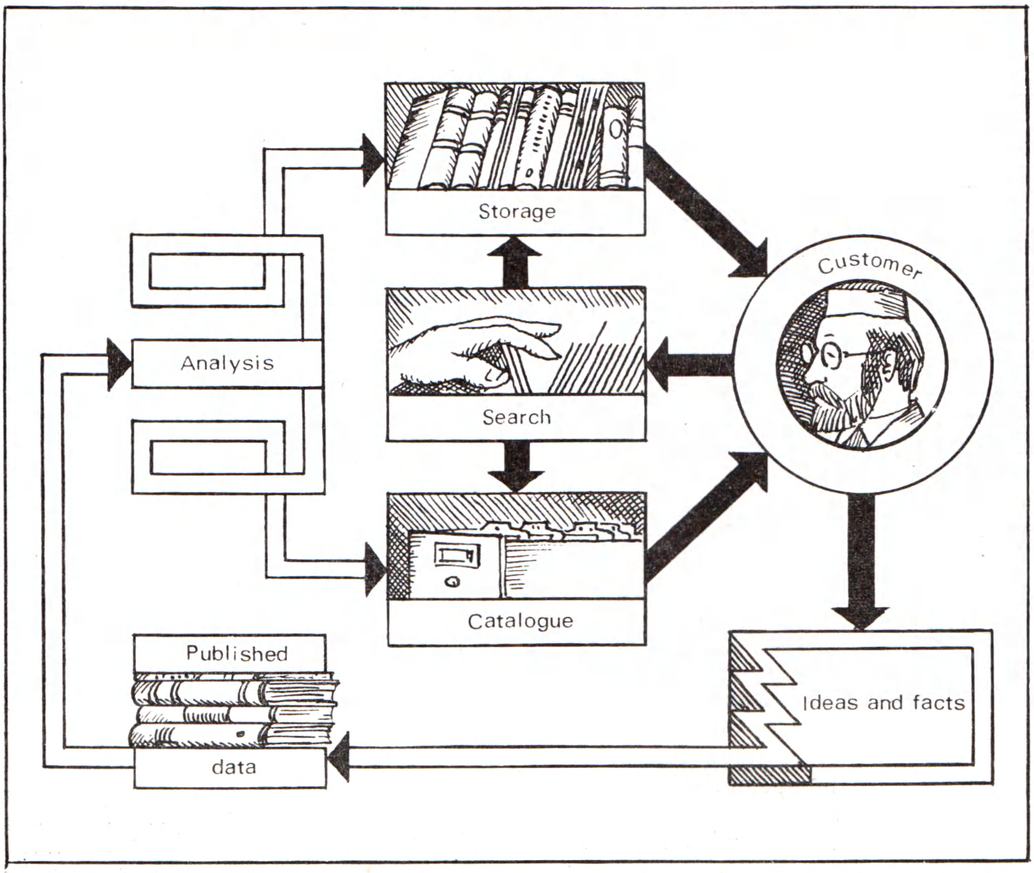
In 1953 a description of an interesting technological innovation appeared in the American press: replaceable tyre treads. Only in 1959 did Soviet specialists come across the report. A fortnight later the Yaroslavl tyre factory began manufacturing such treads, so simple was the idea. It was highly economical, but how much was lost owing to the six-year delay!

American scientists have also been in similar situations despite their excellent scientific and technological information service. It was once reported that one American firm spent five years and 200 000 dollars on a device which, it was later discovered, had been built in the Soviet Union. Furthermore, a report of the work had been published before the American firm began to tackle the problem. American industry first heard of Soviet turbine drills six or seven years after their development had been reported in the Soviet press. And this is not a question of negligence, rather it is a matter of misfortune, that engineers and scientists are increasingly incapable of coping with the mass of printed information.

What must a scientific extract be

like if it is to serve its purpose? Firstly, it must be brief and to the point: better to read the original paper than a verbose exposition of it. At the same time it shouldn't be overabridged because, by its very nature, it must contain information that does not lend itself to abridging, such as formulae, dates, geographical names or names of investigators. Finally, in our age of mathematical linguistics, bionics, space chemistry and other hybrid sciences, even narrow specialists cannot afford to miss parts of papers dealing with adjacent sciences. Frequently the same paper is of interest to researchers in different fields, for instance in chemistry, mathematics and biology. This means making three extracts from a single paper. But extracts are convenient as a source of information only so long as there are not too many of them. Yet already the annual output

An example of a data retrieval system.



of the Soviet institute alone runs to a thousand thick volumes.

Incidentally, in 1965 some 1500 journals of extracts were published all over the world. Yet even so they are no longer capable of encompassing the steadily growing avalanche of information.

We are often fascinated by the wealth of the major world book repositories. For example, the Lenin State Library in Moscow has 22 million volumes of books, journals and newspapers. Its total shelf length exceeds 300 kilometres, and each year another 15 kilometres of shelves is added. But a large proportion of this wealth is no more than so much deadweight: about half the material in the Lenin Library has never been requested by readers. The reason? The same one: the files and catalogues are engulfed by the sea of printed matter.

No wonder many scientists maintain that if an investigation is not too costly it is cheaper to carry it out rather than hunt for a needle in a haystack in an effort to establish whether someone has or has not carried it out before. Indeed, "excavating" the paper deposits of American libraries, for instance, costs 300 million dollars a year. It has been estimated that one-fifth of the investment in scientific research throughout the world is spent on gathering and distributing information. Yet most scientists spend perhaps one-third of their time on painstaking research in the quest of results already obtained by someone else.

We admire modern printing machines, forgetting that whilst they have helped boost printing, they have not made pre-publication preparation any faster. The first Russian printer, Ivan Fedorov, spent eight months and nine days setting and printing his *Instructive Scriptures*. Four hundred years later the 11th volume of the complete works of Charles Dickens, which required no editing, took eight months and twenty days to be published, and volume 30 took more than a year. For articles published in 1916 in the *Journal of the Russian Physico-Chemical Society*, the time lag between initial composition and final readership was two and a half months; in 1966 the time lag in the *Journal of Physical Chemistry* was 19 months. And this at a time when the tempo of scientific progress is so fast that manuscripts can grow old in a few months!

Such is the problem of information processing in only one department of data handling, the importance of which has not yet been fully realized. The difficulties facing the information industry are multiplying with every passing year.

What are the prospects?

It is cybernetics and electronic computerization that hold promise of a real revolution in the information industry.

One of the problems is swift location and retrieval of all pertinent data on a given subject. Data retrieval systems are being devised to ensure the most rational organization and complete automation of the process. They employ microfilms, punched cards and electronic computers. Such a system, for example, was developed in Moscow at the Vishnevsky Institute of Surgery. In Kiev, at the clinic of thoracic surgery headed by Professor N. Amosov, an archive has been organized in which case histories are recorded on punched cards. The information thus stored is intended for computer processing. Workers of the Cybernetics Institute of the Ukrainian Academy of Sciences are studying ways of transmitting medical data over distances in a digital and diagrammatic form.

An "electronic encyclopaedia" is being assembled for chemists, and a data retrieval system on the mathematical theory of experimentation is being designed.

Machines will make work easier for bibliographers. A machine was used to compile the index for the complete works of V. I. Lenin—55 volumes. The job took several hours. It would have taken months if not years for a staff of manual specialists.

Another important problem is that of automating the process of translation from one language into another. At present "manual" translation from Russian into English embraces only one-tenth of Russian scientific literature. Obviously, even unedited word-for-word texts prepared by electronic translators would help solve the translation problem.

However, even if machines are able to translate all, or almost all, the printed matter appearing in the world, no hundred-eyed Argus could hope to read it all. That is why, from the practical point of view, the thing is to automatize not only translation but the making of extracts too. This requires machines capable of not just choosing the equivalent foreign words, but of "understanding" the meaning of phrases as well. This is no simple task, but it is already being tackled.

Today libraries make wide use of microphotography, which enables books and journals to be compressed into the size of a spool of film. Thus, a whole library or archive can be stored away in a single cupboard. Tomorrow's microduplicating machines will be capable of compressing the contents of a 30-volume encyclopaedia into the volume of a writing pad or even, some day, a pinhead!

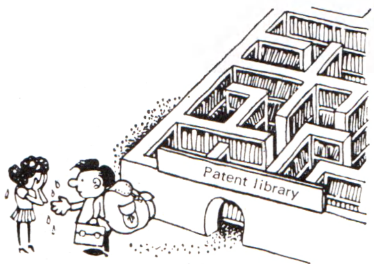
In response to telephone requests automatic machines will locate, retrieve and transmit information to be represented as an image on your home TV set. The first such experiment was carried out by Soviet scientists in 1957. The contents of several printed pages stored in the machine's memory were transmitted through the city automatic telephone exchange. At the receiving end a screen presented a clear impression of the printed message.

While progress in electronic microminiaturization holds promise of markedly increasing the capacity of data repositories, achievements in laser techniques will help expand the handling capacity of communication channels for transmitting those data. The visible light wavelength range in which laser transmitters operate, has a capacity millions of times greater than the total range of wavelengths in which the sound and television transmitters operate today. Experimentally, light rays are being used as substitutes for telephone cables. At the Economic Achievement Exhibition in Moscow there is on view a TV installation which transmits both image and sound not by ultra-high frequency waves but light rays.

Communications satellites will make it possible to establish a fast operating system of data exchange between libraries and publishers all over the globe.

It is not accidental that already today men realizing the importance of coping with the torrents of printed matter and the flood of information, predict that soon "the day will come when paper will be replaced by electronic impulses spanning vast distances and processed easily by machines. The information service will develop into a stupendous system of machines connected through communication channels to telephones, television sets and phototelegraph apparatus."

All these technological innovations will help the specialist of the new era of cybernetics—the data handler—to chart routes in the boundless ocean of information. His main task, however, will be to curb information about information, to help scientists find their way in floods of news and avalanches of documents.



"Don't cry, dear, I'll be back in a year!"

E

The "Demon" Opens the Door

ENTROPY

In the theory of information
it is a measure
of the uncertainty
of the situation.

Get ready to exploit your patience, for to understand entropy it's patience you'll need most. Don't expect to grasp all features of this new concept at once. There is no need to wonder—many details pertaining to entropy are still open to discussion, there is no unanimity among scientists about them.

Here are some statements by eminent scientists, acknowledged authorities on the question, who have tried to "crack the nut" in simple language.

"The real value of the concept of entropy stems in the first place from the fact that the 'measure of uncertainty' expressed by it proves to be the characteristic which plays a part in various processes occurring in nature and in technology and correlated in some manner with the transmission or storage of information." This is one statement.

And now note the following: "To understand the meaning of entropy in the theory of information, you'll better throw out of your head everything that's in any way connected with the concept of entropy as used in physics."

The third statement speaks of the difficulties of understanding entropy and the problem of entropy (in physics and in information theory).

"Walking through these fields reminds one of walking through the jungle full of traps. Those who are best acquainted with the subject are, as a rule, most careful when talking of it."

Let's note: the scientists are unanimous in stressing the connection between entropy and information theory. This is very important, since information theory has been accepted as a powerful research instrument and serves as the most reliable path-finder in excursions into the most sophisticated labyrinths of numerous branches of modern science.

That's just an introduction, the story about entropy remains to be told.

The word "entropy" was first used by the German scientist Rudolf-Clausius just over a hundred years ago in 1865, when he explained why heat could not go over from a colder body to a warmer one. Translated from the Greek the word "entropy" means "I turn inside", "I go into myself".

This aroused keen interest of the Austrian scientist Ludwig Boltzmann, and he decided to crack the problem. Far-reaching studies of this scientist resulted in the appearance in 1872 of this definition of entropy.

Let's imagine a system, i.e. a gas enclosed in a vessel. What are the parameters of the system in this case? A definite volume, pressure and temperature—a set that is usually termed macrostate.

But how did it come about? Through microstates: the positions and velocities of particles in certain moments of time. These states change from one moment to another. A macrostate of a system corresponds to a set (a sum) of all its microstates. Evidently, one and the same macrostate may be the result of numerous sets of microstates, just as one and the same sum may be made up of various additives. A question may be asked: are all sets of microstates responsible for the same macrostate equivalent? No, they are not. This is what Boltzmann proved: a system free from outside influences (an isolated system) tends to become disorganized, tends to increase its entropy. At the same time, as is universally accepted, the system "searches" for its most probable state. Therefore, according to Boltzmann, entropy may be regarded as a measure of the probability of a set of microstates. From physics we know that a system (to be precise, its macrostate) tends to equilibrium. Does that mean that microvolumes of the system, into which it may be subdivided, are in equilibrium every moment of time? No, such a set of microstates would be highly improbable, the more so the higher is the temperature of the system. A definite number of them (on the average) must every moment of time be a definite distance away from equilibrium. Thus, the macrosystem as a whole has equilibrium macroparameters every moment of time (to be precise, the deviation from such parameters, while present always when the temperature of the system is above absolute zero, is relatively very small), each given microvolume has equilibrium parameters averaged over time, but every moment of time the parameters of every microvolume are not equal to their equilibrium value. Each parameter may be said to oscillate around its equilibrium value. The amplitude of such oscillations is the higher the higher is the temperature of the system and the smaller is the microvolume.

Maxwell's "demon"—now a classical example—too, will help us to understand this unfamiliar concept of entropy.

The "demon" of the famous English scientist Clerk Maxwell made his home in dozens of specialized and popular-science books. The essence of the "demon" is, of course, the same in all books, only it is expressed in different words.

To avoid retelling this example anew let's take it in the form it was cited by the "father of cybernetics" Norbert Wiener.

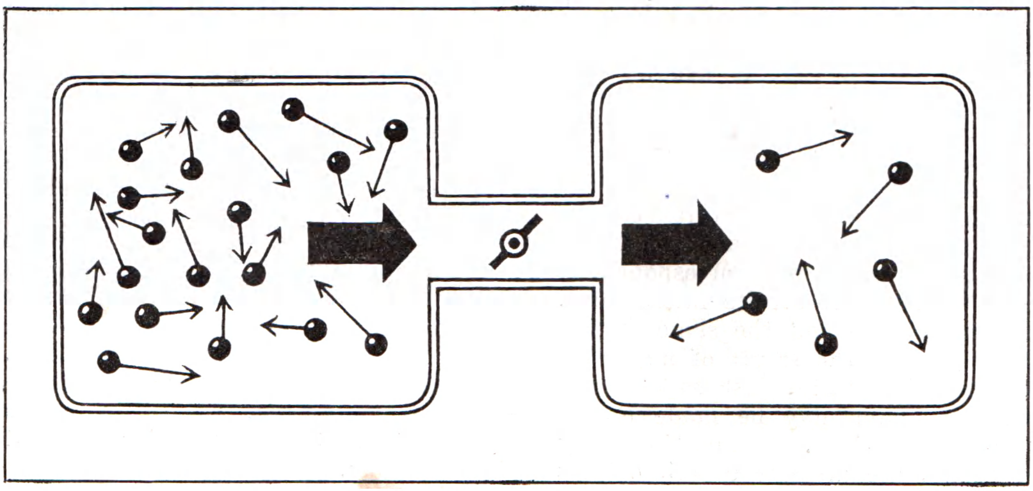
"Suppose we have a container filled with gas, whose temperature is everywhere the same, and suppose that some molecules move faster than the others. Suppose further that there is a small door in the container through which gas flows into a tube leading to a heat engine, and that the exhaust of this heat engine is by means of another tube connected through another door with the gas chamber. Each door is attended by a tiny being who watches the approaching molecules and, depending on their motion, opens or shuts the door.

"The 'demon' lets through the first door only the molecules with a high velocity and stops those with a low velocity. The task of the 'demon' at the second door is opposite—he opens the door only to molecules leaving the container with low velocity and stops molecules with high velocity. This results in the temperature on one end of the container rising, and on the other falling."

To facilitate the understanding of the example with Maxwell's "demon" Wiener proposes his own analogy:

"Perhaps I will be able to clarify this idea with the aid of the example of a throng of people fighting their way into the subway through two turnstiles, one of which lets through people that move sufficiently fast, and the other those who move sufficiently slowly. Random motion of people in the subway will then assume the form of two streams—of fast-moving people from the first door and of slowly-moving people from the second.

A simplified diagram of Maxwell's "demon". The molecules with long arrows move faster.



"If both doors lead to a single passage with a treadmill on the floor, the stream of fast-moving people will rotate the platform in one direction faster than the stream of slowly-moving people will rotate it in the opposite direction (the fluxes of "fast" and "slow" people being assumed equal). Thus we will be able to extract useful energy from random motion."

In other words the rotating door in the subway and Maxwell's "demon" both are in a position to reduce the entropy of their "parishes". So there is a contradiction to be overcome: the "demon" reduces the entropy, which, according to the laws of physics, can only rise. A paradox, isn't it? Yes, it is. And it remained so for a long time, until the Hungarian physicist L. Szilard published a paper under a very learned heading: "On the Decrease of the Entropy of a Thermodynamic System Due to the Interference of an Intelligent Being".

Here the scientist again mentions Maxwell's "demon".

Why does he arouse interest? Firstly, because the "demon" can only act if he gets additional energy for his work—the opening and closing of doors alternately to fast and slow molecules. Only by spending this energy can the "demon" keep his subjects "locked", so that fast molecules stay on one side and the slow on the other. In other words, only then can the "demon" reduce the entropy of the system. But what does the "demon" spend the received energy on?

On organizing activity, says Szilard—and proves it—trading energy for information as to where should definite molecules go.

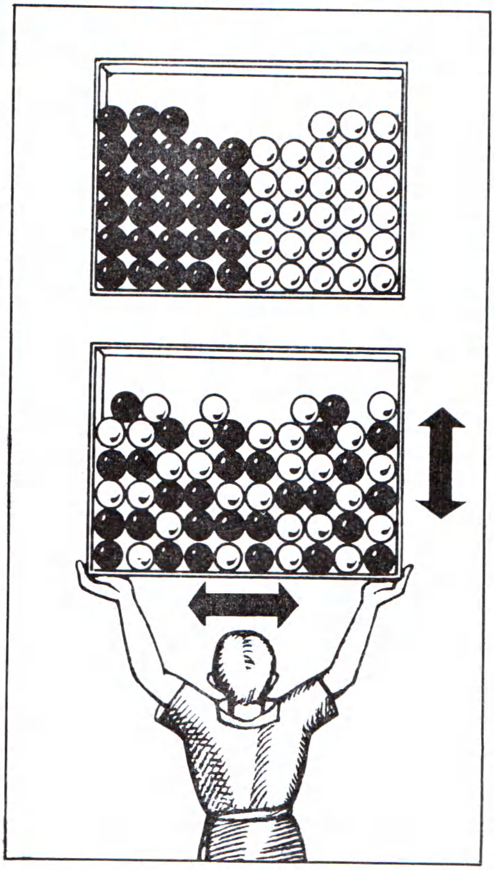
The proof presented by the scientist is very complicated and specialized. There is no sense in repeating it here. So let's take his results for granted, all the more so, since they have been recognized by the scientists the world over.

Hence the conclusion that information and entropy are interrelated. This is a very important conclusion, since it entails the proposition that information is inversely proportional to entropy. The famous American scientist Claude Shannon regards information from this aspect: it is something that reduces the uncertainty of choice.

Let's recall Boltzmann's micro- and macrostates of a system. There information can tell us how, along what ways, the molecules move, help us to assess their motion. In the same way it is possible to assess any other category, difference in the meaning of letters, for example. This is the reason for Shannon to apply the formulae of entropy for the evaluation of information—in mathematics the real meaning of the letters in the formulae is of no importance.

This conclusion about the deep-rooted analogy between entropy and information was interesting enough for the famous French physicist Louis de Broglie to pronounce it "the most important and the most beautiful of ideas born out of cybernetics". The leading authority on the theory of information, the prominent mathematician of modern times A. Kolmogorov says that "such mathematical analogies should always be stressed, since through concentrating attention on them progress of science is promoted".

You have certainly not failed to notice how careful the scientists



The entropy of a simple system of black and white balls occupying separate volumes in a box increases upon arbitrary shake-ups.

themselves are when dealing with this question. They refuse to go beyond analogies. Why? Because the "characters" of the physical and informational entropies are quite different, and this leads to a difference in behaviour.

For instance, if the entropy of one of two bodies increases as a result of their interaction this is always at the expense of the other body. But this does not hold for information. As Louis de Broglie wittily remarked, "When I send you a telegram informing you of the downfall of the ministry I supply you with information, at the same time I do not lose anything of it myself."

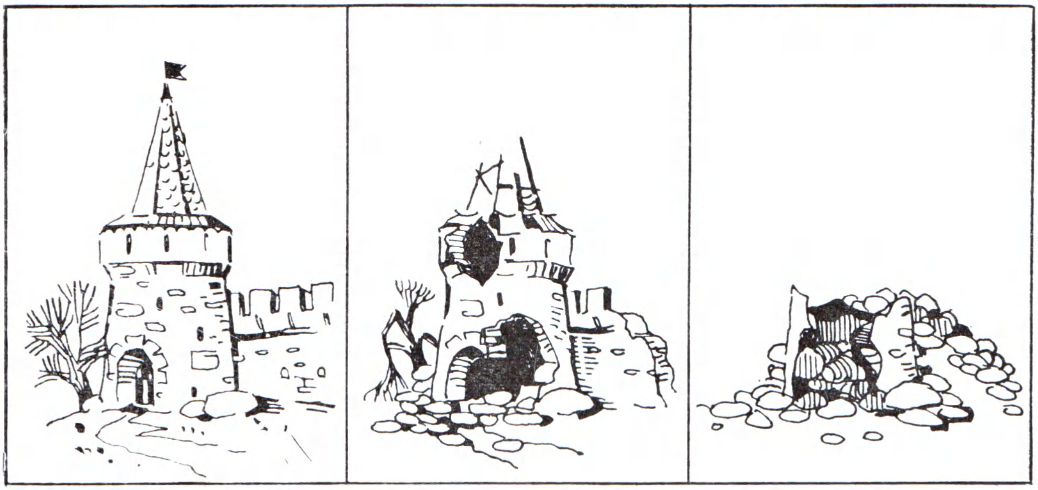
A scrupulous and deep analysis of information and entropy was made by Norbert Wiener. He wanted to know the reasons for the interconnection of information and entropy. The conclusion he arrived at was astoundingly simple: because both characterize reality from their own particular point of view—both entropy and information regard the world from the viewpoint of relationship of chaos and order. Wiener states expressly: entropy is a measure of chaos, information is a measure of order.

It can be said that at last the concepts of entropy in physics and in information theory became somewhat clear: one has been detached from the other, we know their "individual peculiarities", their "traits of character".

But then one wonders whether there was any sense in drawing a line between these two concepts when now efforts are being made to merge them again. What is the content and where lies the necessity for this "step back"?

For the answer to these questions let's turn to the already familiar example of a container filled with gas. But this time the analysis will be made by another prominent scientist—Leon Brillouin.

Again we have before us a gas-filled container. The gas consists of constantly moving molecules, and we simply do not know—cannot know—either their exact positions or their



A tower built by man, a "purposeful physical system", displays a high degree of order. As years go by, under the influence of random non-directional forces the tower will tumble and turn into a stone-heap—the entropy of the system will increase.

velocities. But we know the macroscopic parameters of the system: its volume, pressure, temperature and chemical composition. Although we are in a position to measure all these parameters they tell us nothing about the behaviour of individual molecules or groups of molecules distinguished by some characteristic (i.e. location in the container, velocity, etc). To gain information about this we must know more about the "inner workings" of the system, to be exact, about the interactions between the molecules, between the molecules and the container walls, which result in constraints on their motion. In the absence of such information the only thing left to us is to assume that the molecules do not interact, i.e. are free, and the entropy of a free molecule of gas is the greatest possible. It follows that the less we know about the behaviour of the molecules, the greater is the uncertainty. Hence, the greater the probability of random states, the greater the entropy.

True, it is not always that we are so helpless, don't know anything about the system. Sometimes we do have a bit of information. For instance, about the history of the system, the moment of its birth.

These are very helpful data—they are the key to other data such as the density and velocity distributions.

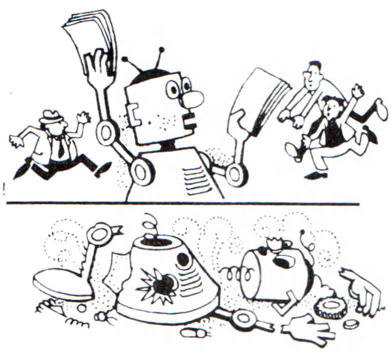
Such additional information is of great value for us, for it enables a fuller description of the system to be made, which, in turn, makes it possible for us to ascribe to it a smaller entropy.

Does that mean that entropy may be regarded as a measure of lack of information, and information as the negative part of entropy, its "negative"? It does, says Brillouin, and defines information as negentropy.

Does it make any difference what to call information—just information or negentropy? It does. The negentropy principle of information unites the concepts of entropy and information on a new basis and points out that they cannot be treated separately but must always be considered together. And this rule is always true for various infinitely distant spheres of application—from theoretical physics to everyday life.

Thus, the circle has been closed. We've read about Clausius who invented the word "entropy" for the new concept, about Boltzmann's theory, linking entropy with the probable microstates of the body, about the ideas of Wiener who identified entropy with the measure of chaos. Our road has been hard—from difference to unity. We learned about the responsible part played by entropy in science, how it helped in the understanding of numerous laws of nature, and how recently theory of information "twisted" entropy and made science take a new look at it.

Tickets for a football match!



F

From the End to the Beginning

FEEDBACK

The action
exercised by the output signal
of a system
on its input.

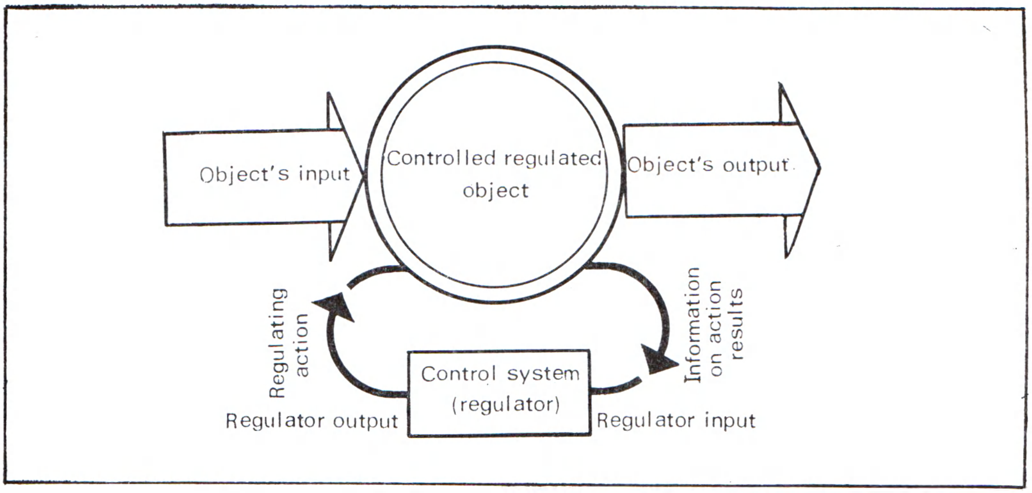
His name was Humphrey Potter. His was, primarily, an active nature, and he couldn't stand monotony. That's why he got tired of the job he was doing in one of England's mines: when water was being pumped Humphrey Potter opened and closed the valves of a boiler.

Why was he doing it? Just because two and a half centuries ago—that was the time when Humphrey lived—a boiler worked not as it does now.

The steam from the boiler lifted the piston in the cylinder. Humphrey closed the steam valve and, at the same time, opened another valve to let cold water into the cylinder. The steam condensed, and vacuum was created. Atmospheric pressure acted upon the piston, it went downwards, transmitting its motion to the pump. After that Humphrey Potter opened and closed the valves in turn again, and so all day long.

You'll agree, this wasn't an interesting job. And, naturally, he grew sick of it. The clever boy decided to get rid of it. He connected the valves by means of strings to the piston rod. As the rod went up and down the strings tightened and opened or closed the valves in appropriate sequence.

There are such specific concepts in engineering as "input" and "output" of a machine. The input of a steam engine is the steam inlet, and the output the motion of the rod. Now you can grasp the strictly scientific definition at the beginning of the



A generalized diagram of feedback devices.

section. When input is connected to output, feedback is realized. This is exactly what the legend attributes to the English boy Humphrey Potter. He invented feedback, devised a system for automatic regulation.

Feedback is the cornerstone of modern engineering. It's difficult to name any of its fields where feedback is not utilized. Temperature regulators maintain the required temperature. Pressure regulators—the pressure. Speed regulators—shaft rotation speed. Voltage regulators—constant voltage in the mains.

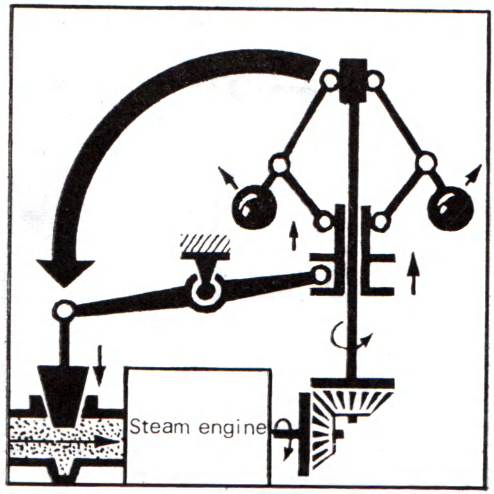
No matter where and when feedback control is employed, it is always very "attentive" and "punctual". It performs all the operations entrusted to it with superhuman precision.

There are numerous examples of various automatic regulation systems. Their design, principles of operation and applications vary, but the interaction between the controlling device—the regulator—and the object being controlled is of the same type.

Here is a schematic diagram of the Watt governor.

For almost two hundred years this mechanism serves as an example of elegance and simplicity of the feedback.

Remember how James Watt built a steam engine with a centrifugal speed governor driven from the engine shaft. The weights of this governor go apart under the action of the centrifugal force depending on the shaft speed. A moving sleeve is connected to the weights. Through a system of levers it moves the slide valve in the tube. The governor is tuned to the required number of revolutions of the shaft. If for some reason or other the shaft speed increases, the weights will go apart and pull the sleeve upwards, and the slide valve will go downwards. The steam flow to the engine will decrease and the shaft's rpm (revolutions per minute) will return to normal. If, on the other hand, the shaft speed begins to fall below the required value, the governor lifts the slide valve and more steam is fed into the engine. This, in turn, leads to the shafts revolutions being increased to normal.



Watt's governor is an example of the elegance and simplicity of a feedback system.

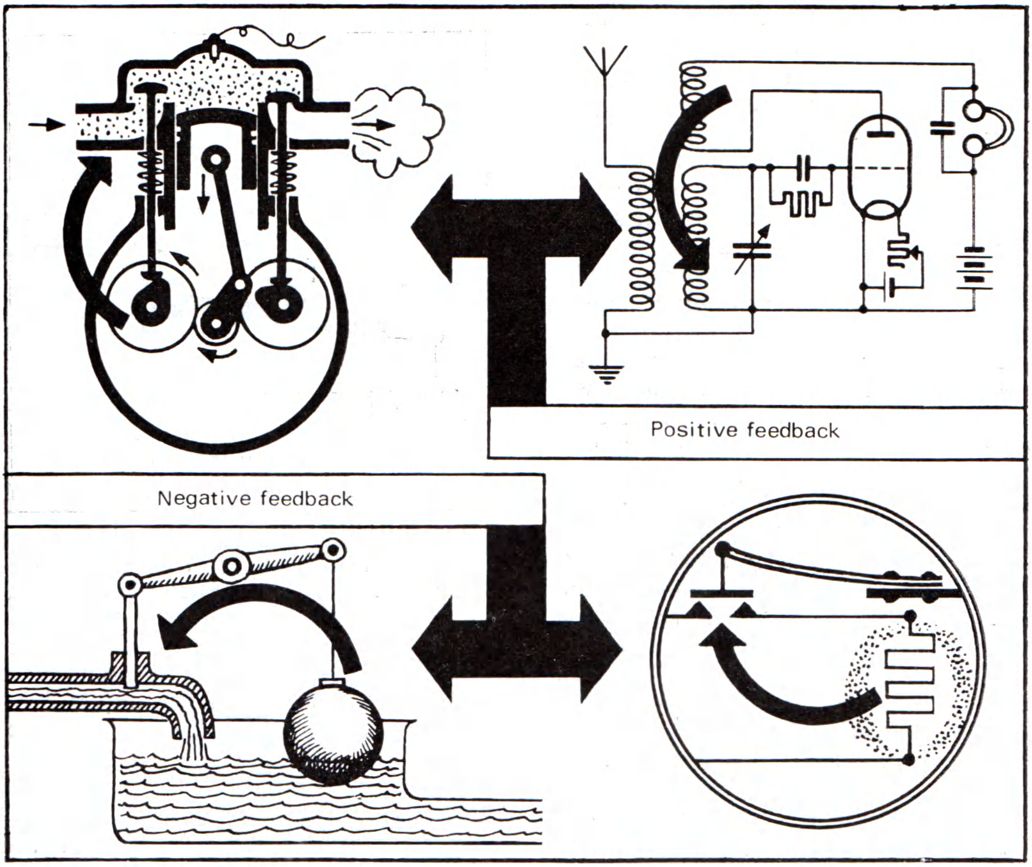
The example of Watt's engine has been used to demonstrate the outlines of a feedback control system. In this automatic regulation system the object regulated is the steam engine. The governor sends to the object being controlled a control signal by way of a lever system and the slide valve—this is a direct connection. The output of the governor acts upon the input of the object. Through the vertical shaft that conducts feedback the governor receives from the engine a signal about the results of its control action. Now the output of the object "reports its behaviour" to the input of the regulator. This creates a sort of a closed circle, a kind of a communication circuit.

Some specialists figuratively compare feedback with two dogs with grudges against each other. One of them, say, the black one, bites the tail of the white one. And the white dog, not willing to give in, bites the tail of the black dog. It's the same closed circle process in which one dog plays the part of a feedback circuit in respect to the other.

Such feedback is called positive. In it the process of reverse action is intensified. Braking systems with external power sources may serve as another example of such a feedback. In these systems special devices are utilized that react to small displacements effected by hand. The displacements are continued until the braking force reaches a value high enough to stop the moving machine.

The feedback in which the intensity of the process decreases is called negative. This is the type of feedback that is being predominantly used in automatic regulators, including temperature level regulators, rpm regulators, pressure regulators, etc.

Suppose the temperature in an electric furnace has increased above the value required for the melting of metal. The automatic regulator acts "negatively": it cuts power being fed to the furnace. If the temperature



Types of feedback: in an internal combustion engine it's a mechanical device; in a regenerative receiver it's an electrical device. The regulators of liquid level and of temperature are feedback devices, too.

decreases, it again acts "negatively" and increases the supply of power.

All further examples will add nothing to the story about feedback that has just been told. We'll always have to do with a regulator tuned to certain rpm or to certain operating conditions which, in case these conditions are perturbed, sends a control signal, the feedback delivering to the regulator a signal about the results of the control action.

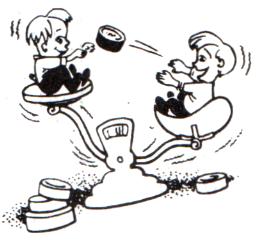
Cybernetics has widened immeasurably the domains of the feedback concept application which now include such "non-technical" sciences as biology and economics.

The most intricate system employing feedback is, presumably, the living organism. What a lot of regulators and control objects it contains!

How great is the number of interconnected positive and negative feedbacks! What exceedingly difficult tasks the organism has to perform: distribute muscle strain in order to uphold the required body posture; react to the minutest changes of pressure in blood vessels; respond to the heat and the cold; watch the contents of acid, alkalies and many other substances; control the incessant work of the heart, the kidneys, the liver, the lungs!

And the more complicated is the biology of the organism, the greater is the complexity and the variety of its "automatic regulators". Feedback may be said not only to take part in physiological phenomena, but to be absolutely necessary for the continuation of life. Without it life is impossible!

Thus, feedback is at work in quite different fields. This enabled scientists in cybernetics to talk about the universal, the general character of the "feedback" concept, to insist that it operates everywhere where interconnected machines and systems form some new combination. These combinations, these new systems must be harmonious, must retain former individual features and at the same time gain new qualities.



A detailization
of the contents of subjects
being studied
enabling operations with them
to be performed
with the aid of mathematical
methods.

The Hard Core of the Matter

Several ways, several methods may be used to describe the world around us.

The works of ancient painters, the books of famous writers, musical masterpieces created by great composers—all are in the voluminous category the specialists call "the methods of description of the sensually perceived world".

The poet inspired by a fine winter morning expresses the beauty of it in verse. The painter overwhelmed by the power of revolutionary forces has his own way of expression: he depicts it as a brave powerful goddess calling the people to glory.

The assembly bell that rang in Russia on the days of popular feasts or popular disasters served as incentive for an oratorium calling the people to arise against foreign invaders.

"Descriptions of the sensually perceived world"—that's just what specialists term the treasures of world literature and art together with the other less illustrious representatives of this category.

Scientists are trying to gain insight into the peculiarities of the "method" used to describe the world around us. They try to do it scrupulously and fairly with the noble aim of establishing how the realities of life and nature are reflected by human senses.

And what have they learned? What conclusions have they drawn? Out of all methods of describing real life, description by words is considered to be most flexible, sensitive and colourful. There's no such thing as couldn't be described by words, no such shade that couldn't be expressed.

The writer saw the sea. At the moment it looked extraordinary, there was something that distinguished it from what it looked yesterday, there was something individual in it, and he was impressed by it. And he wrote: "The sea smiled." That was the way he saw it.

But the word description, besides flexibility, abounds in traits that are subjective, personal. Only he, Gorky, perceived that "the sea smiled". And is the statement that it smiled really creditable?

Scientists agree that word description, being flexible and rich in colours, is at the same time subjective and of a "low degree of creditability".

There is another, quite the opposite approach to description of life and nature, when the colour of the sea and the play of light on the crests of the waves, and the foam on the beach are all ignored. Then the sea is described by the symbols of the chemical elements it consists of and the physical equations describing the intensity of the waves.

Scientists themselves stress this aspect of the scientific approach when they say that science writes a thrilling novel about the hidden secrets of nature not in a colourful language that re-creates live association and bright images, but in its own language, in which everything that's individual, subjective, is sacrificed to the advantage of the abstract, the objective, the general.

Every one of you, probably, paid attention to a newly built house. Storey rises above storey, identical staircases, corridors, doors, identically planned, identically arranged flats, one above the other—everything clear-cut, common, identical. And now the tenants arrive. They arrange their dwellings each in his own way, and the formerly identical flats become different. A difference in furniture gives individuality to the flats.

Roughly speaking, science deals with the "house" of nature itself, in its "uninhabited" state—with only such general regularities, such objective features, which unite objects perceived by us as different into classes and groups.

Dry and rigorous schematic diagrams, graphs, formulae, tables, equations and symbols help to "unveil" essential features of the real world, to describe the "structure" of real life, to mark interconnections in nature.

The difference between the scientific method of studying life and the method employed by art is very accurately expressed in the following words: while art makes us cry and laugh, science makes us understand and calculate. The painter, the composer, the poet tell us about colours and sounds. The scientist "shuts his eyes" to the beauty of colours and to the symphony of sounds. From the colours and sounds he extracts their main features, only that which makes a colour a colour, a sound a sound; the scientist reduces both colour and sound to waves (electromagnetic in the first case and elastic in the second) of appropriate length and studies their regularities.

How does science study nature? What methods and what tools does it use?

There's a real arsenal of means of approach to the phenomena of reality.

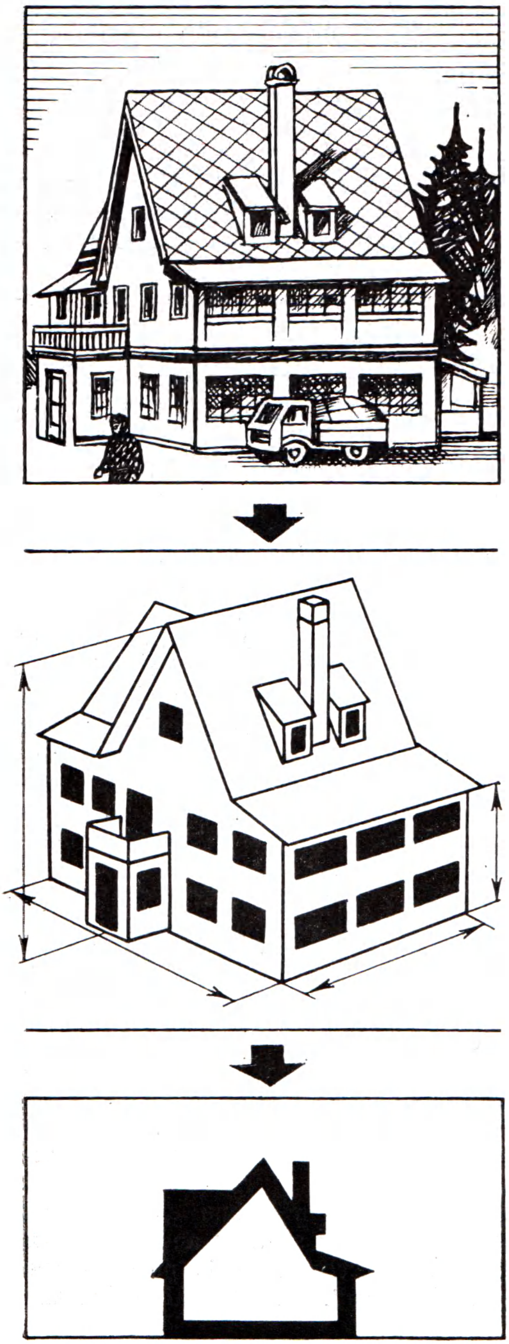
Remember the phrase you often used to hear from your teacher during biology lessons. "Tomorrow we'll start a new subject. We'll study the constitution of, say, the black cockroach" (or of the bombyx moth, or the nervous system of the frog). The example is unimportant, the important thing is that here we are up against the logical method of identification: "the study of the black cockroach", and not of black cockroaches, variously coloured, probably, with feelers of different lengths or with some other individual characteristics. In other words, you are going to separate the general, common to all, ignoring individual features.

There are other ways of approach, as well. Idealization is one example. In this case scientists build ideal models of the objects being studied and deal with their general, essential features and properties. Exactly for this purpose the "absolutely black body", the "absolutely hard body", the "ideal gas", the "absolutely smooth surface", the "incompressible liquid", etc., were invented.

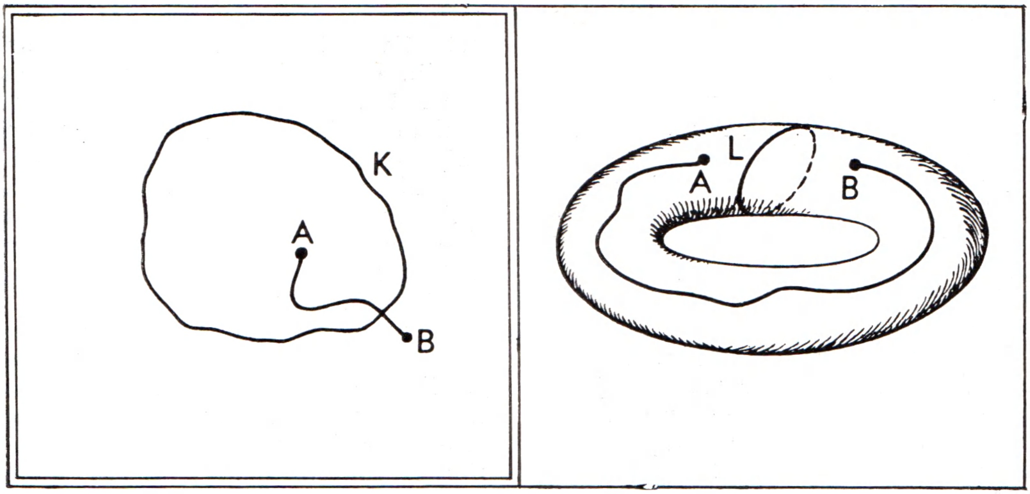
And here is a citation from an utterly scientific publication, from the "Collected Papers on Crystallography and Crystal Physics" by Yu. Wulf.

"The actual surface of the Earth with its incessant variations from highlands to lowlands is quite irregular. The impression of the shape of the Earth may be obtained through the study not of its real surface, but of some theoretical surface. Thereby an element of abstraction from the actually existing irregularities is introduced into the concept of the Earth's shape, i.e. the Earth is observed from a distance sufficiently great to make these irregularities irrelevant. Such a method is quite valid, because the Earth's radius is very large as compared with the highest mountains and the deepest ocean recesses, so that the presence of them does not alter the general 'mathematical shape' of the planet."

Scientific knowledge makes use of such simplification to ascertain hard features of the object under study, to detail its properties, to outline its contour, to discover its structure. In other words, no matter what the principle underlying the gnostic method is, that of identity, idealization, simplification, abstraction, it always, as you couldn't fail to have noticed, involves "roughening", "stripping", "sharpening", the stressing of the paramount, general, main factors.



◀ This may be assumed to represent the "formalization" of a house.



A closed line L drawn on the surface of a thoroid (a life buoy) will not necessarily divide this surface into inner and outer parts.

Having gained knowledge by these methods, scientists proceed further. The regularities discovered by them, elaborated, specified and generalized, form the basis of scientific theory, which is accepted as ultimate knowledge the world over. Here's what scientists themselves say: "A scientific theory is considered to be rigorous and precise if the elements constituting it (abstraction, idealization, identification, concepts, etc.) are sufficiently elaborate to enable a single set of rules of operation, i.e. rules distinguished by their formal character, to be applied. For this reason, the process of elaboration leading to such an operation, may be called the process of formalization." In other words, it is a process (together with its result) whereby some scientific subject undergoes such transformations as would make the use of visual aids, e.g. sense organs or their extensions—the instruments—unnecessary. This is all the more true, because very often the sensory method fails, leads to errors. The definition of a non-intersecting closed line, moving along which we will return to the point of origin without ever passing any point twice, based on visual impressions, is one example. Visual impression gives rise to an obvious conclusion that such a line K divides a surface (a plane or the surface of a sphere) into two parts: inner and outer. There are such points A and B that cannot be connected by a line not intersecting the line K. However, here visual impression fails. The second definition is not equivalent to the first, for it refers not only to the closed line, but includes, as well, the specific property of the surface on which the line K is drawn. Thus, a closed line L (according to the first definition) drawn on the surface of a thoroid (a tire or a life buoy) will not necessarily divide this into outer and inner parts.

There is no place for ambiguity where formalization has established itself. Maximum generalization and automatic manipulation with concepts are possible in a formalized branch of science.

No matter what, when and where we formalize, the essence of the problem is always the exposure of the "hard core of the matter", without which a scientific theory cannot be developed.

Remember our example with the house? Well, formalization is just the evacuation from the house of all foreign objects, doing away with the furniture and other things, once again "stripping", "roughening", an effort, so to speak, to "expose" the subject, to leave just the skeleton in order to draw precise and objective conclusions about it.

But how should we "roughen", "strip", "expose", i.e. formalize? Scientists give a clear and precise answer to this question. One should begin with a finite inventory—from A to Z—of all initial elementary concepts used in the particular branch of science. Such an inventarization isn't the work of one scientist, or even of one generation of scientists—this is the result of the long-time development of this branch of science, of a deep logical analysis of its structure, the inventory so complete as to leave out no essential concept, and so precise as to include no superfluous concept.

But that is by no means all. For the process of formalization it is necessary also to construct a finite—from A to Z—axiomatic system. This is made up of sentences that include the main concepts from the inventory as definitions in the form of symbols rather than in the form of visual definitions. For example, this is how Euclid described a point: "A point is what has no parts." This is a visual definition, and is of no use for axioms, since the latter are sentences built of formulae (and not words).

An axiomatic system obeys strict conditions, too. The first condition is that the system be free from contradictions.

An axiom always states that $1=1$, and not that $0=1$. Next comes the condition of completeness. This means that every statement must either be proved or disproved. Another condition is that of solubility, i.e. there must be a method of finding out whether a statement contained in the system is proved or not. Last comes the condition of independence—the system must contain no axioms that can be deduced from other axioms of this system. And another "must"—the logical system of rules of deduction should also be stated.

Everything we have been speaking about should be written in the special language of symbols.

The thing formalization is called upon to expose, the "hard core of the matter", is always capricious, evasive, hard to sense. And here the trouble only starts. The essence of the matter, even if discovered and exposed, requires elaboration as science progresses. See how the notions of the nature of light changed within a relatively short period of time—a little over one hundred years, from the 17th to the 19th century. At first it was thought that light is carried by light particles. They were called the photons. Later, again on the basis of scientific data available at the time, scientists came to the

$\vee$	$\wedge$	$\rightarrow$	$\equiv$
OR	AND	FOLLOWS	IDENTICAL

From the language of symbols.

conviction that the origin of light lies in the corpuscle, and not in the photon. In the 19th century the application of the most modern methods of research brought about the electromagnetic theory of light. And at last in the 20th century quantum mechanics established the duality of the nature of light: in some phenomena it behaves like particles, in others like waves.

And here's another example. The great German scientist Immanuel Kant, basing his arguments on the state of knowledge at the time, considered the principles of chemistry to be purely empirical, purely practical "and therefore quite incapable of explaining possible rules of chemical phenomena since mathematics cannot be applied to them". Kant doubts the ability of chemists to predict the course of a chemical reaction. The modern chemist has no doubts on this account—a specialist in physical chemistry is able to precalculate accurately numerous reactions with the aid of mathematical relations.

Thus it turns out that formalization often comes to grips with a new situation in science, when former methods of formalization become insufficient, powerless, incapable of reflecting "the hard core of the matter". The place of old methods is taken by new, more advanced ones. In this way formalization scales the stairs of progress.

For this reason the progress in scientific knowledge at the same time manifests itself as a process of perfection of the means of formalization used in the promotion of knowledge.

Such a situation is quite normal. It reflects the essence of the process of cognition. It's a specific illustration of the law of gaining knowledge about the world and nature.

To sum up, formalization is called upon to unmask the essence of the matter, contain all individual, unreproducible features within strict bounds of logical and mathematical symbols. It, so to speak, tears out of reality only such facts as can be arranged into "rigorous systems", "finite inventories of concepts". The impression arises that formalization is a product of "pure thought" of the mathematician.

But this impression is utterly wrong: no matter how the formulae and the symbols look as though they exist "by themselves", formalization, which deals with them, is always and in every case a process of unmasking the different aspects of the real world.

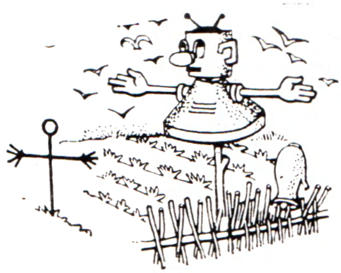
Formalized science makes sense only if it can eventually be applied in practice. Sometimes the time interval separating the creation of formalized science and its application can be quite considerable—centuries or dozens of centuries, but still the practical issue of formalization can always be subjected to inspection. This is done with the aid of a methatheory, for instance, with the aid of methamathematics. The latter studies and controls the structure and properties of formal systems, regards them from the positions not of formal, but of substantial science. Methamathematics is interested in the substance, and not in the symbols.

Nowadays people speak of formalization in a wide and in a narrow sense. In the narrow sense it means such an elaboration of the contents of the subjects being studied that enables mathematical operations with them to be performed. In the wide sense formalization is understood to mean the study of subjects, the elaboration of their contents in accordance with the rules of formal logic. Formalization is the child of the end of the 19th century and the beginning of the 20th. So far it has been carried out—in the narrow meaning of the word—only in mathematics and mathematical logic, and, to some extent, in physics.

Some scientists presume, on the other hand, that its "embryo" appeared at the same time as language and thought. In their view the assigning of a name to an object can already be considered a kind of formalization.

An object receives a name for itself: the "sky", the "bear", the "stone", the "water", the "mountain", the "food", etc. This conspicuous process of assigning a name, so to speak, establishes the ability of the object to be distinguished from other objects, underlines its stable features, its "hard core".

Later the written language appeared. It gave mankind an extremely valuable means of storing and accumulating information. Step by step the natural languages were supplemented by special signs, logical forms of thought came into being. Yet, such a mathematized science as cybernetics still, though it would seem strange, remains unformalized. Up to now there is no single generally accepted logical definition of the contents of cybernetics, there is no inventory of its main concepts, no axiomatic system—all of which are indispensable for the formalization process. Of enormous importance in cybernetics is the formalization of mathematics and logic. It is because of formalization that mathematical logic could be applied in electronic computers which operate in accordance with its laws.



G

GAMES THEORY

A mathematical discipline with the aid of which quantitative relationships in conflicting situations are established.

"Reds" Versus "Blues"

No one can boast of having played all existing games—they are too many in number. Each game has its rules, its peculiarities. Hockey, for instance, is different from football, hide-and-seek from cops and robbers, the dominoes from naughts-and-crosses, the battle of ships from the word game, etc. And yet these different games are identical in principle.

Where does this identity lie? It lies in the conflict of interests.

Basil and Pete play the battle of ships. Both want to win at all costs—that's the conflict of interests.

"One, two, three, four, five, I'm out to seek!" warns the one who seeks. His job is to find someone; those who hide must try to keep out of his sight. Again a conflict of interests.

Two prominent football teams "Dynamo" and "Spartacus" meet on the football field. One is to be the winner. There is no doubt that "Dynamo" is going to do its best. "Spartacus", too, is not lacking in resolution. A conflict of interests.

A conflict of interests exists not only in games. It occurs often, much more often than we imagine. Just follow from this viewpoint the course of one of your ordinary days. How often have your interest come into collision with those of someone else! Situations in which different people have different interests and dispose of different means of attaining different goals are very frequent in everyday life. In other words, all of us come frequently across conflicting situations. This happens so often that conflicts, collisions of interest, have been accepted as one of the main subjects of literature.

We overcome a conflict when we play chess with a friend.

A conflict is experienced by a child who in spite of his parents' wishes stubbornly refuses to go to sleep.

Conflicting is the situation of the vendor who, naturally, wants to sell dearer and the buyer who wants to buy cheaper.

The confrontation of rival political parties during an election campaign is an example of a political conflict in capitalist countries.

The conflict between the hare and the fox as biological species in the struggle for existence.

Conflict ... we imagine it to be a complicated, sometimes personal, often emotional and always a difficult affair. It is never easy to resolve a conflicting situation. Yet, modern mathematical science considers it feasible not only to analyse a conflicting situation, but even to "calculate" what line each of the rivals should take to attain his ends.

Mathematics has its own approach to collisions of interests, and the men to exercise it are specialists in the theory of games.

The first thing to do before the mathematical analysis of a conflict can be carried out is to clarify, to unveil the conflict of interests most rigorously, make them so clear and doubtless as in a game where even a layman sees who is on whose side.

That is just what mathematicians do: they build a simplified model of the conflicting situation and call it a game. This model-game is played in accordance with certain rules. For the sake of simplicity and clarity and perhaps by force of habit the mathematical theory of games adopted the terminology of ordinary games. The partners in the game are called players, the result—the gain or payment.

True, the context of terms is somewhat different here. In the theory of games several people with a specified interest confronting one or many adversaries may be termed a player, the same term being applied to the adversaries. Thus a player is just one interest group. A football match from the standpoint of the games theory would be "calculated" as a game of one player against the other. In this respect it is not different from a chess game.

The prominent French mathematician Louis Borelle already at the beginning of our century published a great many-volume *Course of Theory of Probability and Its Applications*. The last but one volume contained "supplements to games of chance". Here the scientist summed up the results of his extensive studies of games of chance which interested him from the mathematical point of view. Borelle introduced into the theory of games audacious and original ideas. His predecessors considered only cases where the course of the game was determined by chance and not by players. Borelle endeavoured to find a mathematical formula for the games which would take account of the proficiency of the players. In the course of time many scientists developed the theory of games to such an extent that it became much wider than the theory of games of chance, and its results found extensive application.

As is usually the case, the game is very difficult to explain, it is much easier to show how it should be played. And it will be easier for us to grasp the main concepts of the games theory with the aid of one of numerous examples cited by specialists.

Imagine two players A and B. Each of them independently of the other writes on a piece of paper one of the numbers 0, 1 and 2. Next they show the numbers to each other and add them up. If the sum is even, B pays A the sum of money equal to the sum of the numbers. If the sum is odd, the payment is made by A to B.

The writing of the numbers and showing them to each other is termed a move. The premeditated choice of a system of moves is termed strategy. A player makes the decision: "In such conditions I shall act in this way." And the gain of one or the other rival is, as you already know, termed payment.

Let's try to follow the course of the game.

The results of all possible moves can be envisaged beforehand. A writes 0 (zero), B writes 0, too. The sum is zero, and nobody receives anything. A writes 0, B writes 1. The sum is an odd number. A loses and B wins one rouble. A writes 0 again, B writes 2. The sum is even. Now B loses and A wins two roubles.

The same may be done with numbers: (1, 1), (1, 2), (2, 1) and (2, 2). It is easy to see that the number of possible combinations from which A and B have to choose independently is $3 \times 3 = 9$.

Let's denote by A_1 the strategy of A when he writes 0, by A_2 when he writes 1, and by A_3 when he writes 2. In the same way we shall denote B's strategy by B_1, B_2, B_3. All possible gains and losses (gains with the minus sign) can be summed up in a table.

The table containing gains and losses of the rivals resulting from the application of all possible strategies is termed payment matrix, and the game itself a matrix game.

What does an analysis of the payment matrix yield? To begin with, player A must expect player B to be sufficiently clever to evolve a strategy which would minimize the gain of A irrespective of the latter's strategy. Next, A must choose such a strategy that will guarantee him the maximum from the minimum gains. Such a strategy for A is to continue writing 0. In this case his loss will never exceed 1 rouble.

Likewise, player B will also choose a strategy which promises him minimum losses. To arrive at it we should look through the columns of the payment matrix and find the minimum gain of A.

The gains of A and B are written underneath the table.

The goal of the theory of games is to evolve recommendations for each of the rivals as to their tactics in the game. With the aid of these mathematical recommendations the rivals can choose the best (optimum) strategy that would guarantee them best results in the game. True, one strategy is practically never used throughout. The partners frequently change strategies, and they become mixed.

But notwithstanding the course of the game or the changes in A's and B's strategies the rivals always strive to act against one another; their interests are al-

Entries		Sum	Gains Losses	
A	B	Σ	A	B
0	0	0	0	0
0	1	1	−1	+1
0	2	2	+2	−2

A

	B_1	B_2	B_3	Minimum
A_1	0	−1	2	−1
A_2	−1	2	−3	−3
A_3	2	−3	4	−3

B

min·max = 2 *max·min = −1*

The strategies of the players A and B and the payment matrix.

ways clashing. A strives at the maximum from the expected gains (this is termed maximim); B, in his turn, wants to minimize the maximum sum he will have to pay A (this is termed minimax).

As you can see, the main aim of the player is to get maximum gain at the expense of his artful rival, who is determined to beat him. This means that the player wants to win but at the same time cannot count on his rival to make an error. The player knows that no matter how good his strategy is his adversary cannot fail to make the best response. For this reason, when calculating payments the player counts on the worst he can get.

But how to assess quantitatively how much one of the partners (both so accurate, so free from emotions, incapable of mistakes and capable of logical reasoning) is going to win? This is fairly easy. For every game there is a definite payment that a good player receives from another good player. This payment is called the price of the game. This price limits the gain: we can never win more than the price of the game, if our rival makes no mistakes.

Correspondingly, if we do not make mistakes, our loss will not exceed the price of the game. Which one of the rivals is going to receive the price of the game, and which one to pay it, depends on chance. Such chances in most games of chance for two perfect players are fifty-fifty. There are also games where nothing is left to chance, i.e. the initial conditions are strictly identical for both players. There the theoretical result is always a draw.

With this aim in view let's analyse another simple game with two adversaries and two strategies. The symbolic term for it is "the bombing mission". Suppose that two "Blue" bombers are sent on a mission. One carries bombs, the other radar jamming equipment, various equipment for the assessment of damage, etc.

The bombers fly in such a formation that the first is better covered by the guns of the second than the second by the guns of the first. There is the danger of the bomb-carrier being brought down by a "Red" fighter—there's only one fighter, and it can make only one attack before the bombers reach their target. The problem is which plane should carry the bombs—the first or the second, and which one should the "Red" attack, i.e. what should both adversaries do to achieve best results.

The following strategies are open.

"Blues"-1—the bomb-carrier in inferior position.

"Blues"-2—the bomb-carrier in superior position.

"Reds"-1—attack the bomber in inferior position.

"Reds"-2—attack the bomber in superior position.

Suppose, the chances of the bomb-carrier to survive are 60 out of 100 if it is attacked in the inferior position, 80 out of 100 if it is attacked in the superior position, and 100 if it is not attacked at all.

Let's write it out as it is usually done in the theory of games—in the form of a matrix.

Naturally, the "Reds" and "Blues" will have to change their strategies. It has been calculated that for every 20 cases of the first strategy there would be 40 cases of the second. Hence, the "Blues" should in the ratio 40 : 20 favour the covered position of the bomb-carrier. The same ratio (40 : 20) should hold for the "Reds" in attacking the covered bomber.

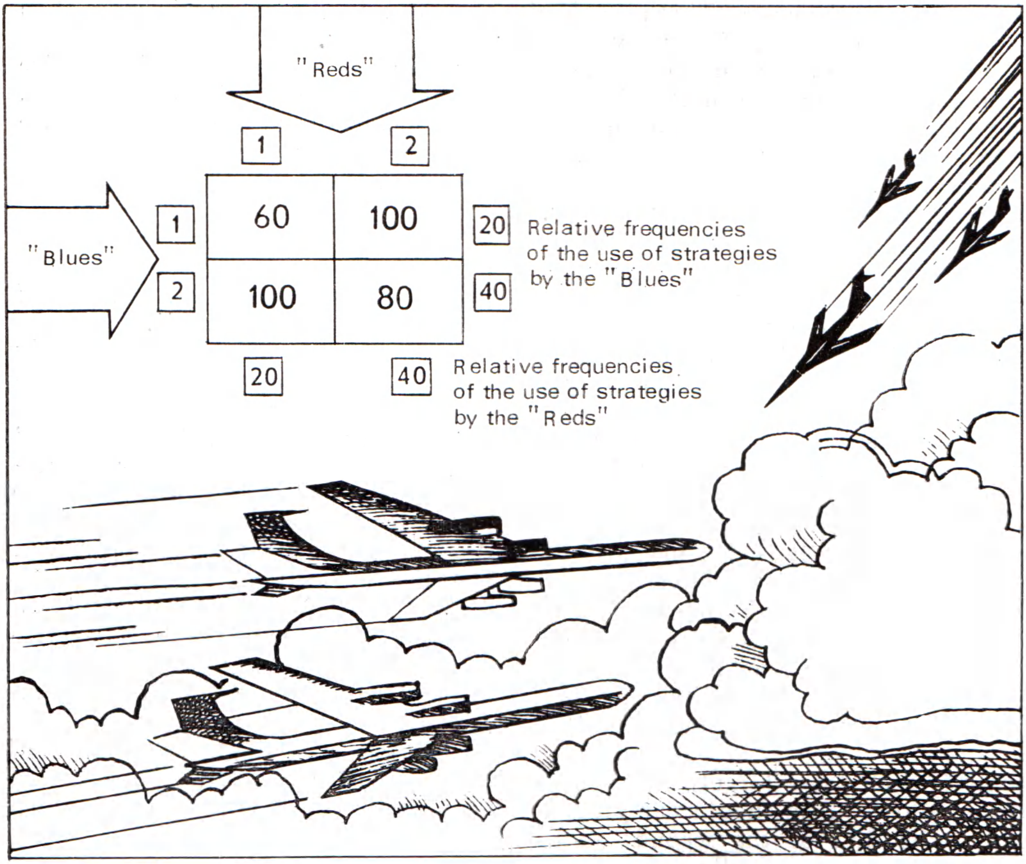
Now we can calculate the price of the game for the "Reds", i.e. the chances of the bomb-carrier to reach its target:

$$\frac{20 \times 60 + 40 \times 100}{20 + 40} = 86\frac{2}{3}\,\%$$

And now after tiresome logical reasoning read about a scandal that took place some years ago in Europe's casinos.

At first no one paid any attention to them. These young men strolled into casinos to watch roulette being played. They stopped at green tables and entered winning numbers in their notebooks. When asked for their motives they answered: "Just so, for the fun of it."

Two months later a storm swept



The game under the code name of "The bombing mission".

over Monte-Carlo, this capital of casinos. The same young men came back. But now they ceased taking down numbers and started playing themselves. And they did it without losing. Marvellous! Unexplainable!

The journalists started looking for an explanation. And they think they found it. It appears the young men wrote down winning numbers, these strange arrays of numbers, not for fun. Moreover, they encoded them and sent them over to their companion in London. The latter fed them into a computer. Evidently, the computer managed to do something that was beyond the power of man: having processed some millions of numbers it guessed several accurate winning combinations.

True, many specialists maintain that this could happen only if the roulette had some constant defect. But even if this was the case, it was not known either to the owners of the casino or to the people who took part in the calculations.

What was the amount of calculations the computer had to perform? This is not known. But some other facts are. One American mathematician calculated that in order to find winning combinations in the pip card game one would have to analyse 34 million card combinations. True, this is beyond man's faculties, but the eager-to-win mathematician got hold of a computer. He set it to work on a 10 thousand man-hour programme, and the computer calculated some "guaranteed to win" combinations.

In the "American case" the computer programme (algorithm for the search for combinations) was aimed at increasing the chances of a favourable outcome of the game, and to achieve it the computer tested mountains of numbers basing its play against an imaginary rival on the rules of the theory of games. It will be reasonable for you to remark that there wasn't much sense in creating a new branch of mathematics just to help people win in the games of chance. Of course, the theory of games wasn't created for the sake of this (let's note, by the way, that for such games as roulette and lotto there doesn't exist a programme of action which would always give a strictly definite winning strategy).

Games of chance, models of games play the part of guinea pigs which serve to test much more important problems of the theory of games.

Specialists in cybernetics try to evolve with the aid of the theory of games a rational line of conduct for all sorts of systems struggling against some other system.

What do we mean by the struggle of one system against another? Examples are manifold in different fields. For instance, the theory of games can be adapted for military communications' purposes, to anti-aircraft defence (of course, the problems there are much more complicated than the problem of the bombing mission that has been solved above), to problems facing a commander in action.

The work of an experimenter who draws up a programme of action—a plan of experiments—too, can be considered from the viewpoint of the theory of games.

The experiments may be considered to be a game between the scientist and the nervous system of the animal which he studies.

The economist planning the work of a producing plant "plays" against the moves of his "adversary"—the consumer.

In some respects the relations of the sides (for example, in the court) can be considered to be a game in which the rivals strive to attain opposite aims.

And in most cases in the games we have to operate with numbers and numbers again, to perform a maddening amount of calculations.

So it's not just by way of chance that computers are being taught to play different games: dominoes, chequers, fifteen and, of course, chess. Chess, boasting of an astronomical number of variants of the game—some $2 \cdot 10^{116}$!—open up a wide scope for research.

The computer match between the American and the Soviet chess programmes continued for a whole year. The scientists attached great importance to computers' skill displayed in the match, since the solution of some complex problems in the theory of games depended on the "chess-playing talents" of the computers, i.e. on the programmes compiled by the mathematicians, and this, in turn, could help in the solution of important scientific, industrial and military problems.

Now you see why the mathematicians play the "Reds against Blues" game on paper and teach electronic computers to play various games with expert skill, so that they would make an experienced top-grade rivals.

H

HEURISTICS

The science
that studies the laws
of creative activity.

Why This Way and Not That?

It's easy to guess that the science of heuristics derives its name from the world-famous exclamation of Archimedes: "Eureka!"—"I have found!"

What does this science study, what's its subject?

It studies creative activity. A man, referred to as creative, creates something personal, something different from what others have done: he composes symphonies, writes poems, paints pictures, makes scientific experiments and inventions.

Though the validity of such a concept of creativity is not to be denied, it is, as yet, too limited. To think of it, a doctor prescribing a cure to his patient solves his problem creatively. A detective investigating a crime also uses his creative abilities. A turner thinking of the way to improve the cutting tool for his lathe formulates a problem to be solved creatively.

Thus, the term creative activity should be taken to mean such a way of thinking which gives man a new system of action; makes him act in a new manner; discloses laws of nature previously unknown; makes man search for new information in order to use it.

Heuristics strives to penetrate into the secrets of creative activity, disclose technological methods peculiar to creative process, formulate its laws. It was by a step-by-step process that people came to understand the essence of creative, or as it is termed by specialists, heuristic, activity.

Previously it was assumed that there were no methods in such activity, it being a matter of inspiration.

But as the laws of thinking were established people began to discern the basic principles of creativity, and to try to find ways of explaining this interesting and sophisticated phenomenon.

At first scientists presumed that a whole crop of associations springs up in the mind, and they determine the creative ability.

But it was soon understood that associations cannot account for new previously unknown solutions. A more complete and accurate explanation was to be found. The result was the trial-and-error method. In essence the method consists in obtaining a solution through a series of probes, the erroneous probes being discarded.

Then came the turn of another trend—"Gestalt-psychology". Here the conduct of a man, his activity, is determined by his vision of the interconnection of elements in the problem to be solved.

These were not the only trends in the efforts to explain the nature of creativity. Neither individually nor collectively could they present a clear picture of this marvellous faculty of man.

With the appearance of cybernetics it was natural to apply its approach to problems of creativity.

The main questions of interest to specialists in cybernetics were: what is thought; what are the peculiarities of creative forms of brain's work; how does the brain arrive at new solutions?

Electronic computers were of major help in solving these problems. They enabled the study of heuristic activity to be made with the aid of models. A prominent place among these belongs to chess, which is truly the acid test for modelling thought. This is because chess is rich in conditions and possibilities—the number of possible combinations of figures on the 64 squares of the chessboard is too great to be imagined—$2 \cdot 10^{116}$.

In cybernetics every position of chess figures is presumed to correspond to a cross-point of a labyrinth.

Why make a labyrinth out of chess?

Let's first recollect a funny episode from Jerome K. Jerome's book *Three Men in a Boat* about Harris in the Hampton-court labyrinth.

"We'll just go in there, so that you can say you've been, but it's very simple. It's absurd to call it a maze. You keep on taking the first turning to the right. We'll just walk round for ten minutes, and then go and get some lunch," impeached Harris his relative.

But, alas! Not only did he lose his way, but he led astray people whom he undertook to help out of the labyrinth.

In accordance with his tactics Harris always took the right turn. Time went by as the party under his leadership sought in vain for the exit from the labyrinth throughout the morning. Even when they changed their tactics—now they turned indiscriminately—all their ways brought them back to the centre. This continued with such regularity that some members of the party simply stayed where they were and waited until the rest returned after their stroll.

Poor Harris didn't know as he strayed from one crossing of the labyrinth to another that thereby he was demonstrating the use of the creative method of trial and error and that if he could try out all possible ways he would solve the problem. But here the limit is set by time, and this, of course, will exceed ten minutes allotted for the purpose by Harris.

So, if all the variants of "in-out" ways are tried out, the problem will be solved.

And now see if you can try out all ways of a labyrinth with $2 \cdot 10^{116}$ crossings.

This is why "test possibilities" of chess are so attractive for specialists in cybernetics. Naturally, man doesn't try out all variants—he makes use of some other methods to cut short the way to solution.

Nowadays specialists in cybernetics try to rise above the simple "try-out" method and to approach the creative method of solving problems. This they try to do with the aid of heuristic programmes. The name speaks for itself. Computer programmes were based on the results of the studies of the process of problem solution—of heuristic activities—of man.

According to the authors of the new method, the task before them arose "mainly out of the desire to understand the essence of complex transformations leading to the successful solution of problems. For instance, it was our wish to understand how the mathematician arrives at the proof of a theorem not knowing from the start how to solve the problem or even if he will be able to solve it at all".

The most important thing in a heuristic programme is the strategy of the search for solution.

The computer working to a programme assesses the results of intermediate operations and accumulates in this way additional information.

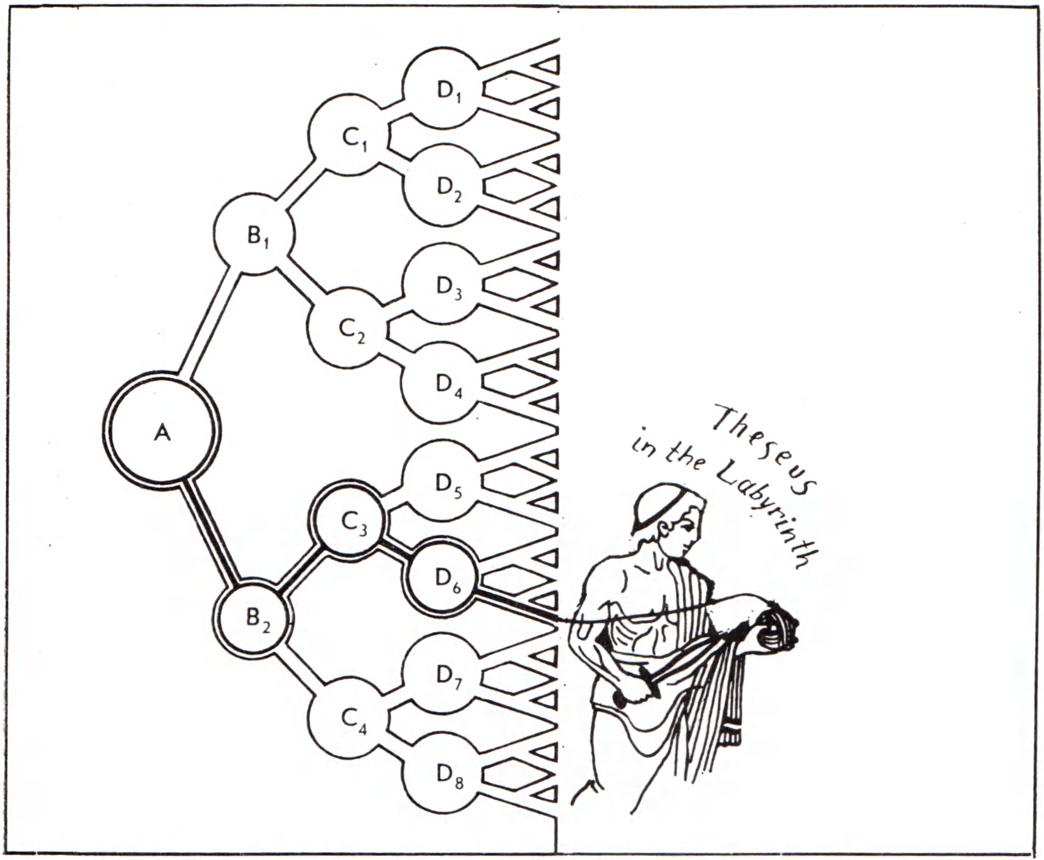
Heuristic programmes discard search variants which do not promise success and concentrate on searching for a solution in the directions where such a solution exists.

Here is a diagram of a labyrinth and its crossings. It will serve as an introduction to one of heuristic programmes called "the universal problem solver".

The solution of the problem of exit from the labyrinth by the "try-out" programme would involve the testing of all variants—even those that are known to be senseless, such as walking around a crossing. In heuristic programmes chance elements are also present, such as arrival at a "good" crossing by chance.

To cut the number of crossings (or ways) being tried out "the universal problem solver" makes use of the terminal crossing of the labyrinth-problem and of the distance to this terminal crossing.

The computer begins its work according to programme by testing variants issuing from the entry. The testing continues until the programme reaches a crossing nearest to the terminal. In our diagram we denote such a crossing by B_2. Then testing begins anew and results in a new jump—nearer to the terminal. Now our programme has reached the crossing C_3. New tests, followed by a new



A diagram of a labyrinth and its crossings.

jump. And so on until in the course of some test the programme reaches the terminal D_6. Thus the last jump leads to a successful solution of the problem.

Have you noticed that "the universal problem solver" divides a problem into several simpler problems? That's what makes it different.

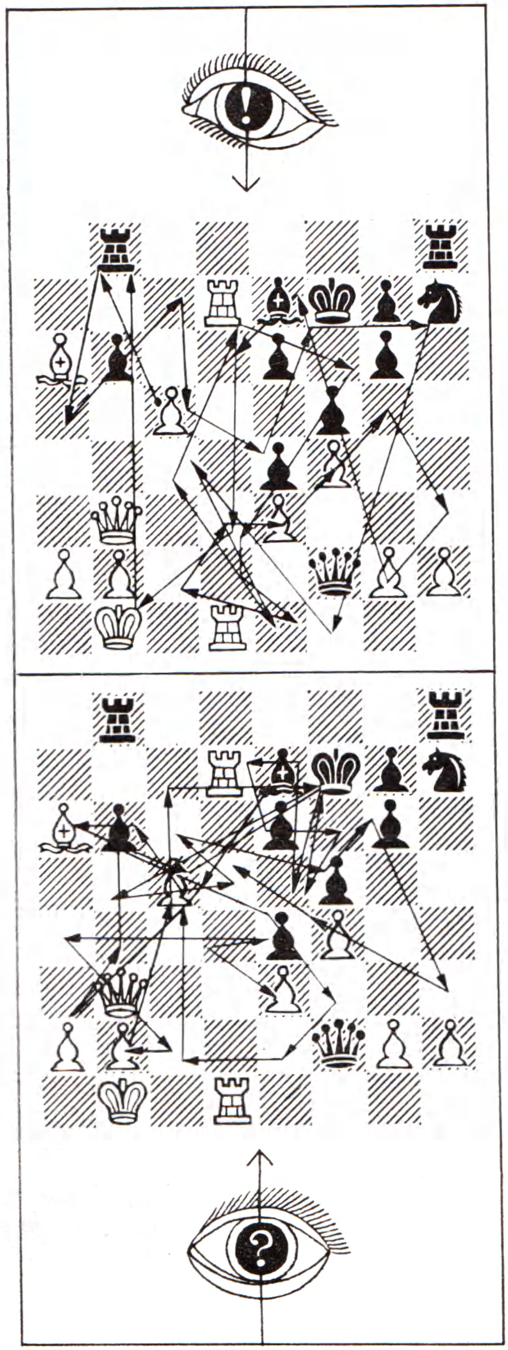
But have you noticed as well that notwithstanding the difference of heuristic programmes from simple "try-out" programmes the test method still plays a big part in the "universal problem solver"? So it turns out that the computer can tackle such problems only because it works very fast. A man working much more slowly (a hundred, or a thousand times slower) can, on the other hand, successfully solve problems of the "chess type".

This conclusion makes some specialists cast doubt on the universal validity of heuristic programmes. In their opinion creative heuristic activity of man cannot be attributed merely to heuristic programming which helps to cut down the number of possible variants. It's more probable that man works out his strategy on the basis of a quite different process.

What is this process?

Let's return to chess. A position in the middle game can be taken as the entrance to the chess labyrinth and mate as the exit. Hence there are numerous entries and exits in chess, and the number of ways leading from each entry to each exit is so great that in testing variants one runs into gigantic numbers.

Some interesting experiments with chess have been carried out at the Institute of Psychology of the Academy of Pedagogical Science. They lead to the assumption that heuristic activity of man is based on the construction of situation models. For instance, looking at a complicated chess position man of all the figures chooses only those the interconnection of which is to be established. Thereby he at a stroke discards many moves and shortens his "wandering through the labyrinth". In this way man formulates his strategy of behaviour arriving through the models of individual elements at the situation as a whole. In other words, the crux of the matter is how the man sees the whole problem and the individual elements of the problem.



The diagram at the top depicts the movements of a chess-player's eyes when he tries to memorize the position. Below are the movements of the eyes of a chess-player solving a chess problem.

It is true that up to now heuristic programming has, too, failed to divulge completely the mechanisms of human creative activity. But a great stride forward in this direction has been made: new programming principles have led to the idea of studying the work of the brain on a new, intermediate level—on the level of information processes. This will make it possible to link information processing with the physiology of the brain.

This method has been compared to the method, used in chemistry, of decomposing complex chemical compounds into simple elements.

Heuristic programming and heuristics as a whole are of special importance for the progress in electronic computers. Before the advent of heuristic programmes electronic computers were able to solve only problems rigorously limited by mathematical description. Now it appears possible to solve problems devoid of such a description.

From the point of view of heuristics modern electronic computers have many deficiences: they are straightforward, unintelligent, inflexible, not clever, etc.

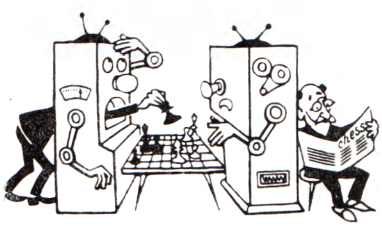
The role assigned to heuristic programmes is to find means of making the computer sharp and clever, capable of finding its way in an unexpected situation. This was the idea behind the famous "electronic" chess match between the Soviet and American computers which took place in 1966-67.

American scientists in all games adhered to a single heuristic programme. Soviet scientists used two programmes—one simplified, another, in their opinion, more sophisticated. This opinion proved right—the second Soviet programme won.

This match right from the start took on the character not of a sports game, but of comparing scientific ideas. As is often the case in cybernetics, chess was used to test the principles of heuristic programming with the aim of increasing the capabilities of computers in a wide field of their application.

Look at a modern computer centre. Even in such a highly automated plant many preliminary operations are made "by hand". Heuristic programmes will put an end to this. The possibility will become real of going over from partial automation of "white collar" work to full automation.

In the opinion of specialists, the use of heuristic programmes in medicine, transport, astronautics, physiology and neurophysiology, production control and many other important fields of science and technology will be very effective.



I

IDENTIFICATION OF IMAGES

The theory and principles of systems capable of recognizing objects, phenomena and situations and of grouping them into images.

What Is What?

Nobody wonders at one of the most marvellous faculties of man—the ability to recognize objects. No sooner have we seen, than we already know what is before us: a ship, a butterfly, a cup, an elephant, etc. We recognize it instantly and unerringly, be it the object itself or its reduced or enlarged image.

This amazing faculty is no wonder to us; its loss, on the other hand, is considered to be unnatural, to be a symptom of a malady....

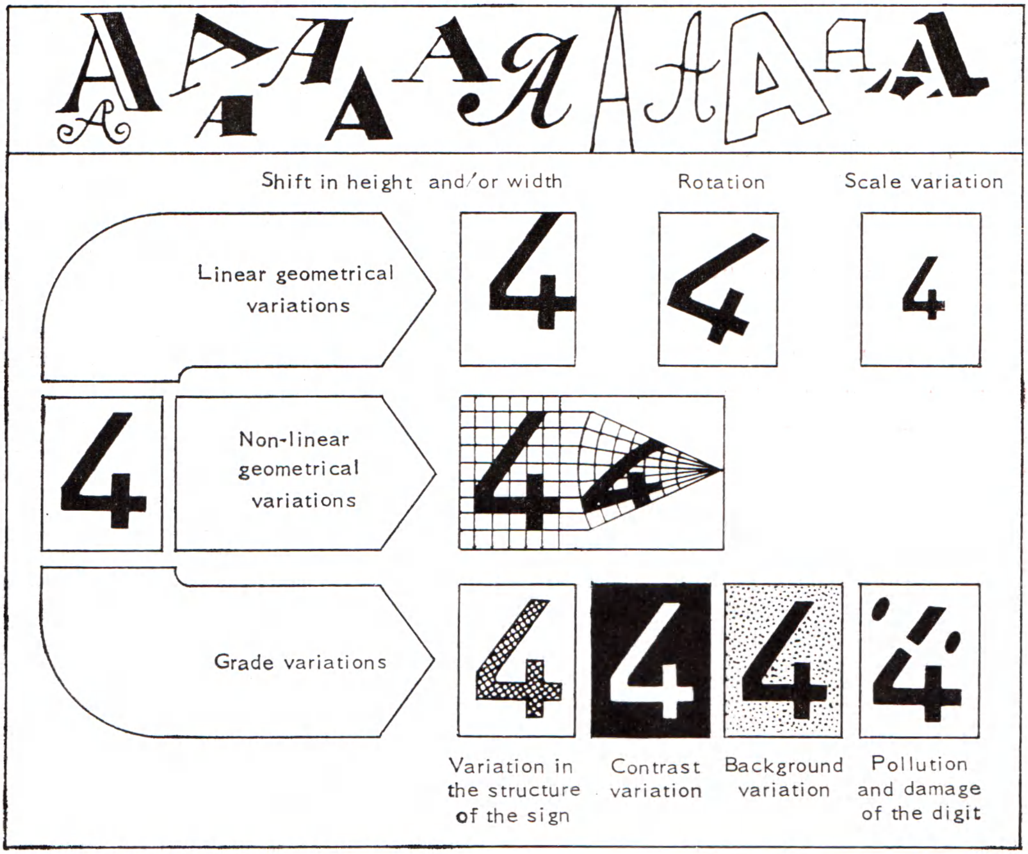
We live surrounded by images—by phenomena, by objects, by situations. When we perceive them we always combine similar images into groups—classify them. Frequently groups of similar images contain quite different objects, but something in them must be similar, some of their basic principles must be identical.

Let's take ABC letters as an example. No matter in what "difficult" handwriting they may be written, we shall always recognize the letter "y" as the letter "y", the letter "d" as the letter "d", the letter "z" as the letter "z".

Or let's compare two quite different drawings: a human portrait drawn by an artist and a picture drawn by a child. The difference is striking, yet there is a likeness as well: nobody will be in doubt that both artists—the grown-up and the child—have depicted a man.

These examples will suffice. You may say that all this is evident and does not need explaining.

Evident? Is it really so?



We call all the figures shown at the top the letter "*A*", despite the great difference of shape. Any sign of the written language—a letter or a digit—may experience all sorts of distortion in the course of writing.

Man has the faculty of recognition from time immemorial. And yet, up to now scientists have not found out how he does it. How does he manage on the basis of barely perceptible signs and frequently incomplete characteristics to construct in his brain the concept of an image? Of the image that plays a major part in his perception of the surrounding world and in the processes of its cognition and revelation of its secrets.

And here again we encounter a paradox—one of many that spring up when we deal with the riddles of human brain, of human mentality: scientists don't know how man builds up an image, but they know the value of this faculty. They maintain that the perception of actual phenomena in the form of images enables the memory to be used more sparingly. This is because the image makes it unnecessary for us to remember innumerable concrete objects and phenomena. The image, in particular, enables us to make use of accumulated experience.

Scientists state authoritativety that without the ability to group objects into images we would be puzzled by every new phenomenon (just like the electronic computer), since no object, no phenomenon is an exact repetition, a precise copy of those we met before.

How do we acquire this faculty, the value of which can hardly be overestimated?

Through education, of course.

In the course of education, as his experience accumulates, man learns to classify what he sees, to recognize images.

At this stage scientists come face to face with the question which is quite unexpected to the layman but quite legitimate for a cybernetician: can the electronic computer be taught to model the process of image identification?

We are tempted to answer this question with a citation from a specialized encyclopaedia publication:

"The solvability in principle of the image identification problem follows from the ability of human beings and other living organisms to identify images. The ability to classify complex situations in animate nature is acquired through education. It is, therefore, advisable to apply the principle of education to the creation of classifying automata. The latter is possible even if the designer is initially ignorant of the features constituting the basis of classification, provided he disposes of an adequate number of examples of situations being referred to a certain class."

Since it was deemed possible in principle to create an identifying machine, scientists all over the world began looking for ways to implement the principle.

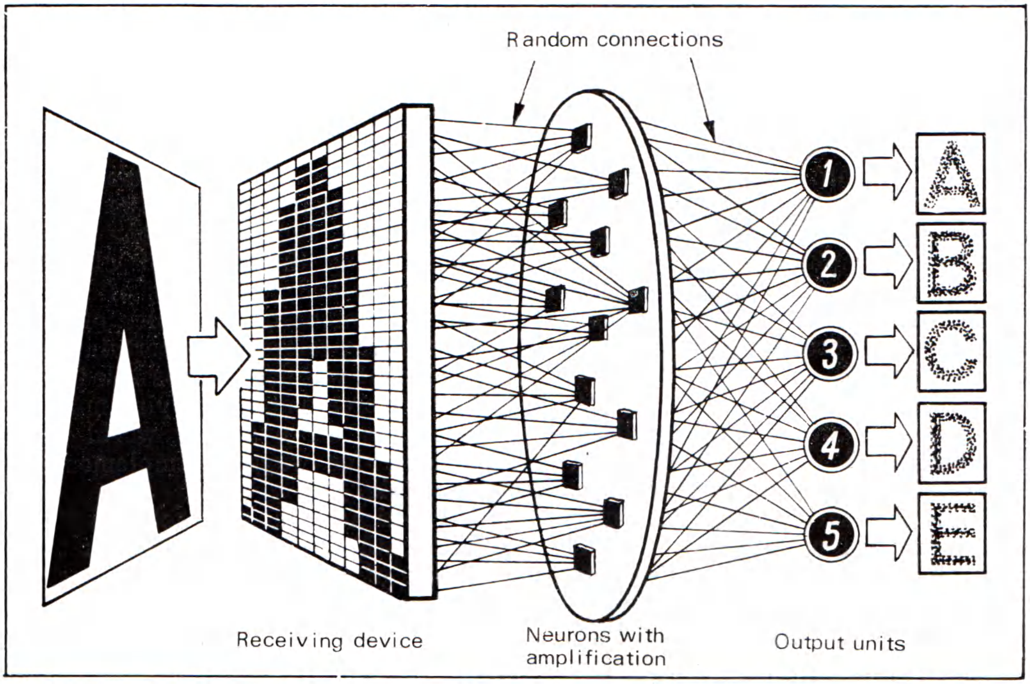
The American cybernetician F. Rosenblueth built one of the first machines of this kind and called it the "perceptron". The name stuck.

The "perceptrons" are reading machines. The scientists worked long and hard to educate the computers. At last, these "literate" automata were born. To tell the truth, their looks can hardly be distinguished from those of their "illiterate" brethren—the same familiar narrow metal cabinet. Only with "eyes"—screens. This optical eye of the photo-voltaic cell scrutinizes the text and enables the machine to identify the images of letters.

Let's try to find out how the perceptron works.

Let's start with the American machine. There is a screen in front—an artificial retina made up of four hundred photo-voltaic cells. The screen perceives the image. The electric signals which are generated in the retina when an image is perceived reach the first row of "neurons"—electronic elements designed to model nerve cells. There is another "neuron" above them—the main neuron—which receives input signals from the lower row. A special device provides "punishment" signals. This is the skeleton diagram of Rosenblueth's perceptron.

Now several letters are placed before the screen. They, naturally, vary in trans-



This is how a perceptron works. After the process of learning the letter "*A*" has been repeated many times to a satisfactory result, the system is "turned over" to the letter "*B*", and so on.

cription. However, the machine recognizes them, confidently distinguishes "a" from "b", "b" from "c"—in fact, any letter from another.

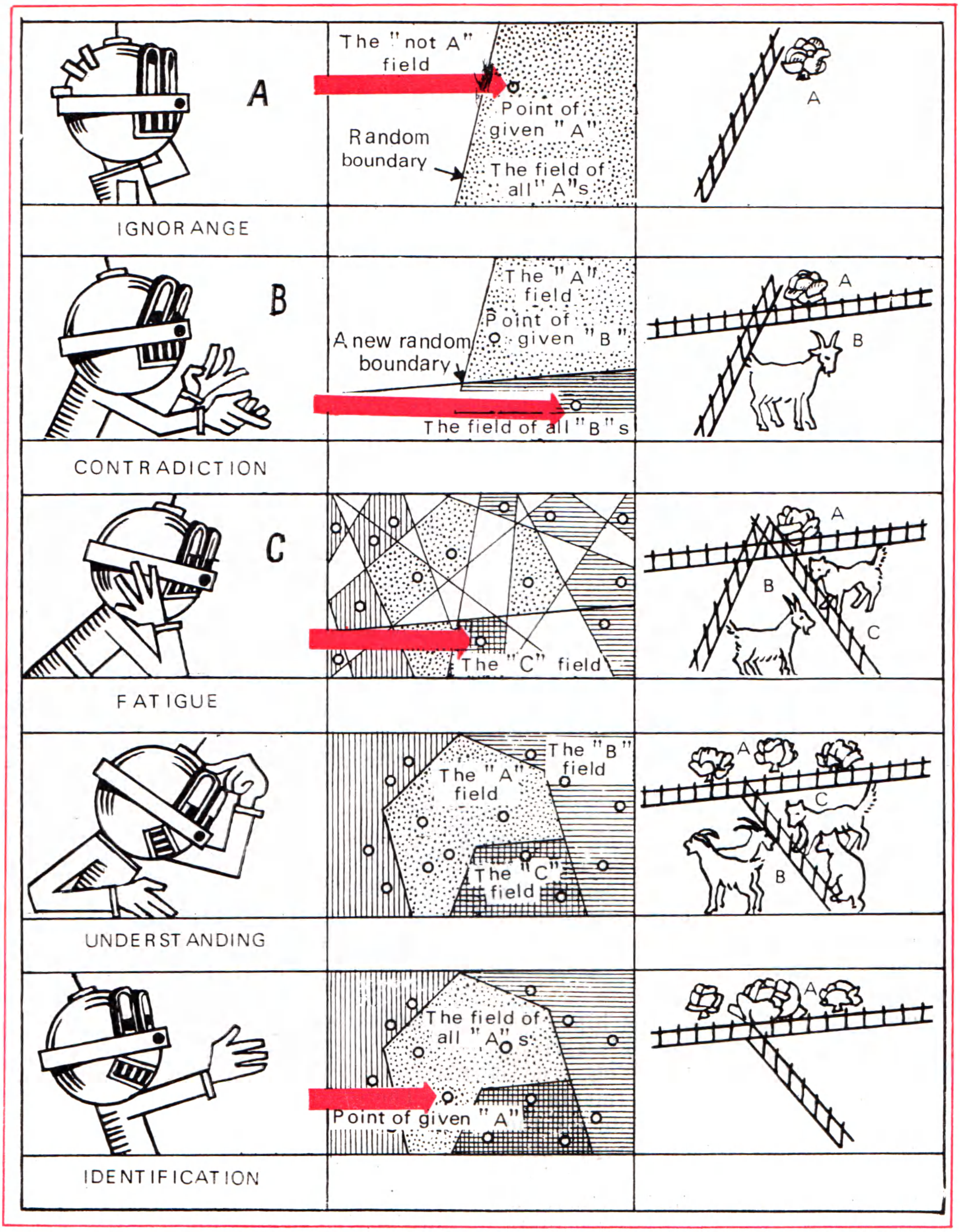
Did it take long to teach the machine this art? Yes, quite long. At first the perceptron made many mistakes and was "punished" for them. When the machine made a mistake, the operator pressed the "punishment" button, and the signals of the wrong answer reaching the main "neuron" were attenuated. Then the figures were again shown to the machine, and its answers were assessed again. When all signals assembled to the "conference" presided over by the main "neuron", the "culprits" were in minority.

In this way the machine heeding its own errors learned to identify images.

Soviet scientists devised a quite different principle of identifying images. It is based on the hypothesis of compact sets. Let's see what it is.

The teacher wants to teach a youngster to identify an image, i.e. the letter *A*.

An identifying machine based on the principle of "compact sets". A point, corresponding to the given letter, falls inside a definite field. The machine remembers the image the points of which occupy this field, and identifies the letter. ▶


A
The "not A" field
Point of given "A"
Random boundary
The field of all "A"s
A
IGNORANGE
B
The "A" field
Point of given "B"
A new random boundary
The field of all "B"s
A
B
CONTRADICTION
C
The "C" field
A
B
C
FATIGUE
The "B" field
The "A" field
The "C" field
A
C
B
UNDERSTANDING
The field of all "A"s
Point of given "A"
A
IDENTIFICATION

To this end he tells him about the features by which this letter may be recognized, for instance, by two inclined sticks with a cross-bar in between.

However, there's another way open to the teacher. He may lay out before the pupil 20 different letters *A* and tell him that they all are *A*'s. After that he will show him 20 letters *B*, 20 letters *C*, etc. And the pupil will begin to recognize the letters unfailingly. He has evolved for himself the visual image of each letter and will not fail to recognize them, no matter how they are written.

The hypothesis of compact sets is based on the assumption that when man sees the letter *A* a point—the image of the letter—is instantly fixed in his mind. When next time he is shown the same letter, but in a different handwriting, another point is fixed in the vicinity of the first. The different transcriptions of the letter—the third, the tenth, the hundredth are all reflected by corresponding new points fixed in his mind. But all these points are arranged in a compact lot.

Lots of points that reflect the different transcriptions of *B* form another compact set. The same happens with the images of other letters.

And each set is separated from the other by clearly defined boundaries—they are divided by a sort of fence.

"Is there a need for an identifying machine?" you're going to ask.

Since the "electronic calculators" work with the speed of lightning, it will not be difficult for them to compare hundreds or even thousands of features of various images with the standards that can be introduced into the computer "memory".

This is all true. But one shouldn't forget that the capacity of the computer "memory" is always limited. Moreover, there are no two images exactly alike in the minutest detail. It turns out that, if all features are strictly taken into account as should be done for a computer, it is even impossible to find two identical type letters. What then remains to be done? To describe each image with scrupulous precision? This is a totally impractical task.

And there is still another obstacle: computer operation according to "standards" is impossible without the collaboration of man. It's man who has to describe the standard and provide a whole set of features by which the comparison with the standard should be made. The scientists, however, have set the goal to teach the computer to identify images by itself. This is no idle task aimed only at solving an interesting theoretical problem, but one that will enable identifying machines to be used in practice.

The need for such machines in practice is very great. Here's a vivid example of the way in which a perceptron could be useful. Imagine a geologist who has to decide on the evidence of geological survey whether a given stratum is oil-bearing.

The interpreter-geologist (there is such a profession) analyses the data relating to the properties of the stratum, assesses its electrical, radiative and geometrical characteristics.

There's literally an ocean of combinations of characteristics that correspond to an oil-bearing stratum. A water-bearing stratum, from which the interpreter has to distinguish the oil-bearing stratum, has just as many.

The task becomes immensely more difficult because there are no rules in geophysics for classifying the stratum as water- or oil-bearing. And this gives rise to mistakes—a very considerable proportion of them, from 5 to 80%. No wonder, then, that the possibility of setting up an automatic classifying system is being closely studied. Such a system using definite characteristics would be able to solve the problem of oil content in the stratum infinitely more accurately.

The nature of information automata, too, would experience a great change. The machine would be able to operate at sight. This would obviate the translation of the text from the "human into the machine language", and enable direct communications with the machine to be established.

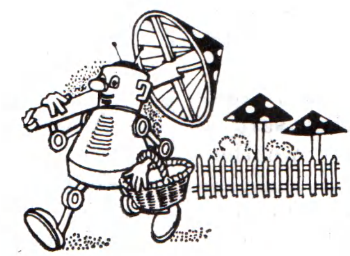
With the aid of the identifying machine it will be possible to automate the recording of reference data for electronic computers the amount of which is at present estimated as being equivalent to several billion words; to automate the sorting of letters at the post-office; to process bank documents; to automate type setting, etc.

Obviously, mechanized translation, too, will be greatly facilitated.

There is another point, as well, to the exploitation of identifying machines. Having started by imitating man's ability to perceive images of the world around him, the perceptrons will end by helping to reveal the mechanism by which man "builds up" images, classifies phenomena, events and objects.

There are different roads along which scientists of various specialities approach the solution of the problems of identifying images, a problem that is important both in principle and in practice.

This is unavoidable and justifiable since the task of creating identifying machines is extremely difficult.



"Mushrooming."

The isolation
of characteristics
which unambiguously define
a sound of speech.

Let's Talk Like Human Beings

Man. Were you glad it rained this afternoon?
Machine. No, I prefer sunny weather.
Man. In hot weather man needs at least one bath a day.
Machine. Yes, I was outdoors and suffered from heat.
Man. When Xmas comes it will be cold.
Machine. Cold? Yes, it's usually cold in December.
Man. Today the weather is fine. Will it continue so for a long time?
Machine. Permit me to refrain from lying. That would better suit a salesman. How can rainy weather be fine?

This dialogue between man and machine isn't an excerpt from a science-fiction story. It was conducted in plain English several years ago at the Toronto University in Canada.

The American computer nicknamed "Brick" because of its small size, hasn't as yet learned to speak. However, it can identify spoken words which have something to do with arithmetic.

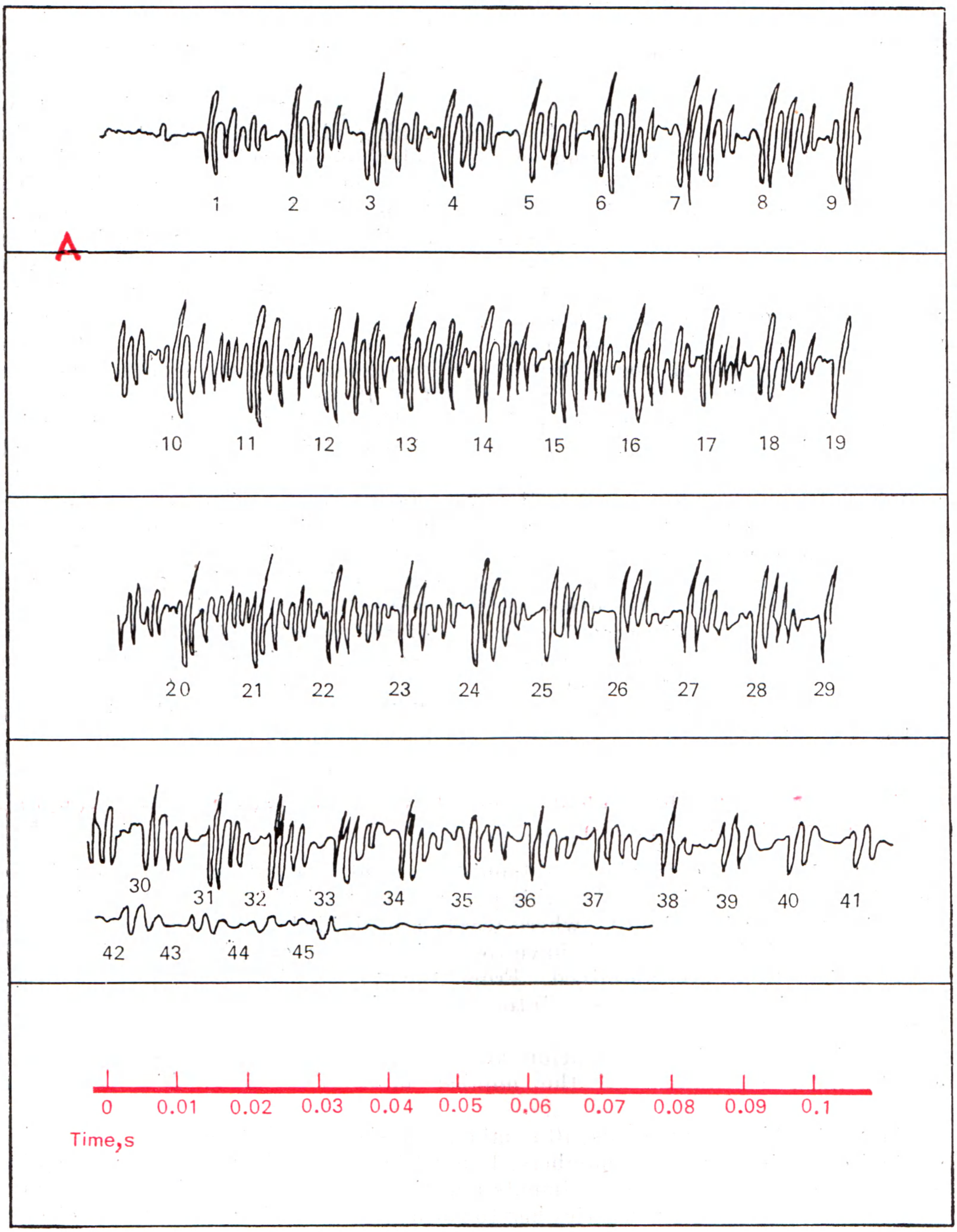
The "Brick" is quite fastidious. It can't stand poor pronunciation and demands precise and clear diction. Probably, for this reason it cannot very well understand words addressed to it by women. For the sake of fairness to avoid being too captious to the "Brick" it should be remembered that another representative of the breed of talking machines, too, has a "capricious" character. It "lives" at the Institute of Linguistics of the Georgian Academy of Sciences. It was taught to pronounce words and phrases in the Georgian language. It coped well with this task. Then an attempt was made to "tune" it over to Russian speech.... It spoke with a peculiar southern accent.

To "teach" the computer to speak with man scientists spend a lot of time and resources "stuffing" the computer memory with huge information.

There is no end to information that the computer working to a programme deferentially called "Sir" had to digest before it could answer a question quite elementary by our standards—as to the number of fingers John has.

Isn't that really very interesting—a machine capable of listening to and understanding human words? Na-

The sound wave producing the sound "A". ▷


A
1 2 3 4 5 6 7 8 9
10 11 12 13 14 15 16 17 18 19
20 21 22 23 24 25 26 27 28 29
30 31 32 33 34 35 36 37 38 39 40 41
42 43 44 45
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.1
Time,s

turally, everybody would like to know how it can identify sounds. The answer is twofold: it is, at the same time, easy and difficult to identify sounds. At first let's find out about the easy side—the acoustical, physical aspect of the problem.

Sounds are, by nature, vibrations of air, waves of varying length. Every sound is characterized by a corresponding frequency. In consequence, sounds may be produced not necessarily with the aid of vocal chords, they may be synthesized.

For this purpose the machine is made to listen to words pronounced many times by the same person and by different persons. Naturally, everybody pronounces the same word in his own manner: the timbre of the voice, the intonations, the purity of pronunciation are all different. The machine has to "average" over individual pronunciations, exclude individual hues, so that when it hears the familiar word in future it makes no mistake.

What takes place inside the machine?

The processes are similar to those taking place when you talk over the telephone or radio: sound oscillations are transformed into electric oscillations. Special filters filter them according to their frequencies. Then their "pattern" is compared with that of the standards stored in the machine's memory. This "pattern"—the image of the sound—is the average sound that the machine has been taught to identify.

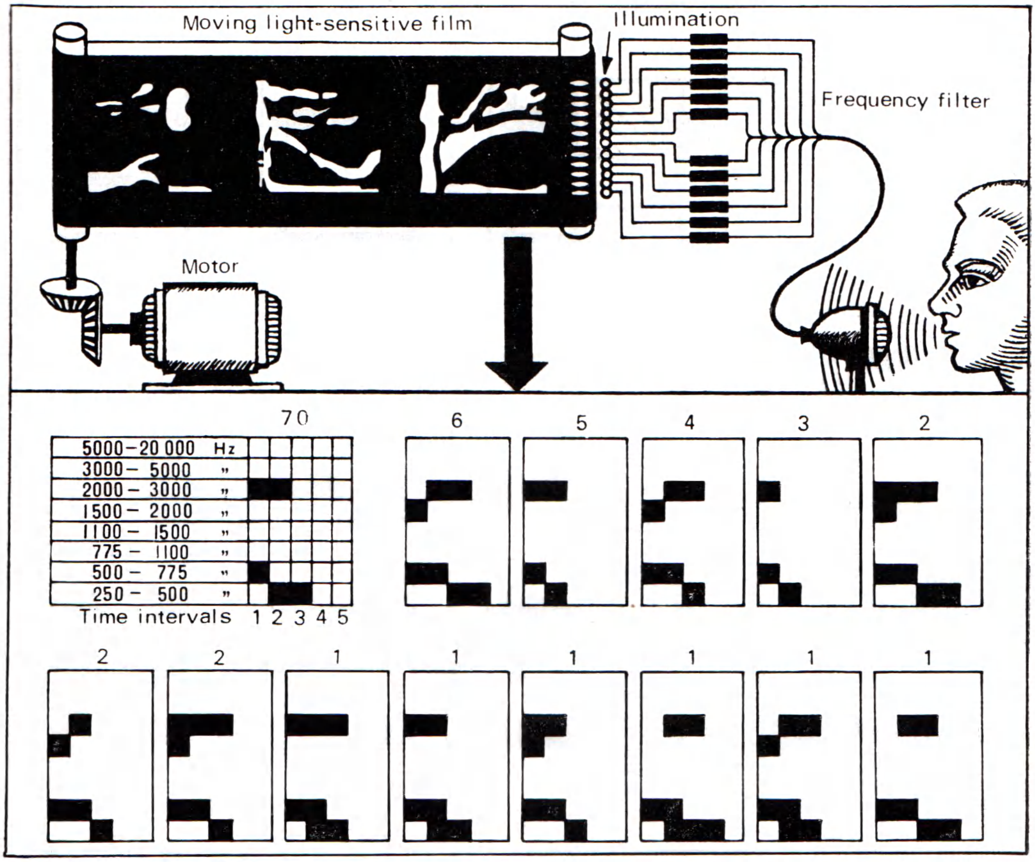
The production of the pattern is a rather difficult and monotonous job. For instance, in one experiment the man under test pronounced the sound "a" 100 times. The sound was described 100 times by 14 variants of pronunciation, also called images. Next the frequencies of appearance of the resulting images were compared. Out of 14 variants one was encountered more often than the others. This image was recorded in the machine's memory.

The machine is taught to identify speech in various ways: by words, syllables, phonemes (individual sounds).

The "Brick", for example, was taught to identify words by the alteration of voiced sounds and sibilants. For this purpose the "Brick" has been supplied with a special "separation circuit" where words are divided into groups according to their characteristics. The words have to be distinctly spoken into the microphone, after which they are amplified. From the "separation circuits" the words transformed into pulses pass into the registers and the computing circuits.

Here the results of the separation are analysed. The number of the output circuits must correspond to the number of words the machine can identify.

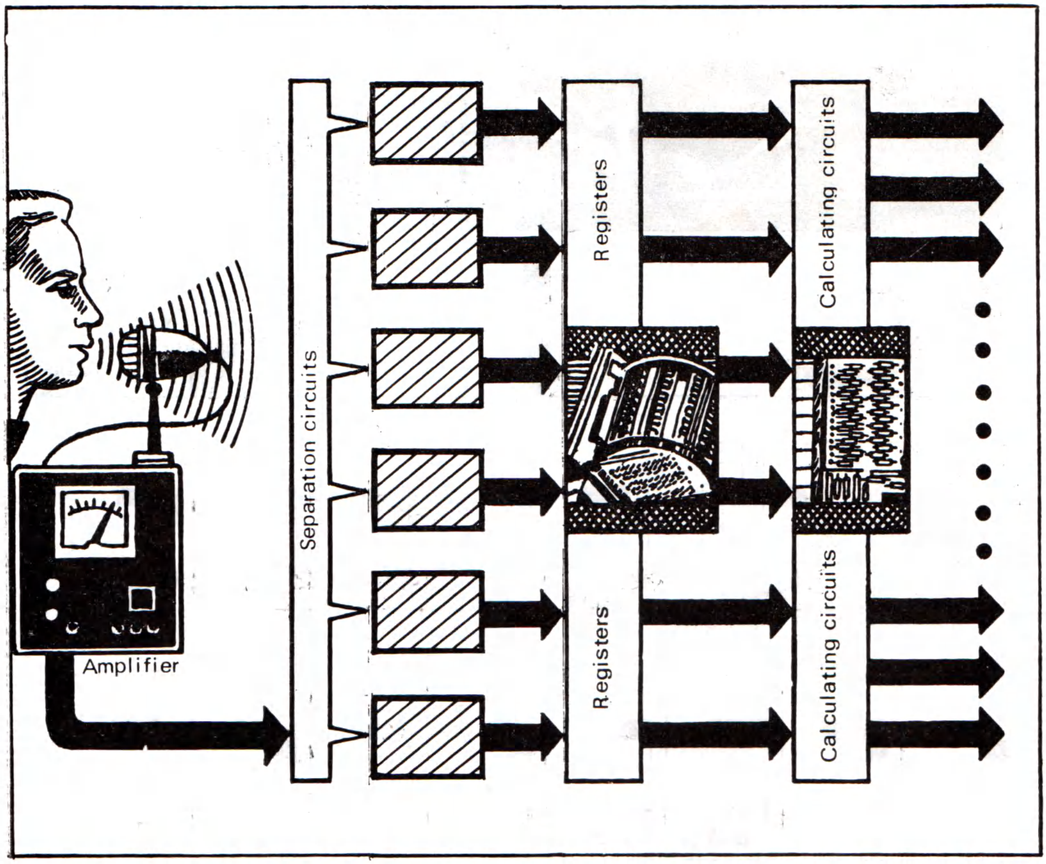
The "Brick" knows 16 words, 10 numbers and six special orders relating to arithmetical operations with the numbers. It must be admitted that this work requires a lot of money, resources, experiments and time. And still, this is an easy job as compared to obstacles cybernetics has to surmount in solving the problem of identification of speech.



This is how speech is made "visible". The microphone converts the sound into electric current of corresponding frequencies. This current is passed through the frequency filter. Each filter corresponds to a definite sound pitch range. Small electric lamps are connected to the filters, and their brightness changes with the changes in the current intensity.
The brightness changes are recorded on the light-sensitive film. Below are fourteen different pictures obtained when the sound "A" was pronounced 100 times.

Now let's tackle the subject of the difficult side of the problem. The machine must be able not only to identify sounds, but to understand speech. To understand speech is a totally different matter. At present the machine cannot understand any of the living languages.

Almost any spoken phrase may be understood differently. Even a phrase as simple as that: "The factory produces tractors" is too difficult for the machine to understand. And homonyms that sound identical but have different meanings? And images, hyperboles, comparisons? How can the machine be made to understand them?

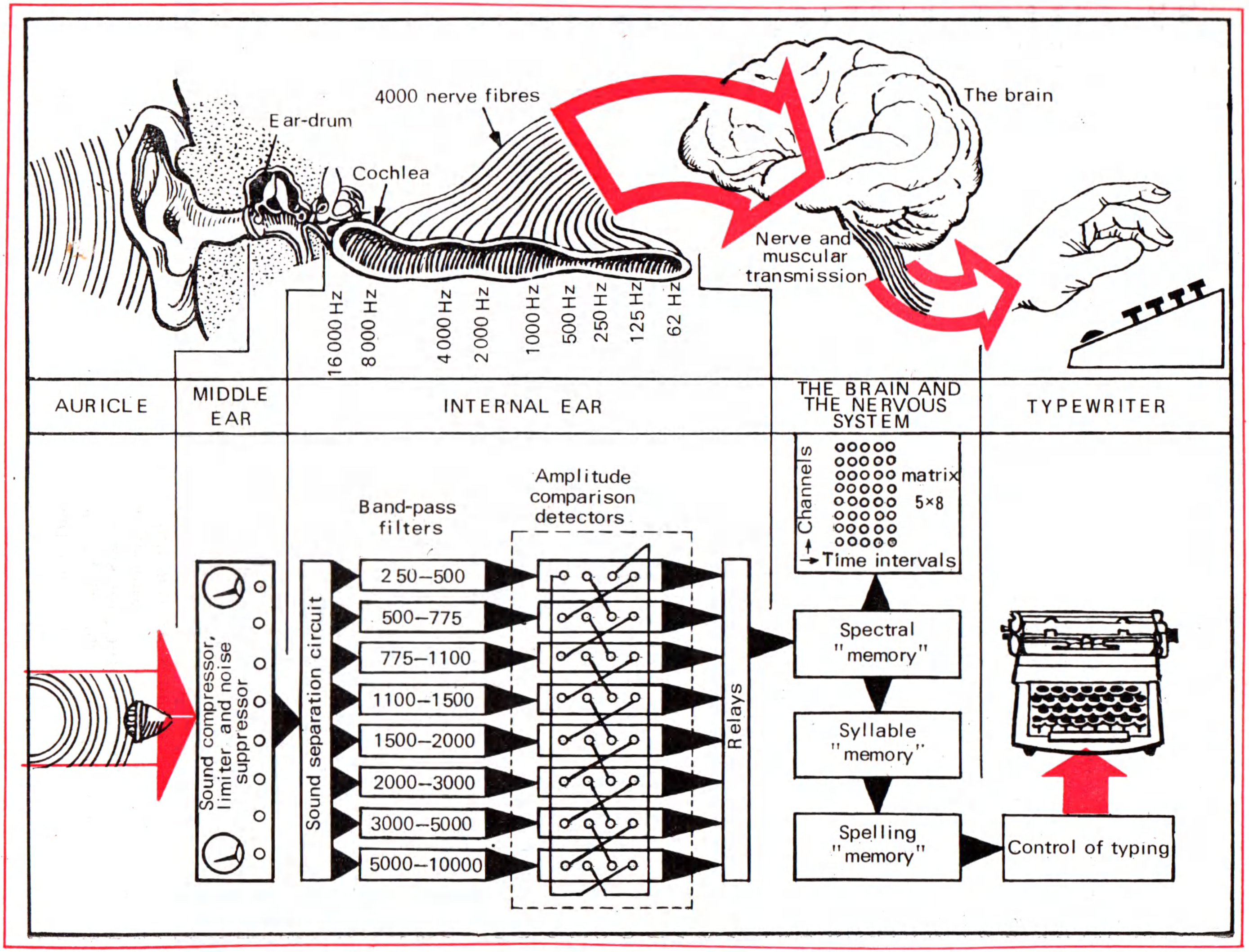


The computer "Brick" identifies words by the alteration of voiced sounds and sibilants.

The machine is not flexible, it is awkward in perceiving words, unable to distinguish between the shades of emotion and of meaning. It is incapable of figurative thought: dry logic, strict unambiguity, rigorous precision—that's what it needs, and no freedom, no flexibility, no allegories!

It is immensely difficult to overcome this semantic barrier, to make the machine understand live human speech! Scientists use various methods, try various "pedagogical devi-

The dictation typing machine identifies over fifty single-syllable words. Amplified sound is passed through the filters where it is separated by frequencies and transmitted to the comparison block. Here the sound is re-coded into numbers. Next the digital code is compared with the codes of the syllables to be identified previously recorded in the "memory". If the recordings coincide, this means that the appropriate syllable has been found, and the machine prints it. ▶



4000 nerve fibres
Ear-drum
Cochlea
The brain
Nerve and muscular transmission
16 000 Hz
8 000 Hz
4 000 Hz
2 000 Hz
1000 Hz
500 Hz
250 Hz
125 Hz
62 Hz
AURICLE
MIDDLE EAR
INTERNAL EAR
THE BRAIN AND THE NERVOUS SYSTEM
TYPEWRITER
Sound compressor, limiter and noise suppressor
Sound separation circuit
Band-pass filters
2 50–500
500–775
775–1100
1100–1500
1500–2000
2000–3000
3000–5000
5000–10000
Amplitude comparison detectors
Relays
Channels
Time intervals
matrix 5×8
Spectral "memory"
Syllable "memory"
Spelling "memory"
Control of typing

ces" on their metal pupils. Among them the method of the Soviet scientist Andrei Ershov has been recognized as the most effective. Here's how the author himself describes the method and the underlying principle.

"Suppose, the machine 'speaks' some input language that represents a sufficiently comprehensive formalization of the Russian language. Man ignorant of this language addresses the machine in any convenient form. The electronic computer has a programme which determines whether the given text is comprehensible or not. If the computer understands the text, it starts working on the problem. If it fails to understand the text, it will ask additional questions laying stress on vague points. You'll answer, again in the form you will think best. These answers will be a kind of paraphrase of the points the machine failed to understand—the same ideas expressed in other words. Having received these paraphrases the machine inserts them into the original text and analyses it again. If anything still remains obscure, it will again put additional questions. In this way a dialogue will start between man and machine. In the course of this dialogue man will continue to simplify the formulation of the task until the machine understands it.

"Such a dialogue can be compared to that of a teacher and a negligent pupil. The pupil has no desire to understand what the teacher wants from him and continues asking questions until everything is spoonfed to him. With the machine the situation is more difficult. The dialogue of man with the electronic computer may be characterized as the adaptation of man to the capabilities of the computer, as a sort of 'getting used to one another'.

"... The relationship between man and computer should be such that with each new task the computer would learn to understand better, so that in case of similar tasks the computer would not repeat similar questions.

"In other words, the computer should be made to retain in its electronic 'memory' the records of all its conversations with man and to use the newly received tasks in its future work. This is tantamount to teaching computer human language."

But in the meantime.... We speak with the computer in the form that's convenient for it rather than for ourselves. However, rapid progress of computer engineering and extensive use of electronic control systems require closer ties between man and computer. Communications between man and computer must be made free of delays: man says, the computer carries out. To achieve this end efforts are not being spared to teach the computer understand human language.

The advantages of a close contact between man and computer are undisputable.

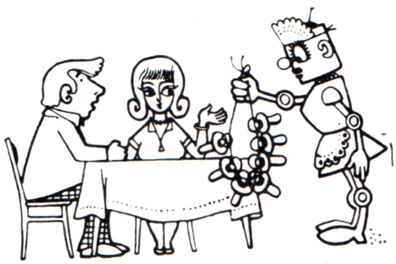
Just imagine how this would simplify the job of the specialists in computer translation. There would be no more need for coders who convert the text into the number code. Just read phrases distinctly and clearly into the microphone—the computer will understand everything.

Or an information machine that having heard a question as to where, when, by whom, to whom, for what invention a patent was issued would instantly hand you a precise and comprehensive reference.

Everywhere would there be room for talking and understanding machines. "Electronic arithmometers" would perform arithmetical operations on voice orders. Control systems would receive oral information, process it and issue necessary commands. Such machines could be employed in scientific research centres, in industry, in transport.

And how great is the need for such machines! Already now it is not only the computer programmists who have to conduct dialogues with the computers, but inexperienced people, as well: economists, who use them in industry, controllers, supervising automatic control systems. And in the near future these will be supplemented by many other professions.

Today electronic computers can perceive dozens of spoken words. They are like a small child that builds up its vocabulary, learns to pronounce words in order to start speaking "like everybody".



"But I've ordered sausages . .

Intelligence
about the ambient world
and about processes
taking place in it
obtained by living organisms,
control machines
and other systems in the course
of their life or their work.

Not a Substance and Not Energy

You wake up in the morning and find yourself in the world of information: when you see, you receive information; when you hear you receive information; when you talk, you receive information.

Information is brought to you by books, magazines, newspapers, advertisements, cinema, theatres, radio, television... the list is too long to be continued.

Man has been surrounded by information from time immemorial. There is every reason to define information as a data system of the world around us.

The whole process of cognition consists in receiving, processing, recording and transmitting information about this reality. As knowledge develops these data become more complete.

The word "information" stems from the Latin. During its long life it underwent considerable evolution, in the course of which its bounds were either widened or extremely narrowed.

The original meaning—"notation", "concept", "outline"—was later transformed into "intelligence", "data transmission". In recent years scientists decided that the general perception of the word "information" is too "elastic" and reduced it to the "measure of certainty of intelligence".

What's the reason for such evolutions in the meaning of the word "information"? The reason is its rather strange character, its elasticity that is so loathsome to the scientist.

And yet, this concept is so definite that it is recognized as one of the main subjects studied by cybernetics, and that a separate branch of science—the theory of information—dealing with the problems of collecting, transmitting, storing, processing and calculating information has been created.

No matter what are the variations in the meaning of the word "information", the important thing remains that it carries intelligence, tells us something, makes us acquainted with something, i.e. puts an end to the lack of knowledge, destroys uncertainty.

Practical requirements were responsible for the appearance of the theory of information. By the second half of the 20th century the globe was, so to speak, humming with information being transmitted along telephone and telegraph cables and radio channels.

Lately they were supplemented by information processing machines such as control and mathematical machines.

Here, too, the peculiar character of information made itself felt. When designing or operating communication systems or channels the engineer cannot limit himself with the solution of physical and power problems. From these points of view the system may be quite perfect and economical. But if the designers of the transmitting system did not pay attention to the volume of information being transmitted by it, it will not be worth a dime.

Don't wonder. Information can be measured quantitatively, can be calculated. One goes about such calculations in quite the usual way: by abstracting from the contents of information, just as the concrete meaning is ignored in familiar arithmetical operations (for example, when we add two apples and three apples, we turn to adding numbers in general 2+3).

Scientists are not afraid to concede that they have "totally ignored the human value of information". They attribute a definite value of information to, say, a sequence of 100 letters, no matter whether it has any sense or not, and without regard to the practical application of this sense. This quantitative statistical approach is the best developed branch of the information theory.

As scientists say: "According to our definition a sequence of 100 letters—be it an extract a hundred letters long from a newspaper, a Shakespeare play or Einstein's theorem—contains an equal amount of information." (Remember arithmetic. There, too, it makes no difference whether it's apples, buildings, men, words, ships, stars, etc.—always 100+ +20=120.)

"Our definition of the amount of information," scientists state authoritatively, "is extraordinarily useful and practical. It exactly corresponds to the problems of the communications engineer who has to transmit the full text of a telegram, no matter what the value of this information is to the recipient."

A communications channel has no soul.

And this is not only because it is an "unanimated system", but also because it is indifferent to the information it transmits: be it joy or sorrow, news about birth or about death. One thing is important to the transmission system—to transmit the required amount of information.

How is the amount of information in a concrete message to be calculated?

The evaluation of the amount of information is based on the laws of the theory of probability. This is quite understandable. A message is valuable, it carries information only if we learn from it of the outcome of some event of a casual character, if it is to some extent unexpected. A message, the contents of which are known to us, does not contain any information.

If anyone rings you up and says "today is Saturday, tomorrow will be Sunday", such information will strike you not by its novelty but by its absurdity. Quite another thing is, for example, the news of the outcome of the final of the chess tournament. Who's going to win—Ivanov or Petrov? Or is the game to be drawn? Here the outcome depends on chance.

The greater the number of chance outcomes of an event, the more valuable will be the news of its result, the more information will it carry.

News of an event with two equally probable outcomes contains a unit of information called the bit. You have, probably, guessed that the choice of the unit of information was not casual. Well, indeed, it is linked with the most widely used binary method of coding information.

Let's try to grasp the notion, albeit in the most elementary form, of this general principle of quantitative evaluation of information that is the cornerstone of the entire theory of information.

We know already that the amount of information depends on the probability of specific outcomes. If an event has, in the words of scientists, two equally probable outcomes, this means that the probability of each outcome is equal to 1/2. Such is the probability of heads or tails falling out, when a coin is thrown. If an event has three equally probable outcomes, as in our example with the chess tournament, the probability of each is equal to 1/3. Notice that the sum of the probabilities of all outcomes is always unity, since one of all the possible outcomes will certainly materialize.

An event, as you understand, can have outcomes that are not equally probable. Thus, in a football match between a stronger and a weaker team the probability of the victory of a stronger team is great—say, 4/5. The probability of a draw is much less, say, 3/20. The probability of defeat is, on the other hand, quite small.

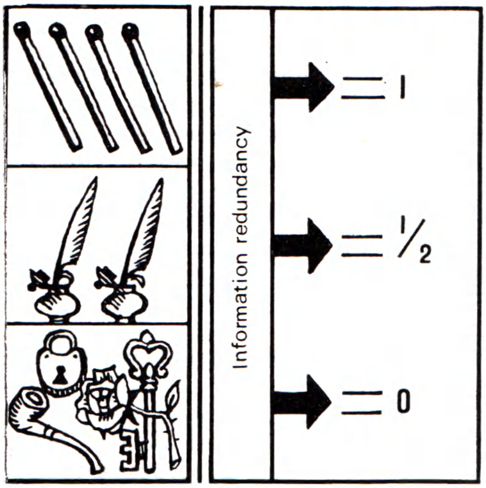
It turns out that the amount of information is a measure of the decrease in the uncertainty of some situation. To calculate it special formulae are used.

Different amounts of information are transmitted through communications channels. The amount of information passing through a channel cannot exceed its capacity. Vice versa, the capacity of a channel is determined by the amount of information it can transmit in a unit of time.

You may remember how one of Jules Verne's personages, the journalist Gedeon Spillet was transmitting over the telephone a chapter from the Bible to prevent his rivals from using the telephone. In this case the channel was fully loaded, but the amount of information passed was zero, since the recipient received intelligence that had already been known to him. This means that the channel was "idling", passing a definite number of pulses that were not loaded with any information.

At the same time, the greater the amount of information carried by each of the definite number of pulses, the more efficient is the use of the channel's capacity. But in order to achieve such results information should be coded rationally, and an economical, concise language should be devised for the transmission of intelligence.

For this purpose information is thoroughly "filtered". To cite an example, in the telegraph code letters, letter combinations and even entire phrases in frequent use are represented by a shorter sequence of



Illustrating redundancy. It's maximum in the first case—equal to unity; in the second it's one half; in the third it's zero.

units and zeros than those that come up less frequently.

However, it often happens in practice that intelligence sent with a code established as a result of most severe "filtering", with a code that's quite convenient and economical, can be distorted because of interference, which, unhappily, is always present in communications channels (atmospherics in radio, black-out of the image in television, transmission errors in telegraph). This interference, or noise, as specialists call it, attacks information, and this sometimes brings surprises.

A magnetic storm can so distort a telegram that instead of "I love you" it will read "I kill you".

If our message "The game has been won by Ivanov", coded 01, as a result of interference will turn into 00, "The game has been won by Petrov", this error will change the entire meaning of the message. To improve reliability of information transmission and processing one has to introduce additional symbols that serve for protection against interference. These surplus symbols carry no actual information in the intelligence, they are redundant.

From the standpoint of the information theory everything that makes the language colourful, flexible, rich in nuances, ambiguous is a redundancy.

How full of redundancies Tatyana's letter to Onegin (in Pushkin's *Eugene Onegin*) would be from this standpoint! How many information "surpluses" it contains for the short and quite comprehensive statement: "I love you!"

In this connection it is appropriate to recollect an anecdote told by the famous American scientist Franklin about a hatter who convened his friends to discuss the design of a signboard.

He planned a signboard with the picture of a hat and an inscription:

JOHN THOMPSON,
the hatter
makes and sells hats for cash

One of the friends remarked that the words "for cash" should be dropped, for such insistence is insulting to the buyer.

Another found the word "sells" useless, since it stands to reason that a hatter sells hats and does not hand them out free.

The third thought the words "hatter" and "makes hats" useless tautology, and the latter were deleted.

The fourth suggested that the word "hatter" be deleted, too, since the hat on the signboard leaves no doubt as to the progression of John Thompson.

Finally, the fifth stated that it was none of the buyer's business whether the hatter's name was John Thompson, and advised to drop it. So, in the end, only the hat was retained on the signboard.

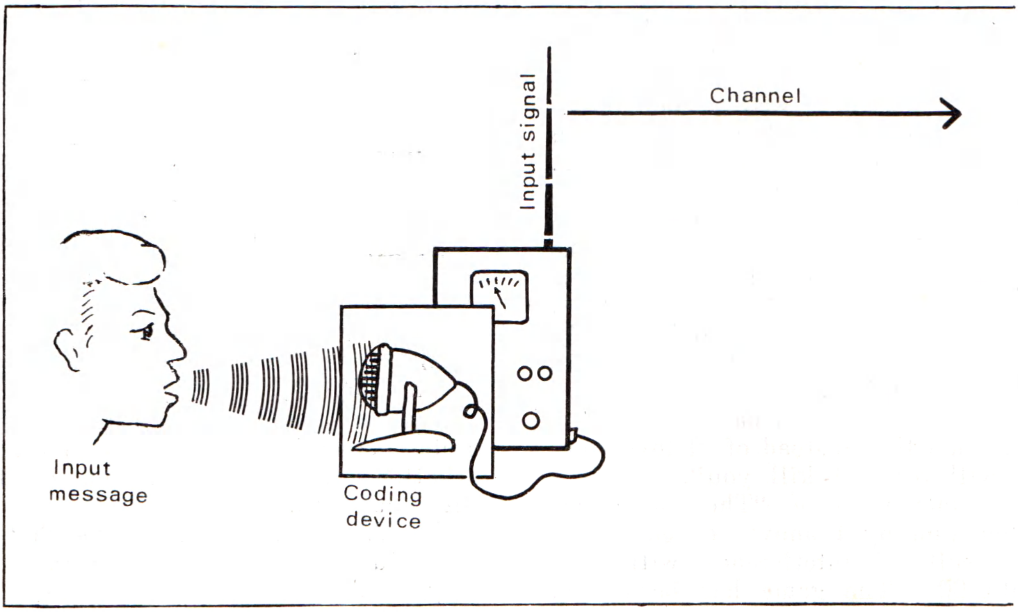
Of course, if people were to use only the economical codes without redundancies in intelligence, all "informational forms"—books, reports, papers—would be extremely concise. But they would lose in clarity and elegance.

Let's discuss the block diagram of an information transmission system.

Every event, every phenomenon can serve as a source of information. In this case the word "source" is quite accurate, since this is the origin of the information stream.

Every event, every phenomenon can be expressed by different means, by a different "ABC". To transmit it in the best way possible—accurately and economically—it should be appropriately coded. Information cannot exist without some material carrier, without energy transport. Coded information assumes the form of signals. They are the carriers that flow along the communications channel. At the receiving end the signals must again assume a comprehensible form.

Information transmission diagram.



To this end the signals are sent through a decoding device, after which they become intelligence to the recipient.

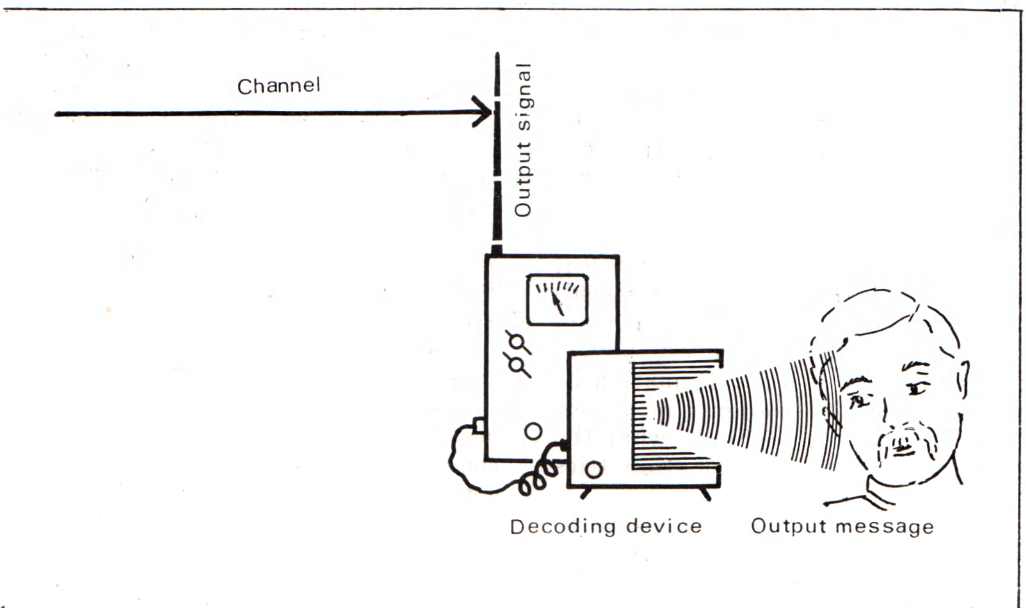
The communications system has worked, the aim has been attained.

All the time we are speaking about communications channels using for the most part the telegraph as an example. But communications channels is a very wide concept that includes numerous quite different systems, this difference being sometimes too great to be expected. To make the abundance of meanings of the "communications channel" concept clear a few additional examples will suffice.

Let's look from this point of view at the telephone. The speaker is the source of intelligence in telephone communications. The coding device that turns the sounds of words into electrical pulses is the microphone. The information transmission channel is the telephone cable. The earphone works as the decoding device. Here the electrical signals are again turned into sounds. And finally, the information reaches the "receiving device"—man's ear at the other end of the cable.

Here is a communications channel of a quite different nature—the live nerve. Here, too, as in the technical system, the process of transmission is the same for all intelligence. True, there's a difference, since in the technical system the direction of information transmission can be changed, while in the nervous system such a change is impossible.

And yet another example—the computer. The main features are again similar. The information from one individual part of the computer to another is transmitted with the aid of signals. The computer is an automatic device for processing



information in the same way as a machine tool is a device for processing metal. The computer does not create any new information, it only transforms information fed into it.

We know already that the quantitative approach is one of the most developed and widespread trends of the information theory. There are other approaches, as well. They, as distinct from the quantitative approach, try to grasp the meaning of information, its value, its quality.

Indeed, the case is not rare when the amount of information contained in two items is identical and the meaning quite different. For example two words "ton" and "not" contain equal amounts of information, since they are made up of the same letters, but their meaning is different.

In everyday life our evaluation of the intelligence received is based, as a rule, on its meaning. We perceive new intelligence not as definite amounts of information, but as new contents.

Look from this point of view at the item "There's vegetation on Earth". Does it contain information? Certainly not, since its contents are not new. And now you transmit: "There's vegetation on Mars". This item contains information, because it reflects the probability of knowledge, the possibility of the phenomenon, not a thing known to everybody.

Can the meaning of information be computed and its contents in a message be calculated? This is what the semantic theory of information tries to do.

Here's another example and another trend in this branch of science. This is the pragmatic-business-like trend.

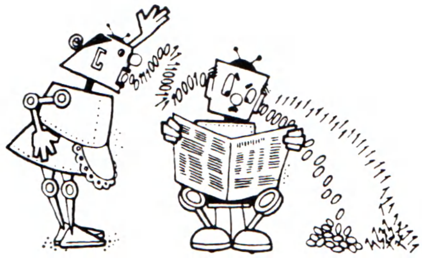
Some passengers are travelling in a bus. The driver announces the name of the bus-stop. Several passengers get out, the rest pay no attention to the words of the driver, to the information addressed to them. Why? Because, as specialists say, for different recipients—this time they are the passengers of the bus—the information is of different value. Those for whom the information was valuable got out of the bus. Consequently, the value of information may be defined as its ability to influence the behaviour of the recipient.

In the opinion of scientists, modern trends in the theory of information will in future be supplemented by new approaches, and new ideas will appear.

The "vivacious", growing nature of this branch of science, the speed and thoroughness with which it enters diverse fields of human knowledge is proof of these anticipations. It has already penetrated physics, chemistry, biology, medicine, philosophy, linguistics, pedagogics, economics, logic, the technical sciences, aesthetics. This is, admittedly, a good start for a young science.

It can therefore be accepted (and it is acknowledged by experts) that the science of information, having been born out of the requirements of communications theory and cybernetics, in the course of time (and pretty soon, at that) transgressed the bounds of these sciences.

And nowadays we are, probably, entitled to speak of information as a new scientific concept that provides the research worker with a new theory-of-information method. This method will open up roads into many branches of science dealing with living and non-living nature, with society and knowledge. It will not only throw light on new sides of the problems, but will enable things heretofore unseen to be seen.



J

The "Talking" Holes

JACQUARD'S METHOD

The Jacquard method,
or the method of perforations,
is the method
of recording information
by punching holes (perforations)
in information carriers
such as punch-cards
or punch-tape.

One out of numerous devices which had, apparently, nothing to do with calculating machines, proved to be of special value for the automation of the technique of calculations.

In Europe's stormy days, when Napoleon conquered one land after another and his army was in great need of fabric, the French inventor Joseph Marie Jacquard, a son of a Lyons weaver, decided to automate the loom. He was tenacious and got his way—he managed to build a loom that even won a medal at the Paris exhibition. Soon there were over 10 thousand such looms working in France.

Jacquard succeeded in finding a method of influencing the intricate workings of different mechanisms. The inventor devised a set of cardboard cards with different sets of holes.

The holes served to designate the working order of the loom. The cards were passed under probes. When a probe met a hole it went down and with the aid of special devices manipulated the thread. Intricate patterns could be woven in this manner.

The method of control by means of perforations in cards or tape proved very efficient and soon was widely used in machines the intricate movements of whose mechanisms required coordination.

The new method was used in musical automata, in telegraph apparatus, in type-setting machines. A mechanical piano (pianola) was built, in which punch-tape was used to control the action of hammers in hitting the keys.

"If with the aid of perforations it is possible to control machine tools, aggregates, musical instruments, why not use punch-cards to feed numbers into calculating machines and to control them?" inquired scientists.

The Englishman Charles Babbage, the dean of the mathematical faculty at the University of Cambridge—the faculty once headed by Newton—was one of those who pioneered in the construction of calculating machines employing punch-cards.

Once in 1812 Babbage was looking through the tables of logarithms. He knew they were full of mistakes, and reflected upon the way of avoiding them in the new edition.

He remembered that French scientists had used a new method to compile other tables. They divided a complex problem into several simple operations, which amounted to addition and subtraction. These operations were performed by people who knew nothing of mathematics, except simple arithmetical operations.

Babbage decided to make calculating machines perform these simple operations.

In 1822 he built a small working model. The idea was enthusiastically received by the British Royal Society. Within a year grants were received, a workshop built, and blue-prints ordered. But progress was slow. Difficulties were aggravated by the inventor striving to introduce endless improvements into the design.

Some ten years passed, and Babbage was left alone with his creation. Work was interrupted and in 1842 stopped altogether.

But Babbage refused to surrender. He drew up another project, a bolder one than the previous. This was the "analytical machine" which became the prototype of modern high-speed computers. The project envisaged it as consisting of three parts: the first, called "depot" by Babbage, with the aid of counters recorded and stored numbers; the second—the "factory"—was to operate with numbers taken out of the "depot", and the third which was not named by the inventor but which could be called the "office" controlled the sequence of operations, chose the numbers and directed the results of calculations to appropriate places.

Babbage estimated his machine to be capable of 60 additions per minute, or of one multiplication of two fifty-digit numbers, or of a division of a hundred-digit number by a fifty-digit one. He planned the capacity of the "depot" at one thousand fifty-digit numbers.

The calculating process could be controlled with the aid of punch-cards. Probes, passing through holes in the cards, set in motion mechanisms that transported numbers from the "depot" to the "factory" and back.

Some parts of the machine were made, presumably, in Babbage's lifetime. After his death the "factory" was partly built by his son. At present the machine is at the London Science Museum.

Babbage had a clear notion where his machine should be employed. He wanted to calculate mathematical and navigational tables, check logarithm tables, check astronomical data, calculate the mean life of man in England and solve many other complex problems.

Progressive-minded people of the time hailed Babbage's invention. The famous writer Edgar Poe wrote: "What should we think of Babbage's calculating machine? What should we think of a machine, made from wood and metal, which can not only calculate astronomical and navigational tables of any required length, but can even make the accuracy of its operations mathematically certain due to its ability to correct possible mistakes? What should we think of a machine, which in addition to all this, can print its own intricate results, attained without the slightest interference of man's intellect?"

Babbage's invention proved to be ahead of its time. His idea was not realized. However, the services rendered by the scientist to the cause of computer engineering are very great. He developed the principles of organization and construction of powerful automatic calculators and was the first to use the punch-card data put in the calculator.

In the year 1890 a population census took place in England. To increase the speed and to reduce the costs of processing the results engineer Hollerith built a special adding machine and called it the tabulator.

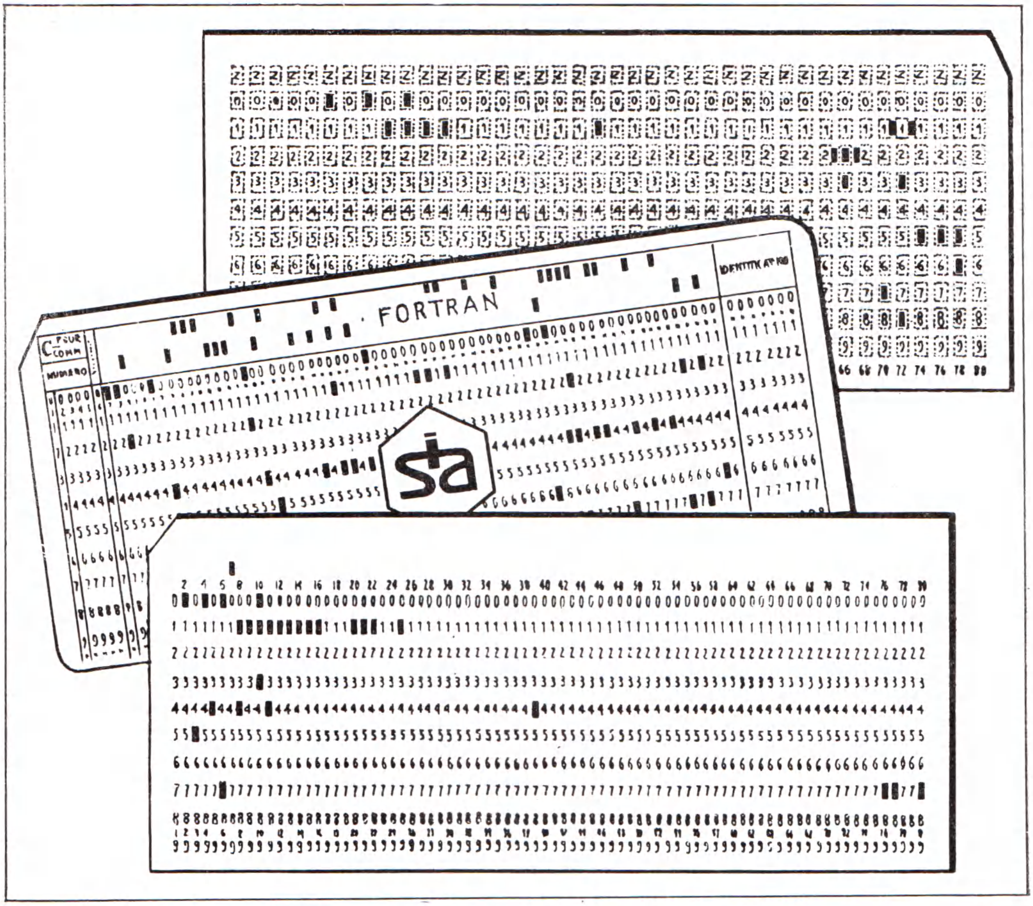
This inventor, too, made use of the punch-card number input system, but on a new basis. He profited by the advances in electrical engineering and constructed his machine on the electromechanical principle. It retained mechanical counters, but was controlled by electrical pulses.

In Hollerith's tabulator the punch-card was sensed by brushes made of thin wires. When brushes came across holes in the punch-card, circuits were closed, and electric pulses appeared. These pulses were used to introduce the numbers and to control the machine.

The first tabulator was very primitive, but, nevertheless, the problem of automatic count with the aid of punch-cards and of electric current was solved not only in principle, but in practice, as well. A new leaf was turned in the history of computer engineering.

A set of modern punch-card computers is shown on pages 166-167. It consists of two groups of machines: for the preparation and preliminary processing of the punch-cards and for calculating operations. The most, so to speak, important machine of the set is the tabulator. Not only can it count independently—add, multiply, divide numbers, automatically combine these operations—but it can even perform some logical operations. The machine does this all with the aid of punch-cards.

In the printing shop a number grid consisting of 80 columns of numbers is printed on the card. The numbers from 0 to 9 are arranged in each column from top to bottom. These are the positions in which holes may be punched. Besides, the card between the ninth and the eighth rows bears the numeration of the lines of columns. In this form the cardboard rectangle is "mute". To make it talk it is necessary to punch holes in the positions of the columns. They are punched, or perforated, with the aid of a special machine, the perforator. After that the cards

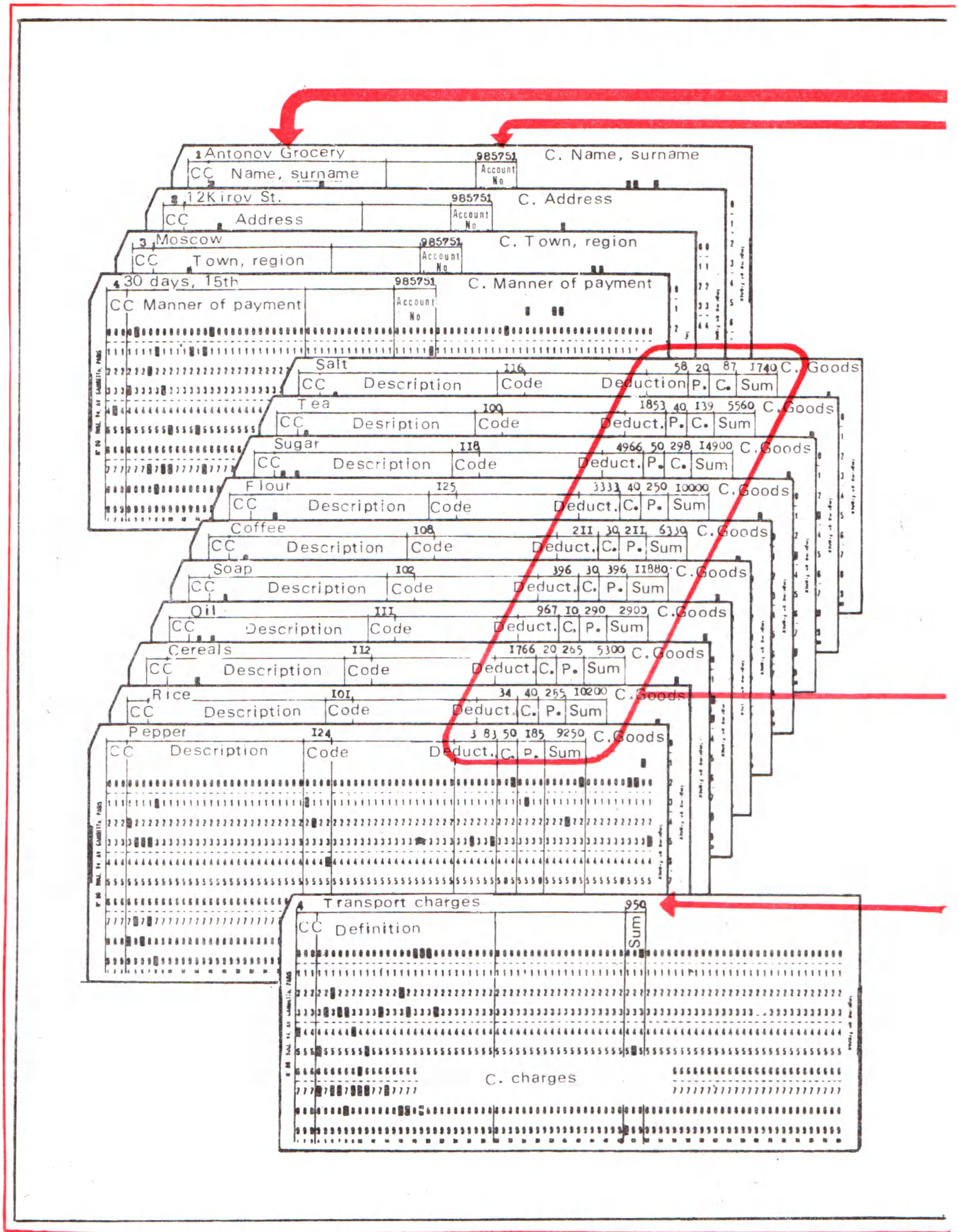


Various types of punch-cards.

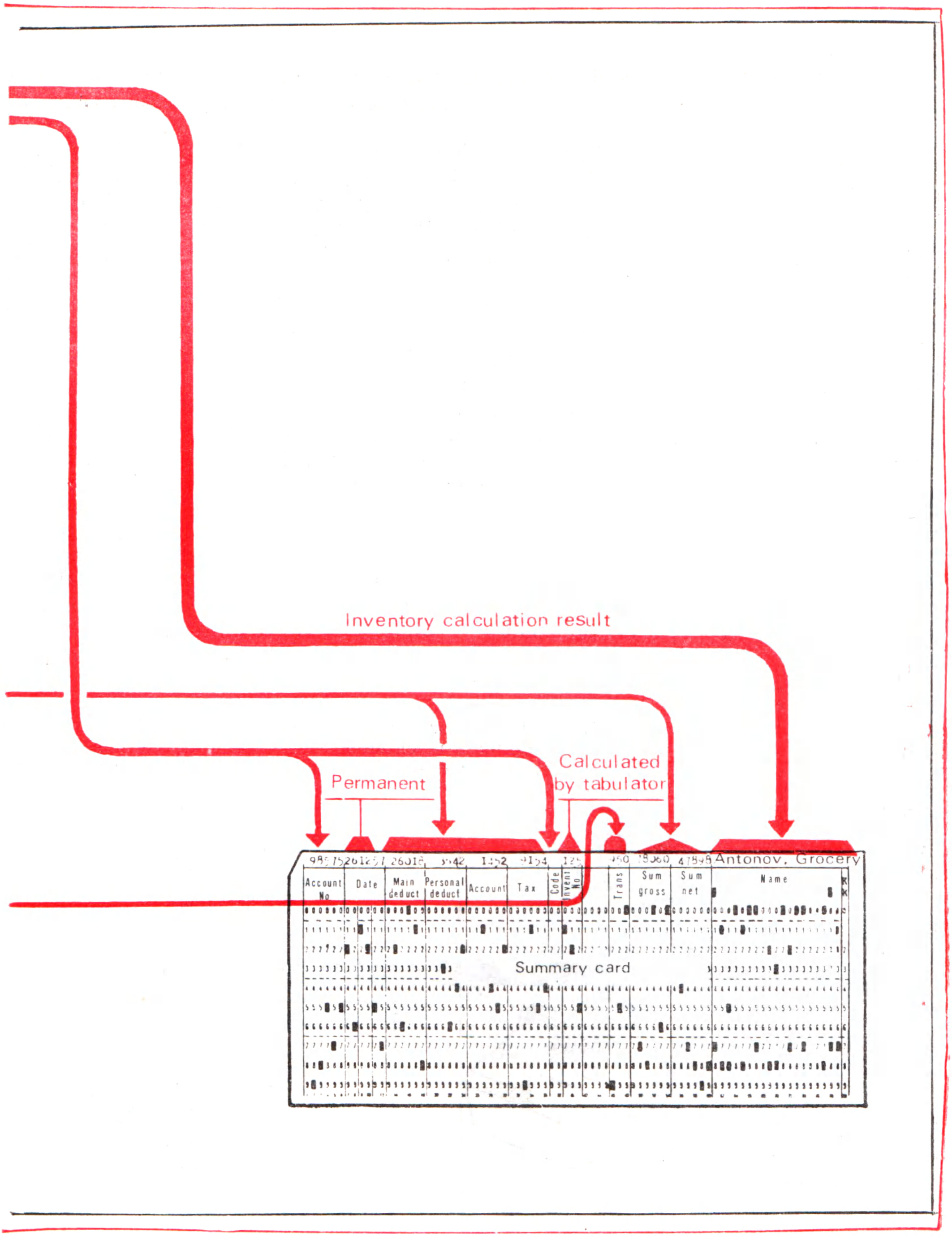
go to another machine, the controller, that checks whether the cards were punched correctly.

Suppose the holes on the punch-card in our example show the data of the working order of a lathe operator. In a month in a large plant hundreds of thousands of such cards will be accumulated. When the time comes to calculate workers' pay, to collect data about the execution of the plan or about production costs, the electrical sorting machine sets to work. It groups cards into separate blocks by various features with the speed of tens of thousands of cards per hour. Then the cards are sent to the tabulator.

Here, to begin with, the cards are read. This is done by a special block of 80 brushes—one for each column of the card. The brushes are connected by means



In this way the computer compiles a summary inventory-bill card for goods sent to the customer from a set of cards. The summary includes the goods, their price, deduction, transport charges, etc.



Inventory calculation result
Permanent
Calculated by tabulator
Antonov. Grocery
Account No
Date
Main deduct
Personal deduct
Account
Tax
Code
Invent No
Trans
Sum gross
Sum net
Name
Summary card

of wires to the counters and the printing mechanisms. The punch-card moves with the tens first. The brushes start by sensing every ninth position, then the eighth, etc.

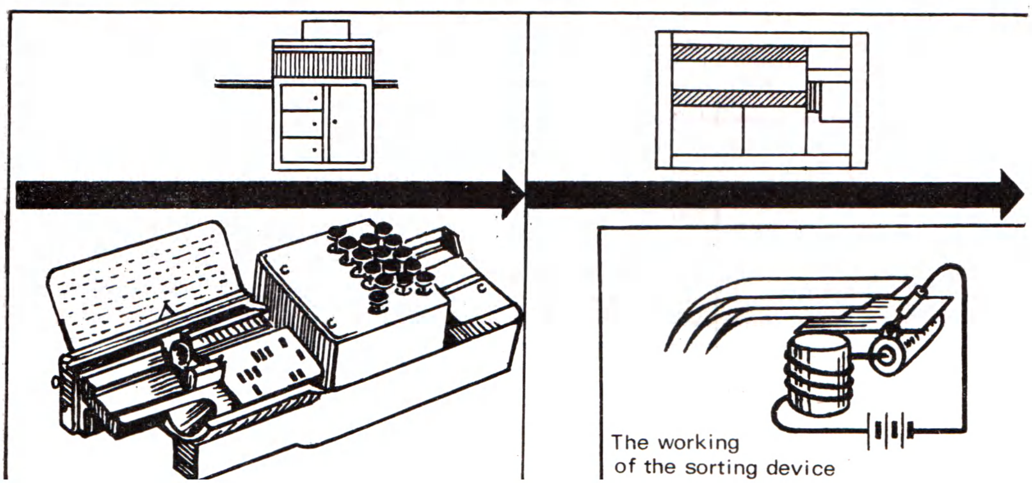
Here's a card with a hole in the eighth position of the thirteenth column. The brush will close the electric circuit, the electromagnet of the number disc will be energized, and the disc will start to turn. The card will move one position forward to the seventh position. The disc will turn the angle of the number and will show 1. The card will move yet to another position—the sixth—and the disc will show 2. The turn of the disc is completed as the brush reaches the zero position. The disc has turned through each of the eight positions and now shows 8. The eight from the punch-card has been thereby transported to counter file that corresponds to the thirteenth column. Addition is done in the same way.

And who controls a big complex computer?

Just these punch-cards and brushes. To enable the electric pulse to travel inside the machine all electric circuits connected with the brushes, counters, printing mechanisms are made to terminate on the commutating panel which with the aid of switches distributes the electric pulses over the entire machine.

The control system of the modern tabulator is extraordinarily flexible and multilateral. A good tabulator is able to process up to 60 thousand cards per hour, or even more. Already in 1950 Soviet engineers produced one of the best punch-card calculators, the "T-5" tabulator. It contains eight 11-file counters. This means that eight columns of multiposition

A calculating and perforating set. The perforator punches holes in the card. The controller checks and sorts them. The tabulator—the main machine of the set—counts the numbers: *1*—magazine; *2*—contact brushes; *3*—contact shaft; *4*—card-guiding rollers; *5*—contact; *6*—coun-



numbers can be summed up simultaneously—70 thousand additions per hour!

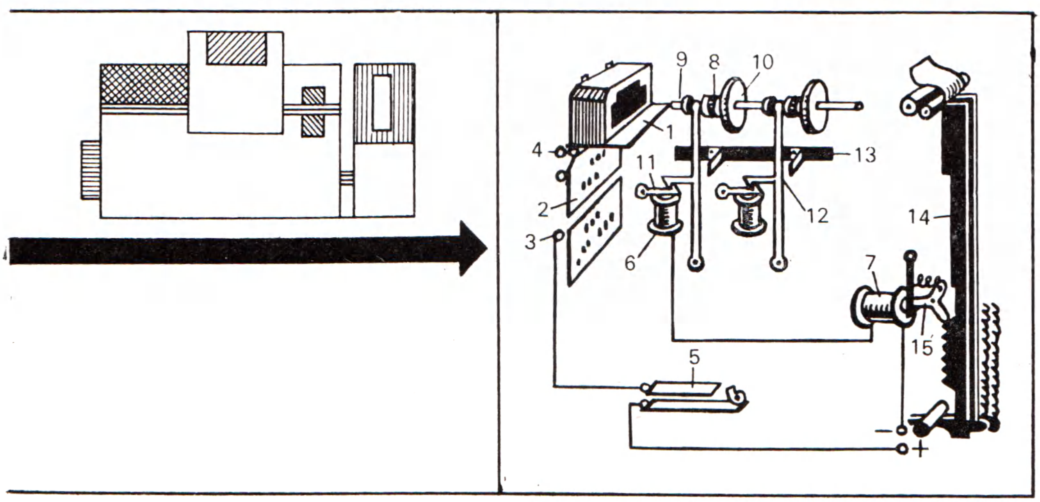
A hundred accountants will be able to perform during this time only 25 thousand arithmetical operations.

According to their principle of operation the punch-card calculating machines are subdivided into mechanical, electromechanical and electronic types.

You've just read about the electric machines. In mechanical machines the holes are sensed—"read"—by special tentacles—the pins. Such machines perform only 100 operations per minute.

The change over from mechanical and electromechanical devices to electronic devices resulted in the speed of punch-card machines being increased. But the punch-card and the principle of organization of the calculating process in the combination of punch-card calculating machines set a limit to the productivity. A point to note is that the calculating speed of the tabulator is some 15 times higher than the speed of key-board summing machines, while the productivity of the whole combination is only 3 to 4 times higher. This is the result of the, as yet, great part played by manual labour: the cards are controlled and punched by operator and transported from machine to machine by man. And even if the lot of punch-cards carried at a time is much greater in this case than in the case of key-board machines, the slow speed of card processing in machine's mechanisms greatly influences the

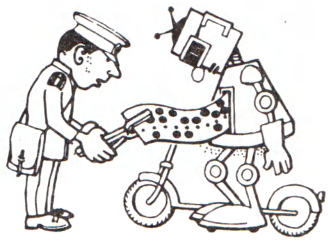
ter electromagnet; *7*—typing electromagnet; *8*—clutch; *9*—counter driving axle; *10*—counter wheel; *11*—anchor lock; *12*—clutch lever; *13*—lever return planck; *14*—digit rod; *15*—three-arm lever.



overall productivity of calculation.

The supply of punch-cards is that number "depot" that Babbage tried to build with the aid of counters working at the same rate as the "factory". He understood that man could be liberated from the necessity to take part in the calculating process only by their concerted operation.

Only after a century of progress in technology were the engineers able, using the modern counting and punching set as the basis, to start work on advanced calculators and later on electronic computers.



Again a traffic offence!

K

"A Secret Shrouded in Darkness"

KEY TO THE CIPHER

A secret system
which enables the meaning
transmitted with the aid
of a cipher to be disclosed.

Ciphering is frequently used in military communications, in diplomatic service—generally, when it is desired to maintain the secrecy of correspondence or of an oral message.

Members of revolutionary underground groups, who had to conduct their correspondence in such a manner as would make it incomprehensible for tsarist gendarmes, were among those who resorted to ciphers.

There are numerous ciphers in existence. Some are purely professional: the simple substitution cipher, the fractional, so-called, diagram, three-gram, *n*-gram ciphers, Vigenère ciphers together with their variants, the Playfair cipher, codes of different types.

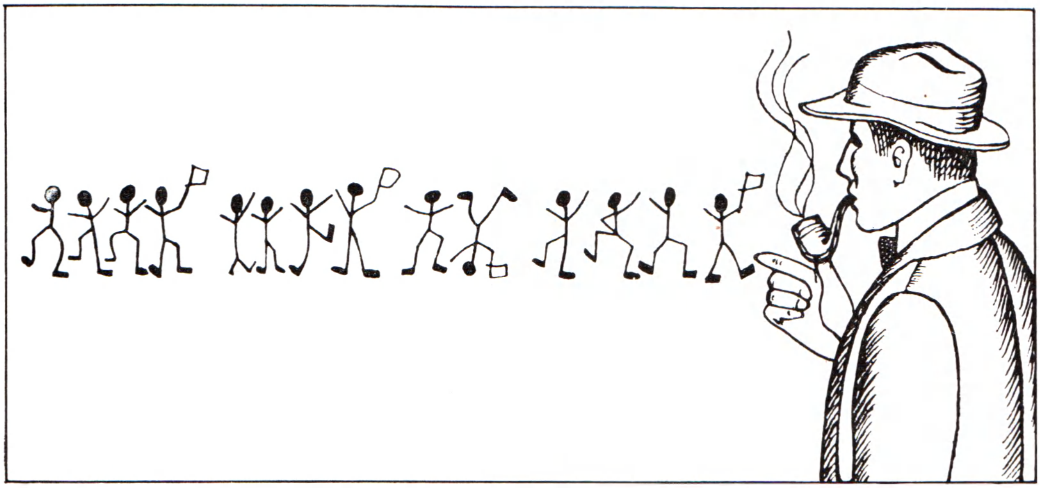
And the cipher, the like of which has never been seen before, from the story "Little Dancing Men" that Sherlock Holmes managed to read?

He was intrigued by the strange notes with the dancing men.

The famous detective was quick to see that this was a cipher, and began looking for the key. Soon the key was found, and Sherlock Holmes after having guessed the meaning of each figure was able to read the notes. He proceeded by writing a letter to the criminal with the same cipher, and the criminal had to face the law.

There is a ciphered message on p. 171 which you are required to decipher. Look what's written there. You may sit for years looking at the message, try billions of combinations, but if you don't know the key, you'll never be able to read it.

To become an experienced deci-



"The little dancing men"—a cipher deciphered by Sherlock Holmes.

pherer in this case you'll have to arm yourself with paper and scissors.

Draw 64 chess squares on a piece of paper. Cut out holes precisely to the drawing, and you'll get a grid.

Lay the grid over the disordered set of letters with number 1 directed upwards.

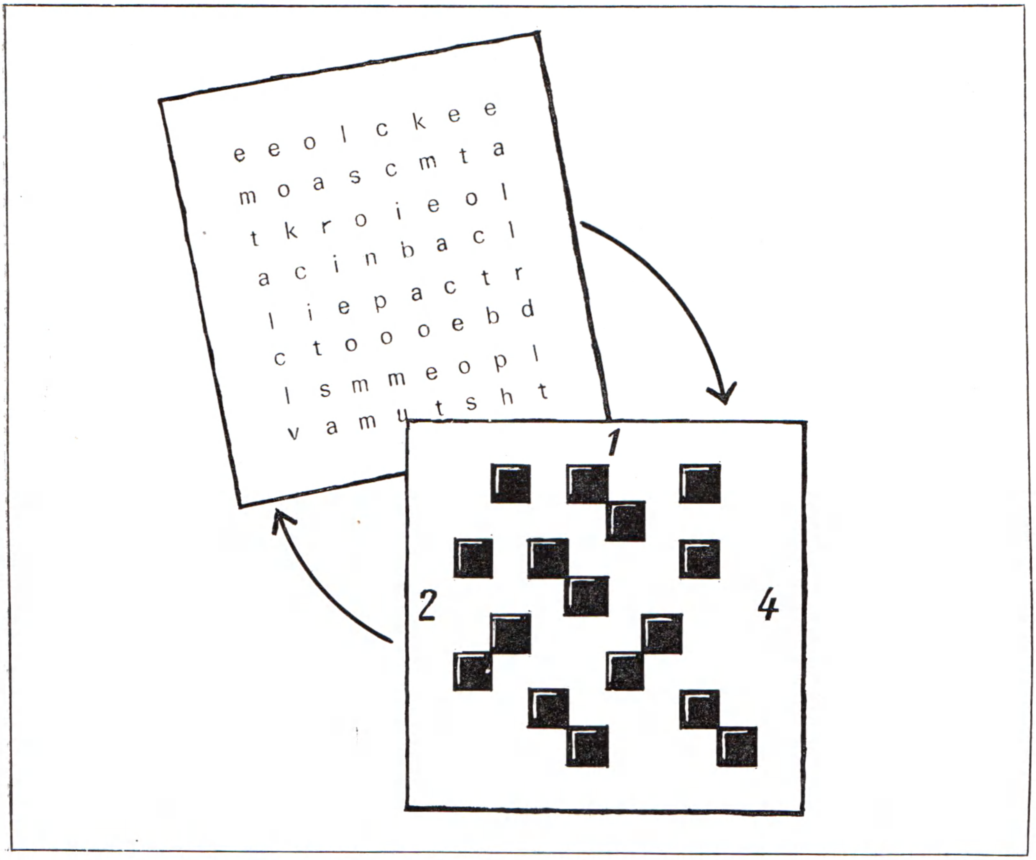
Look, a text has appeared in the holes: *electronic comput....* Now turn the grid clockwise by a quarter of a revolution. You'll get another part of the phrase—*ers are able to solv....*

Another such turn yields *e complicated math....* And the last: *ematical problems*. In the case of this cipher the grid serves as the key that enables the message to be read. Every secret inscription, every cipher normally has only one correct solution, a unique key, the secret of which is to be guarded. Even when a message not destined to be seen or heard by strangers falls into the hands of the enemy, it remains silent until the key to it is found.

It's a general rule that a solution for any ciphering system may, in principle, be found by the simple trying out of all the keys possible in each case. But this trying out is to be continued until the unique key is found that will make the cipher talk.

The American scientist Claude Shannon carried out very informative calculations to the effect. He set himself the task to find the key to a cipher consisting of only 26 possible key combinations. Twenty-six is a very small number. One has to use these 26 key variants, only one of which is the correct variant, substituting in turn all the 26 letters of the English ABC. The scientist obtained a formidable number—10^{12}! That's the number of years that will have to be spent in search of the key to the cipher.

And this in conditions extremely favourable for the imaginary opponent: Shannon assumed that the opponent invented an electronic device

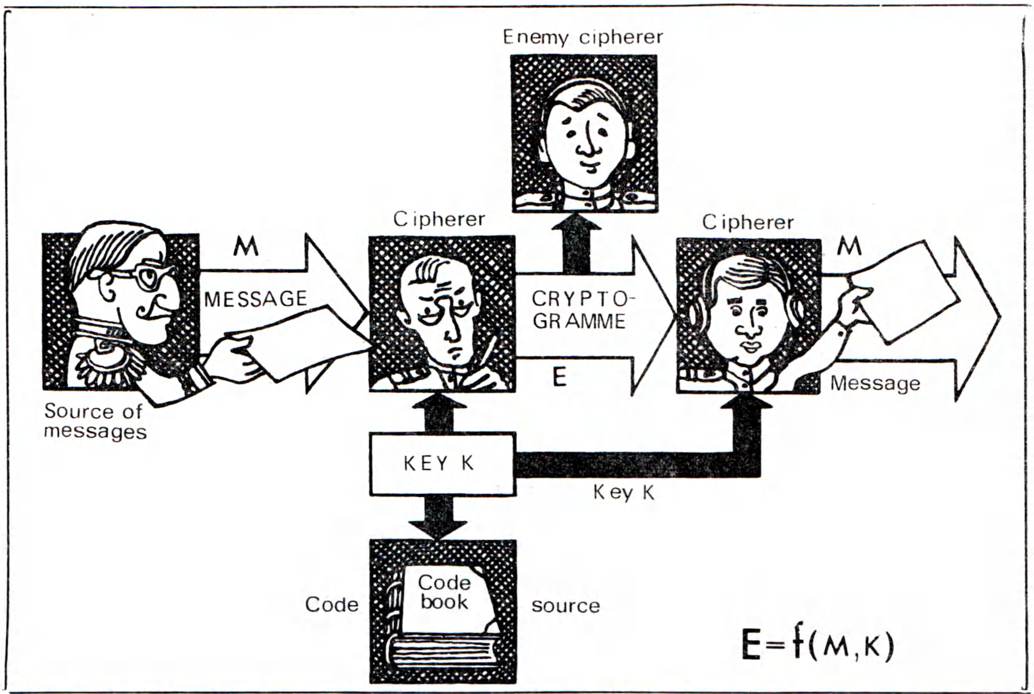


With the aid of this grid you'll be able to read what's written here.

for trying out the keys at a speed of one key per microsecond. The opponent will find the right key after trying out, approximately, one half of the possible combinations!

Here's a vivid proof of the immense discrepancy existing between the "solution of the deciphering problem in principle by the method of trying out the keys" and its practical realization.

Nowadays people are trying to approach ciphering, or cryptography, fully armed with mathematical analysis. The aforesaid American cybernetician Claude Shannon even ventured to develop a diagram of a general secret system to this end. Indeed, all such systems are quite identical in principle irrespective of the cipher and the ciphering system used.



A schematic diagram of a generalized secret system and its formula.

There are always two terminals: the transmitting and the receiving.

The transmitting terminal is always connected to two sources of information: one is the source of intelligence that has to be transmitted, the other is the source of keys that determines the key for ciphering by choosing one definite key out of all the keys of the system.

The completed cryptogram is transmitted along the communications channel. The communications channels may be of different kinds: messenger, post, telegraph, radio. At the receiving end the other cipherer with the aid of the key reproduces the intelligence from the cryptogram, i.e. deciphers it.

It is natural to presume that the enemy will, certainly, try to intercept the message. Therefore, another factor will act on the cryptogram during its transmission along the communications channel—the cipherer of the enemy.

Such is the general lay-out of a secret system proposed by Shannon.

If you take a look at this lay-out, you will not fail to conclude that its bounds are much wider than the secret system in its "pure" form.

Let's take, for example, a message in some unknown "dead" language. The monument of the written language, itself, may be regarded as a "cryptogram", consisting of the source of intelligence (in this case it's what the author of the text wanted to transmit) and the source of keys (in our example it's the ABC used by the author). The scientist who tries to find his way about in the secrets of the unknown language and read the text of interest to him, will assume the role of the cipherer operating at the receiving terminal. True, in our case the intercepting cipherer is totally out of the question.

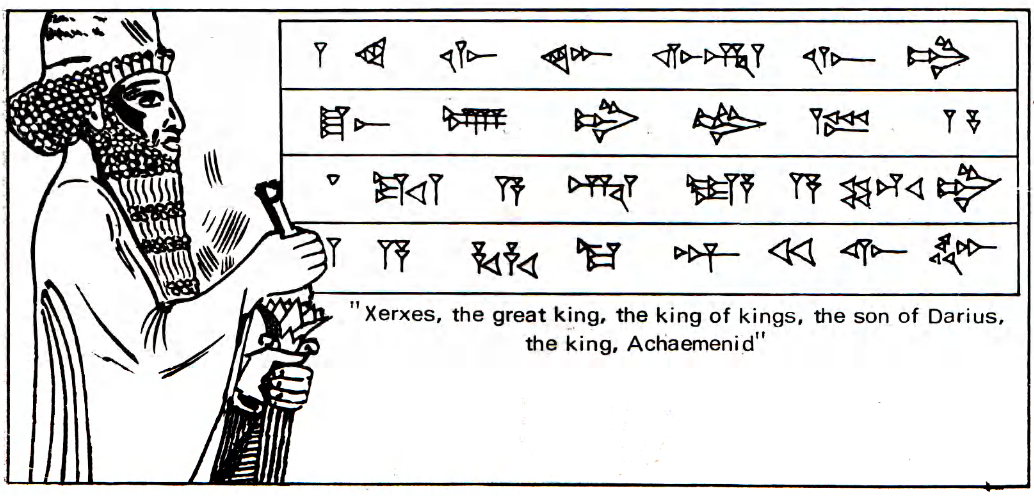
What an enormous number of keys the scientists deciphering forgotten written languages have to try out! What toil, what patience and, frequently, despair accompany their gigantic work!

It's a known fact that the famous Rawlinson who succeeded in reading the clay tables of the Babylonians wrote in 1850: "I must openly admit that when I, after having identified every Babylonian sign and every Babylonian word, for which I could find support in the tri-lingual inscriptions, tried to apply the information to interpret Assyrian inscriptions, I was frequently tempted to give up my investigations once and for all, since I lost all hope of ever achieving any satisfactory results." It took years to understand the Babylonian inscription of Xerxes: "Xerxes, the great king, the king of kings, the son of Darius, the king, Achaemenid".

Couldn't electronic computers be used to decipher ancient manuscripts? The statistical method is of great help in the case. The essence of the method entails the precise knowladge of the signs contained in manuscripts that have yet to be read and of the regularity of the appearance of these signs. For instance, the ancient Egyptian writing contains up to 800 different characters, the Hett—some 500.

The syllable systems of languages contain from 50 to 80 sounds. The European languages usually contain about 30 sounds, the Polynesian only 10-12; some Caucasian languages, on the other hand, 70-80.

Accordingly, the experiments aimed at deciphering the written language



The Babylonian inscription of Xerxes.

of the Maya carried out in Novosibirsk at once lead to the conclusion that Maya signs can be neither of the purely character type, nor of the purely ABC type. The language contains 340 signs. No ABC will hold as many. On the other hand, 340 signs are insufficient for character writing.

In all, seven methods were used to decipher Maya texts. And each proved useful: it either supported the results or controvened them.

The computer was at work for two days. It performed a billion operations. Deciphered 40 per cent of the text. To decipher all known Maya texts 200 computer hours will be needed additionally. The computer will have to perform billions of operations.

Well, it can be agreed that the first step in the computorized deciphering of forgotten languages has been made. It is to be hoped that in due time the scientists decipherers aided by a mathematical cryptographic system and electronic computers will be able to vitalize numerous ancient inscriptions that up to now have remained silent, and those "dead", "forgotten" written languages will tell stories of peoples of by-gone centuries, of their life, of their culture.

And those are not idle hopes. There is a sound basis for them: the Soviet specialist M. Probst has worked out a computer algorithm for deciphering forgotten written languages.

This algorithm has already been tried: it was used to read control texts, texts which had been read before and had been offered to the computer as "examination papers".

Well, the computer, adhering to the "rules for action", dealt effectively even with short texts that are very difficult to decipher.

This computer algorithm was also used for independent research. The electronic computer was instructed to clarify obscure texts relating to the 11-12th centuries found on the territory of modern Mongolia—the Kidan inscriptions.

In the course of previous studies the Kidan written language was classified as relating to the Turk or Tungus-Mongolian groups of languages. The computer "swallowed" large texts, studied the regularities of the language and confirmed that the language of the once mighty state of the Kidans was akin to Mongolian.

Well, let's bid the computer-decipherer a happy journey, let's wish it new successes. The more so because specialists consider deciphering historic written systems to be a particular case of the general problem which they have termed "the problem of formal research of the language".

The initiator of novel trends.
"They'll understand me in the 20th century."

L

LANGUAGE, COMPUTER

Special methods of information recording for its transmission to the electronic computer

Chocolate and "Algol"

Everyone knows that language is the most important means of human communication; that language is the most lively, most abundant, most stable connection establishing entity between the generations past, present and future; that, finally, the language is an exclusive capacity of man. And of man alone!

And suddenly—computer language.

And, yet, it exists. Not only exists, but is being developed, improved in the process of overcoming multifarious difficulties and obstacles.

Since its existence is an established fact, let's meet it; let's learn what it is, what it is for.

It is no more a secret for us that electronic computers, no matter for the solution of what problems they are employed, serve only one purpose—that of processing incoming information. The computer can perform such processing, however, only in case the problem—what the computer should do—and the method of solution—how it should do it—have been precisely formulated.

A word description is of no use to the "electronic arithmometer"—it's very bulky, not sufficiently precise and rigorous. This is because our spoken language has the qualities of great flexibility, ambiguity of words, figurativeness, even some subjectivity.

Just these characteristics make it unsuitable for the computer. It requires uniqueness, concreteness, and precision. That is the reason why problems are translated from the human into the computer language; the list of instructions that the computer must carry out to solve the problem is recorded in a special (binary—0 and 1) code. This list of instructions together with their sequence is called the programme. It distributes all the operations of the computer, describes all calculating processes.

This is how a recording made in the computer language looks: 0001·0000001010.

One thing is clear to the layman—it's some sort of a code. But what is it? And that's the way the computer reads it: "Add the number from the cell number ten of the working 'memory' to the number in the summator."

Here we're up against a definite supremacy of 0 and 1 over the natural language: just fourteen signs, and you have a sentence of fourteen words. High capacity out of all qualities has certainly been realized in the computer language.

Owing to this it is well adapted for information exchange between man and computer and between computers. Computer language also helps in case of information exchange between people effected by means of computers. It enables computers to conduct "dialogues" with other systems and with systems within the computer itself. Its range of action is, as you can see, quite wide.

However, besides advantages the computer language has some defects. And the main, quite essential one is that every class of computers has its own "dialect", which only it can understand. Years of existence of high-speed electronic "counters" brought into being almost 5000 artificial languages! "Cobol", "Fortran", "Jovial", "Alpha", "APS", "Alcopol", "Mathematic"—they are too numerous to be enumerated.

There's no end to difficulties that spring from such language discrepancy. To transmit problems formulated for one computer to another of different design the programmists have to make up a new programme. What costs in labour and time! Imagine a calculating centre employing limited equipment. The day the centre is expanded and the equipment is changed the computer language existing at the centre will "break down".

For this reason programmes compiled at the level of instructions—at the level of a specific computer—could no longer satisfy the scientists in conditions of contemporary state of science and industry, when gigantic amounts, literally avalanches, of calculations are required. They decided to go over from "local computer dialects" to the language of automatic programming—a veritable computer language, which every computer should be able to understand.

This task is much more difficult, much more complicated than the task of simply enumerating instructions in a programme.

What is the automatic programming language for? The purpose is always identical: to help the programmist tell the computer what to do.

Specialists compare such an artificial language with that part of the spoken language which is used in instructions telling people "what to do". For instance, it's very much like the language of an ordinary cooking book. Analogy with some

DESCRIPTION

INGREDIENTS OF THE CANDY

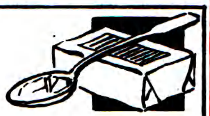
2 cupfuls sugar

1 cupful milk

½ a tea spoonful salt

50 g unsweetened chocolate

2 table spoonfuls corn syrup



2 table spoonfuls oil

½ a tea spoonful vanilla

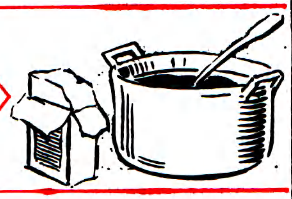
PROCEDURES

ORDER OF PREPARATION

1 Mix the first five ingredients in a simmering pot stirring continuously until the sugar dissolves

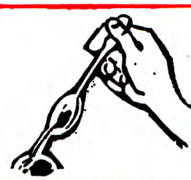
2 Stirring occasionally simmer until a drop turns into a soft ball in cold water

3 Take the pot off the fire and add butter



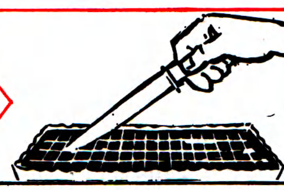
4 Leave to cool (no stirring) until cold enough to hold

5 Add vanilla. Beat with spoon until the mixture loses its shine and small amounts of it when poured from the spoon keep their shape



6 Place into a buttered form

7 Cool. Cut into pieces



recipe from the cooking book is usually resorted to in order to describe the classes of grammatical forms characteristic of an artificial language.

Let's take the recipe for making chocolate candy (see illustration on p. 177).

It certainly hasn't escaped you that the recipe is subdivided into two parts. The first consists of a *description* of stuffs needed to make the candy. The second describes *procedures* that are to be carried out in sequence in order to solve the problem: make the candy.

Similarly, the languages of automatic programming contain grammatical forms of two types. They are called *descriptions* and *procedures*. Descriptions, for their part, are subdivided into two types: the description of data—a list of component parts, and the description of programmes—subprogrammes. The procedures that are to be carried out in accordance with the recipe are similar to an ordinary computer language programme. Next follow the procedural operators—they correspond to sentences and describe operations which are to be performed with the component parts.

In general, operators and data descriptions in the artificial computer language consist of expressions which may be directly built up from numbers, words, abbreviated designations of measures, auxiliary sentences and word groups. Expressions corresponding to words consist of combinations of symbols.

This interconnection of the structures of the "what to do" type is characteristic both of the language of a cooking book and of the automated language. The difference lies exclusively in actions of procedural operators, which depend on the field of application of the language.

The operators "mix", "cool", "beat", "cut into parts", "stir", for example, are relevant to the process of food preparation. Calculating processes, on the other hand, entail different operators: "extract a square root", "take the 24th degree", "attribute the value", "repeat the following calculations until...."

You have thus become acquainted with the general traits and peculiarities of the automated computer language. Now learn about the history and the purpose of its creation.

The automated computer language is needed to "kill two birds with one stone": first, to facilitate the work of the programme compiler—the programmist—who up to this day compiled "instructions for actions" for the computer by hand. The essence of automated programming is, on the other hand, to make the computer compile programmes for itself, to cut manual labour to the minimum. The second (very important) aim—to evolve a single computer language—is already known to you.

At last this single language, which, it is presumed, all the world's computers are going to "speak", came into being. This didn't happen overnight. Much time was spent on preparatory work. In 1958 an international conference was convened in Zurich. And only by the year 1960 did the international organizations connected with the technique of calculations create a working group, which corrected the errors discovered, eliminated obvious ambiguities, introduced greater clarity—in short, improved the language known nowadays under the name of "Algol-60", which means "algorithmic language".

The description of this computer language is preceded by an epigraph: "What can be said must be said clearly, and what cannot be said must not be said at all."

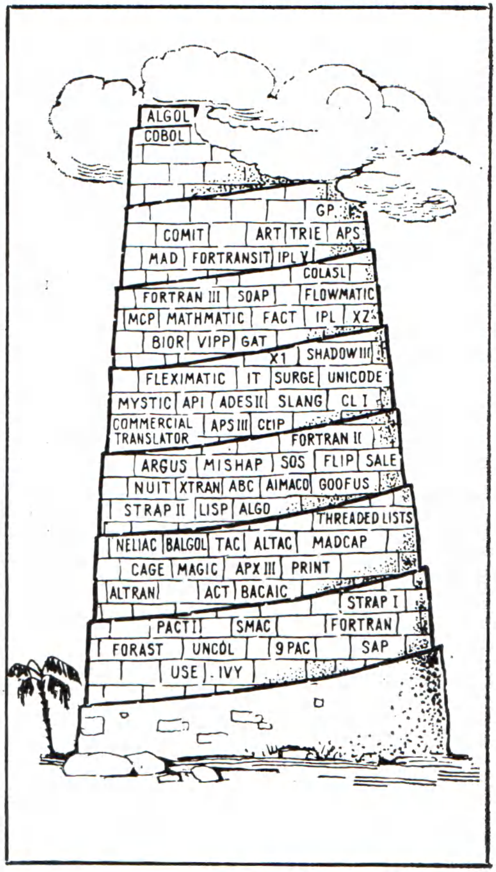
This is why the international cybernetic language consists only of 500 words. These are special instructions needed to control the computer. The diversity of these instructions is limited by the words "begin" and "end".

This computer language, like all languages, has its own letters, numbers, syntax and semantics. But many features are peculiar only to computers. It's very much akin to usual mathematical formulations well adapted for translation into the computer language by the computer itself. But, unhappily, it is so complicated that besides the computer it can be understood only by the professional programmist who at present stands as "priest-medium" between man and computer.

The language of the "Algol-60" type is usually defined as a universal language because it is adapted to quite different computers. But.... Here again obstacles arise in the way of the scientists. Even the universal language turns out to be not truly universal. It is limited by its orientation, its "field of action".

"Algol" is a language designed for scientific and technological computations, for solution of mathematical problems. This language pays little attention to the form and the context of data.

But there are problems where form and context of the data are particularly important. This is true of the

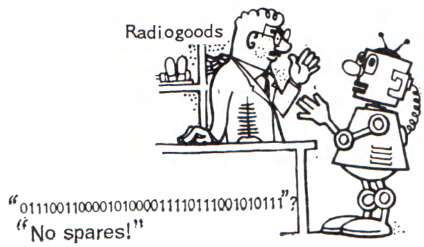


The "Tower of Babylon" of computer languages.

information processing problems: how to process large amounts of data, how to systematize them in repeating operations, etc.

"Cobol" is increasingly being used as such a universal language. It is designed to solve economic problems. "Cobol" is built on the basis of the usual Latin ABC. Moreover, because of its sphere of application, it describes practically everything with words, which have a concrete meaning in the ordinary natural language. Due to this, a "Cobol" text looks very much like a natural language text.

Now you can see what a long and tedious journey the computer languages have made from "dialects" to several general universal languages. There's no doubt that this is rather the beginning than the end of the journey, since the specialists are already discussing the problem of increasing the convenience of automatic programming. And the paramount problem here is said to be the liberation of the algorithmic language from its directivity, from its adaptation to specific fields of action, to specific class of problems.



A scientific discipline making use of mathematical methods to study language and utilizing electronic computers to model language and the operations performed with it by man.

Words and Numbers

Linguistics was until quite recently considered to be one of the most "unmathematical", most descriptive sciences, and nowadays one hears people talk of mathematical linguistics.

The introduction into the linguistics of quantitative and theory-of-probability methods imparted elements of rigour and precision to this humanitarian science, in the same way as the theory of probability revolutionized physics.

The scope of problems the new science deals with is very wide. To begin with let's take a look at one interesting trend—the quantitative description of language.

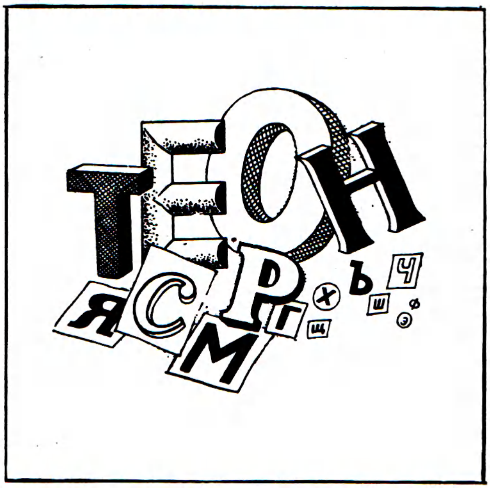
In the opinion of specialists every language is characterized by some simple quantitative relations. How many words are there in different languages, what is the difference between the number of words and that of morphemes and phonemes? What's the relation between words and syllables, between phonemes and morphemes?

Don't these questions seem to you to be too "narrow", just "questions for the sake of questions"? They do, don't they? Still, mathematical research into the language is no play for scientists, it's not idle pedantry. The practical importance of such an approach to the language is very great. It's the quantitative characteristics that throw light on the nature of an unknown written language, help to unveil it. They are useful, as well, for the description of modern languages, for the study of their history, for establishing kinship among them.

The statistical approach sometimes brings startling results. For example, it turns out that such obviously different from our point of view languages as Russian, English, Samoan have very nearly the same amount of information falling on the letter "N", i.e. a little over four binary units (bits).

Such "curiosities", such precise characteristics play a very important part in the compilation of dictionaries for computer translation, in the teaching of foreign languages, even in the elucidation of specific problems of experimental psychology.

The prominent Soviet mathematician, Academician A.N. Kolmogorov made an analysis of the relation between the number of available words and the number of possible rhymes. It turned out that ten words is not nearly enough to enable a rhyming pair to be chosen. Twenty words, too, do not guarantee such a choice. A reserve of 100 words, on the other hand, enables three rhyming words



This is not a chaotic pile-up of letters. The dimensions of each letter of the Russian ABC correspond to its relative frequency of appearance in texts.

to be found, 200 words enable quadruple rhymes to be found. Hence, with 200 words one can write sonets. A reserve of 500 words provides for the poets an abundance of tenfold rhymes.

The interrelation of letters in words, too, was the subject of calculations. Were all combinations of letters possible, with the aid of 30 letters one could compile 30 single-letter words. The number of two-letter words would be $30^2=900$. The number of three-letter words $30^3=27\,000$. The number of four-letter words $30^4=810\,000$, and so on. A language contains some 50 thousand words in common use. If we assume that all words are of seven letters, the percentage of letter combinations that are actually words will be only 0.0002%.

The frequency of appearance of different letters in words is not the same, too. Various texts were studied to find this frequency. For instance, it was established that in the Russian language the relative frequencies are: A—6.2%, O—9%, И—6.2%, H—5.3%, Ю—0.6%, etc.

The probability of appearance of each letter may serve as a measure of the "information load" it carries.

The results of such research carried out by linguists-mathematicians are of great interest also to pure linguists studying languages, and to experts in literature studying how authors work with the language and trying to discover the secrets of their art.

Mathematical linguistics, using the statistical analysis of language structure as a basis, constructs models of the language with the aid of electronic computers. "Literary talents" of electronic computers are just an example of such models of "operations that man performs with the language".

How does a computer write?

The computer learned how to synthesize phrases on the basis of the statistical analysis of the language. Hence, it will not be difficult for it to synthesize, i.e. to build according to a programme, sentences from the reserve of words recorded in the computer memory. It makes no difference to the computer what to look for—for a coded word or for a coded number. To practise the "art of letters" with a computer one should give it a dictionary in which related concepts are designated by close code numbers:

1001001—animal
1000100—bird
1001101—eagle, etc.

In compliance with the programme and with this code the computer will choose words close in meaning. The initial text introduced into the computer will serve as a basis for this "creative" work. The "work of literature" is produced in cycles. With each cycle of programme repetition the computer extends the basic text, every time departing from it still further, however not beyond reasonable limits, so that the text would not lose sense altogether.

This is followed by a process of constructing phrases. Using the programme instructions the computer combines all the words into sentences in accordance with the rules of grammar.

And now some examples of computer literature—in recent years a veritable "collection of works" written by different computers has been built up.

The computer "RCA-301" learned how to write white verse. The word reserve of the poet is 130 words. The metre of the verse is strictly fixed. The computer writes 150 quatrains per minute. It doesn't name its verses, just numerates them.

Verse No. 027

While life creates false totally empty images,
While slow time flows past useful deeds,
And the stars dejectedly orbit the skies,
People cannot smile.

Poem No. 929

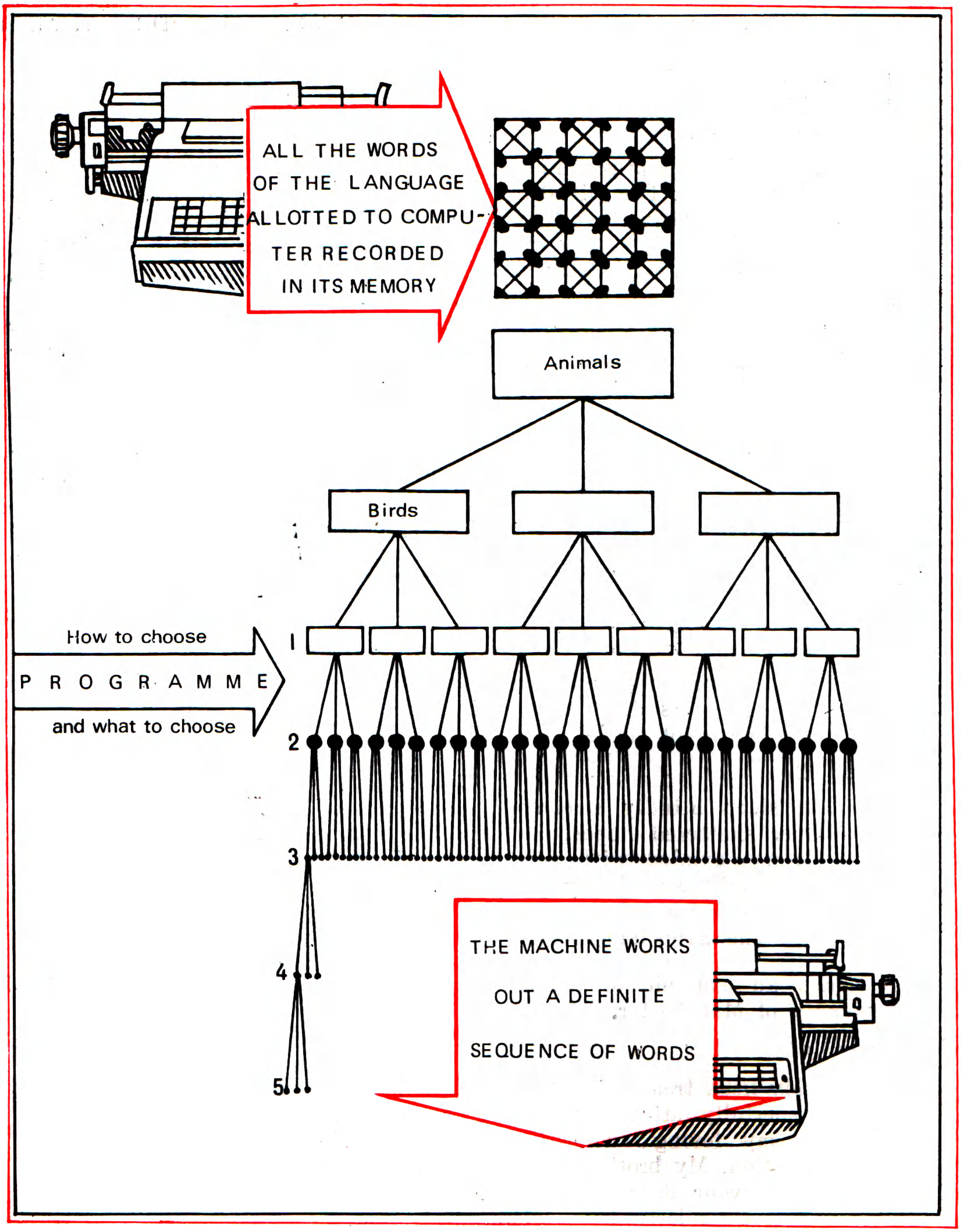
As sleep blindly streamed
Over shattered hopes,
Cosmos exuded with pain over ruined love.
Your light was slowly exiled
Out of secret men
And the skies slumbered not.

And here's an example of the writings of MUC—the "electronic brain" of the University of Manchester.

A Love Letter

My little treasure! My comprehensible devotion wonderfully attracts your tender delight. You are my loving adoration, my breast-widening adoration. My brotherly feeling with secret breath awaits your dear restlessness. The adoration of my love tenderly keeps your greedy zeal.

Your lovesick MUC


ALL THE WORDS OF THE LANGUAGE ALLOTTED TO COMPU-TER RECORDED IN ITS MEMORY
Animals
Birds
How to choose
PROGRAMME
and what to choose
1
2
3
4
5
THE MACHINE WORKS OUT A DEFINITE SEQUENCE OF WORDS

And here's another author—the French computer "Calioppe".

Excerpt from a Story

My horizon consists entirely of the red curtain from which suffocating heat emanates at intervals. The mystical silhoutte of a woman, proud and terrible, can barely be discerned. She is a lady of noble birth, probably one of the seasons. It appears she is saying goodbye. I'm not able to see anything more and move towards the curtain. My hands draw it apart convulsively. There on the other side opens a strange tragic landscape: tsivetta scratches the earth, birds fly from both sides and come down on the branches of trees half-withered. Here, too, is a tortoise resting motionless: it sensed my presence. But why is it covered with frost? A boy comes running along, his plump hands, his serious dark face make him look like a young hero.

A striking resemblance of computer "literature" to formalistic writings of some ultra-fashionable Western authors lies on the surface. The fact that programmes for computers and the word reserves for them are prepared by men is, probably, not the least cause for this. In short, the computer authors produce what's asked of them!

As has already been pointed out, the statistical approach to the language is one of the methods of mathematical linguistics. Another method not inferior in interest and importance is the comparison of natural languages and the artificial languages of mathematical logic. Aided by mathematical statistics, information theory, theory of probability and by other sciences, mathematical linguistics constructs new, more flexible, more simple artificial languages for electronic computers.

In this field there is yet another research tool—the so-called analysing grammatical models and models of initiating grammars. These frightening specialized terms conceal the effort of mathematical linguistics to construct multi-purpose language models.

For what specific purposes? Here we have to restrict ourselves to the statement that the sphere of application of mathematical linguistics is a wide one: the creation of formal computer languages, computer translation,

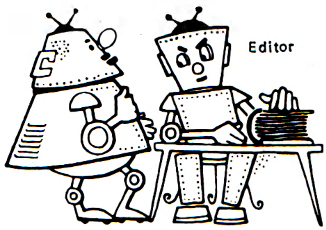
◀ The anatomy of mechanical composition.
1—birds of prey
2—daylight birds of prey
3—Falconidae family
4—eagle
5—steppe eagle

the reading of forgotten written languages, etc. Each of these applications is exciting, full of surprises and has a great practical value.

A few concrete examples will suffice to convince you.

It's the job of mathematical linguistics to find optimum ways of translating texts from an ordinary language, i.e. Russian, English or some other, into the computer logical language, which alone is understood by computers. Mathematical linguistics is also working on the problems of recording human speech for the purposes of constructing automatic stenographers and reading automata. Great is the humanitarian role of this science in the field of research related to the use of computers for facilitating communications between deaf and blind people.

Mathematical linguistics has made a promising start. This gives reason to hope for a successful and productive future.



"How is my new novel going?"
"Sorry, you'll have to be overhauled."

The science which studies forms of reasoning and proofs by mathematical methods.

Three Jinns

There is hardly a schoolboy who doesn't know what algebra is. Children study algebraic problems at school, write algebraic expressions of letters and numbers connected by the signs of operations such as addition, subtraction, multiplication and division.

Has it crossed your mind that since in algebra operations are performed with letter symbols there may also exist an algebra of the language—an algebra which would enable answers to questions to be calculated in the same way as answers to problems are calculated?

The philosopher of the ancient Greeks Aristotle who lived in the 4th century B.C. initiated the science of logic—the science of reasoning correctly, the science dealing with the forms and the laws of thinking. He analysed human thought in the forms of concepts, judgements, conclusions and scrutinized it from the structural, or formal, aspect. This was the beginning of formal logic—the science which tries to reveal the secrets of our reasoning, the science which studies logical operations and rules of thought.

In the Middle Ages these attempts led to the idea that it is possible to arrive at various truths with the aid of mere combinations of general concepts. "Thinking machines" were even built for this purpose. The philosophers of the Middle Ages dreamed to solve with their help all the problems of science, all the riddles of life, all the mysteries of Heaven and Earth. The design of the "thinking machine" of the philosopher, theologist and alchemist of the Middle Ages Raimon Lull was quite simple. Nine questions were written along the circumference of a big stationary disc: "How much?", "Which of the two?", "When?", "Where?", "What quality?" and others of the same sort. Inside this disc five additional discs of decreasing diameter were arranged one on top of the other. They could rotate independently. Each disc was divided into nine sectors (chambers), containing inscriptions. One disc contained the names of nine principal sins and virtues, the other—of nine principal physical properties.

Lull stuffed the chambers with all the wisdom known to him. He turned some of the discs one, two or three points, leaving the others (i.e. the first, the second, the first and the third, the fifth and the second) stationary. And each time different word combinations appeared against the questions inscribed on the stationary disc.

Obviously, such a machine could solve no logic problems. Its "revelations" looked more like absurdities. This was quite natural, since its inventor Raimon Lull, though he named his creation an "object of great art", had no idea of the rules of mathematical logic which serve as a basis for the operation of modern logical computers.

The great German mathematician and philosopher Gottfried Wilhelm Leibnitz is considered to be the founder of mathematical logic. He was the first to try, in the 17th century, to construct logical calculus of the arithmetical and algebraic types. He narrowed the gap between logic and calculations, improved and specified the symbolics of logic.

On the foundation laid by Leibnitz another great mathematician George Boole, father of E. Voynich, the author of the novel *The Gadfly*, built the temple of a new discipline—the mathematical logic. He devised a special algebra adapted to logic constructions. As distinct from ordinary algebra, this algebra uses symbols to designate not numbers, but statements.

When children learn to count, they are embarrassed when having learned, for example, how to add two apples and three apples, they have to add three houses and two houses. But later at school the children get it into their heads that numbers exist by themselves and do not necessarily serve to designate the number of apples, houses, cars, etc. Children learn when studying algebra that the concept a^2 is much wider than 13 apples multiplied by 13.

The same is true of mathematical logic—one has to abstract himself from the contents of statements. They are of no importance to mathematical logic, just as algebra is indifferent to what x stands for—the number of fish, cars or stars.

Since in this logic we are dealing with mathematics the concrete meaning of a statement is of no importance to it. One thing only is important—whether a given statement is true or false.

Note also the following. Actually everyone of us, so to speak, devotes all his time to practising formal logic. Involuntarily we, especially when trying to stress our point, adapt ourselves to the laws of linguistic algebra, for (in the opinion of the specialists) the mathematical logic can be said to form the "skeleton of our thought". It serves as a basis—naturally, in a very broad sense—for the general properties of statements and of reasoning.

Imagine yourselves answering the question "Why is it light in daytime?" with the words "Because light shines in daytime".

You have violated the rules of logic, the logic of reasoning, for you haven't explained anything. Unsubstantiated method of thinking of this sort was branded by Molière in his immortal comedy *Le Malade imaginaire*. In the course of the play a bachelor of science is being examined: "Why does opium promote sleep?" The bachelor's answer is: "Because it contains soporific power, which is capable of lulling senses to sleep." As we see from this example, here the words of normal language taken together in context are devoid of clear, precise meaning.

There is an ancient reasoning that became a classical example of logical proof: "All men are mortal. Socrates is a man. Therefore, Socrates is mortal."

Scientists invented unique symbols to enable precise meaning to be attributed to words. This system of symbols enables the logical structure of an idea or of a judgement to be discovered. With the aid of precise definitions of words it is possible to calculate the interconnections between symbols of words, the relationships existing between them. Things which were formerly difficult to express in words of the normal language can now be easily represented by symbol of mathematical logic.

Here's a simple example: H_2O is the symbol of water. It states that there are two atoms of hydrogen and one of oxygen to a molecule of water. In this transcription the facts relate to chemistry, the numbers to mathematics and the symbols to the logic of symbols.

Let's undertake a step-by-step incursion into the laws of logic. Three different forms in which thought is realized are considered in logic: concept, judgement and deduction.

"This inscribed angle, resting on the diameter" is a concept. In case not all the angles are embraced by it, it is a singular concept. "All inscribed angles, resting on the diameter, are right angles" is already a judgement, since it reveals the properties of the object of judgement.

The process of deducing a third judgement out of the two is called deduction. Its principal form in logic is called the syllogism. One of the judgements in the syllogism—the general one—is called the major premise, the other judgement—the specific one—is called the minor premise, and the deduced judgement is called the conclusion.

Let's take the judgement "All computers make man's work easier" as the major premise, and the judgement "The arithmometer is a computer" as the minor premise. Then the conclusion drawn from these judgements will be "The arithmometer makes man's work easier".

The judgements may be true or false. If they are true, then, provided we adhere to certain rules of constructing syllogisms, we shall always obtain correct conclusions, true inferences from the judgements, as, for example, our conclusion about the arithmometer.

But if, while adhering to the rules of syllogism construction, we obtain a false conclusion, this means that at least one premise was not correct.

And vice versa, if all the premises were true judgements, but the deduction resulted in a false conclusion, this means that some law of syllogism construction was violated. We may obtain the absurd conclusion "All pupils are poor pupils", if we construct the syllogism incorrectly: "Petrov is a poor pupil. Petrov is a pupil."

It turns out that the solution of every logical problem, as well as a mathematical problem, has its own "technology". It's made up of elementary operations resembling addition and multiplication. There are special rules for these operations, and with their aid anyone is able to solve a complex logical problem. The same is true of an automatic computer.

A logical problem for the computer must be expressed in formulae.

It's quite a commonplace thing to transform quantitative relationships expressed in numbers into formulae. But is there a way of compressing into formulae arbitrary logical judgements? For example, how should the judgement "I shall certainly go to the football match if I get a ticket, or if a friend invites me, and if it is not raining" be represented by a formula?

Well, there is a way. But some logical judgements are needed, by way of explanation.

The judgement of the football fan contains several reservations. Here they are:

1. I will get a ticket.
2. I will be invited by a friend.
3. It will be raining.

Simple judgements may be interconnected by the words OR, AND, NOT. Composite statements are always expressed by simple ones with the aid of these words. They, like three jinns, can do everything in logic.

We can agree to designate each of these words, for the sake of brevity, by some symbol, just as in mathematics corresponding signs are used instead of the words "plus", "minus", "multiply", "divide".

The word OR is usually designated by a cross (+), and the word AND, by the sign of multiplication—the point (·).

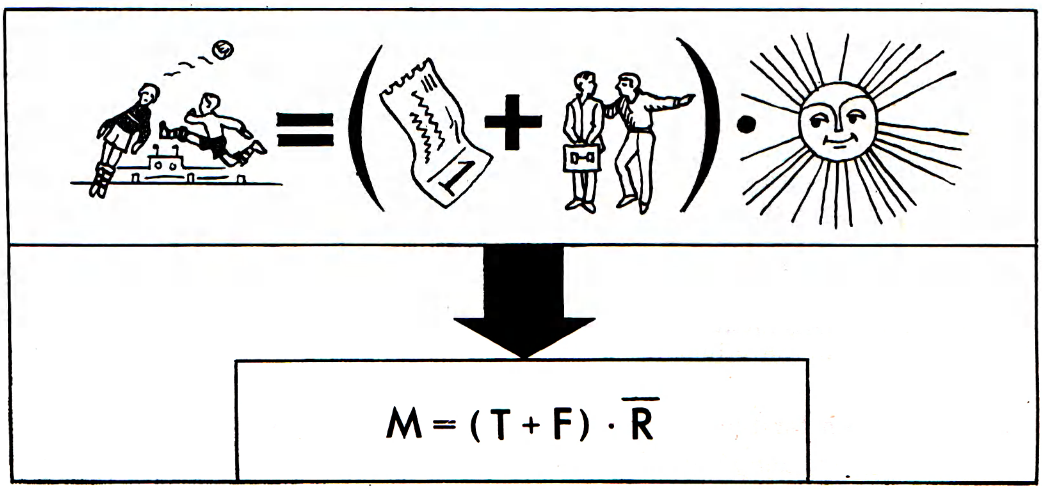
Now it remains, for the sake of brevity, to introduce a letter for each statement. Its negation, i.e. the word NOT, will be designated by the same letter, but with a dash on top. For example:

I will get a ticket—T. I will get no ticket—$\overline{T}$.

I will be invited by a friend—F. I will not be invited by a friend—$\overline{F}$.

It's going to rain—R. It's not going to rain—$\overline{R}$.

Now we shall write with the aid of these symbols the composite statement "I will get a ticket, and it's not going to rain, or I will be invited by a friend, and it's not going to rain".



Here it is:

$$T \cdot \overline{R} + F \cdot \overline{R}$$

As in algebra, the common multiplier can be taken out of the brackets. Now the formula will take the form:

$$(T+F) \cdot \overline{R}$$

It reads as follows: "I will get a ticket, or I will be invited by a friend, and it's not goint to rain."

This composite statement of our football fan is tantamount to the condition of his going to the match which we shall designate by the letter M.

Now the statement can be expressed by a very brief formula

$$M=(T+F) \cdot \overline{R}$$

As you know, every logical judgement may be either true or false. It's been agreed in mathematical logic that true statements be expressed by one, and false by zero. Again 1 and 0. "I've learned all the lessons"—this was what a pupil told her class instructor. Let's designate this statement for the sake of brevity by the letter L. If this statement of the girl is true, $L=1$. Thus, if $L=1$, $\overline{L}=0$, since in this case the statement "I have not learned my lessons" would be false.

And vice versa, had the pupil not learned her lessons, $L=0$ and $\overline{L}=1$.

This is a general rule in logic. If some statement $B=1$, then $\overline{B}=0$, and vice versa: if $B=0$, then $\overline{B}=1$.

It remains for us to observe a few additional propositions of mathematical logic to know all its principal laws.

Obviously, $B+B=B$ and $B \cdot B=B$.

Clearly, the composite statement "I'm going for a walk or I'm going for a walk" is fully identical to the simple one "I'm going for a walk". Similarly "The receiver will work and the receiver will work" is tantamount to the simple statement "The receiver will work".

Two following propositions are just as obvious:

$$B+\overline{B}=1 \quad \text{and} \quad B \cdot \overline{B}=0$$

Indeed, the composite statement "It's going to rain, or it's not going to rain" is true in both cases—it's always true.

Such a weather forecast would always be correct. True, it would be of little use to anyone.

The composite statement "TV set is on and TV set is off", on the other hand, is always false. Opposite judgements connected by AND can never be true.

Now, after we have transformed logic into formulae, let's ask ourselves the question: can truth be "calculated"? The answer turns out to be "Yes".

There is a book called *Mathematical Wit*—a collection of mini-problems for sharpening wits. It contains all sorts of bright problems, mathematical games and tricks. The chapter "Mathematics Almost Free from Calculations" deals with problems the solution of which entails the construction of a chain of sophisticated and acute arguments. One of the problems—"A Criminal Story"—suits well to illustrate this tale of mathematical logic. Here is this problem in a slightly corrected form adapted for this book.

It's a sad story. In one of the school's classrooms a window has been broken. Only one out of four pupils: Lenya, Dima, Tolya and Misha, could have been the culprit.

In the course of interrogation each of them gave three answers.

Lenya: 1. I'm not guilty. 2. I haven't even been near the window. 3. Misha knows who's done it.

Dima: 1. It wasn't I who broke the window. 2. I didn't know Misha until I came to this school. 3. Tolya's done it.

Tolya: 1. I'm not guilty. 2. Misha's done it. 3. Dima is telling a lie saying I've done it.

Misha: 1. I'm not guilty. 2. Lenya has broken the window. 3. Dima can vouch for me as he knows me from the day of my birth.

In the course of further interrogations each of the pupils said that one of his statements was false while two were true.

Let's try and find the culprit with the aid of mathematical logic.

We know that every composite statement of each of them, if true, is equal to one, and if false—to zero.

This means that the composite statement of each boy will be true if the first and the second statements are true, and the third false, or if the first and the third are true and the second false, or if the second and the third are true, and the first false.

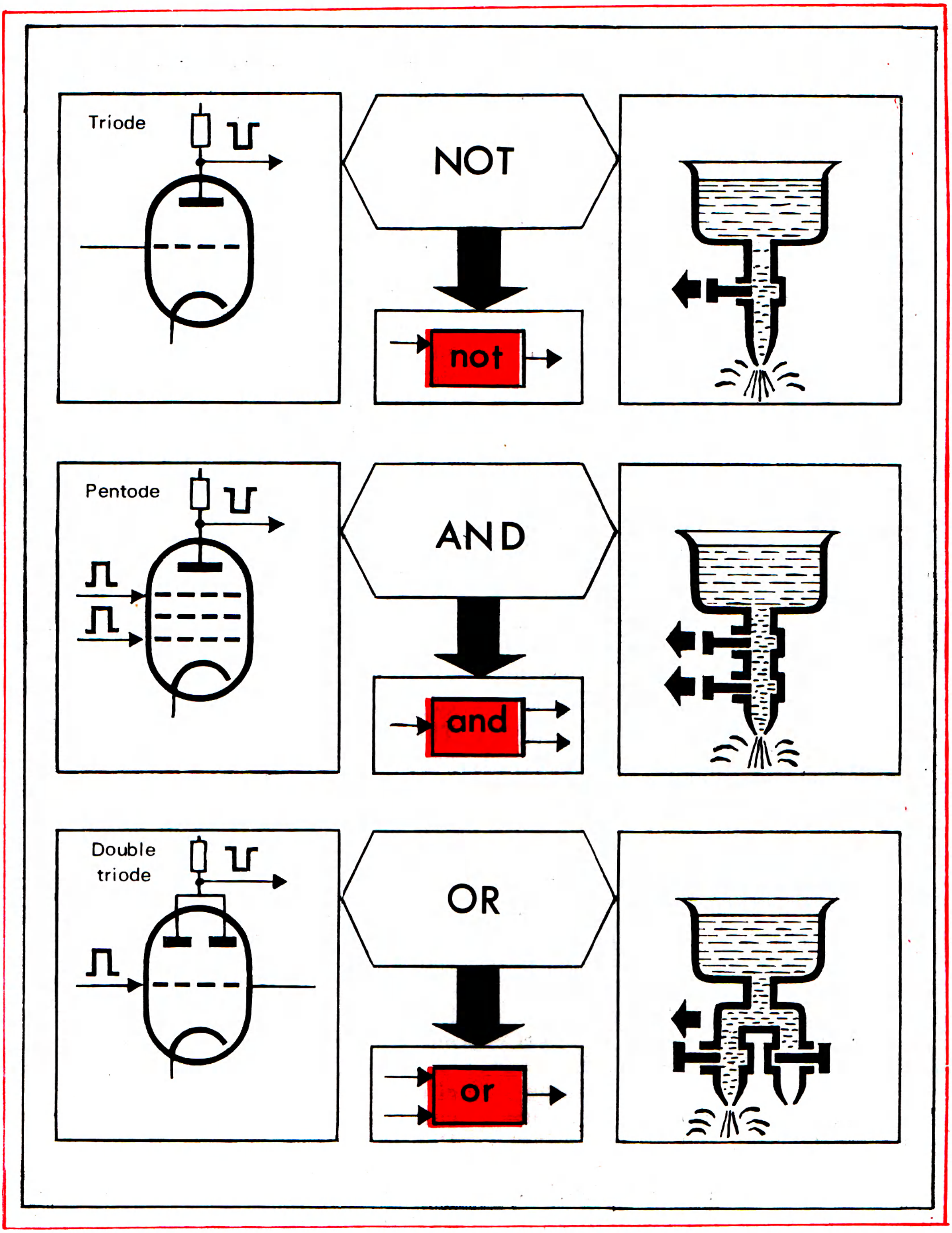
We will denote each pupil by his initial letter and his statements by subscripts. Thus

$$L = L_1 \cdot L_2 \cdot \overline{L}_3 + L_1 \cdot \overline{L}_2 \cdot L_3 + \overline{L}_1 \cdot L_2 \cdot L_3$$
$$D = D_1 \cdot D_2 \cdot \overline{D}_3 + D_1 \cdot \overline{D}_2 \cdot D_3 + \overline{D}_1 \cdot D_2 \cdot D_3$$
$$T = T_1 \cdot T_2 \cdot \overline{T}_3 + T_1 \cdot \overline{T}_2 \cdot T_3 + \overline{T}_1 \cdot T_2 \cdot T_3$$
$$M = M_1 \cdot M_2 \cdot \overline{M}_3 + M_1 \cdot \overline{M}_2 \cdot M_3 + \overline{M}_1 \cdot \cdot M_2 \cdot M_3$$

If we read the statements carefully we will not fail to notice that the first and the third statements of Tolya are equivalent: obviously, the meaning of the statements "I'm not guilty" and "Dima is telling a lie saying that I've done it" is, in essence, the same. Hence, $T_3 = T_1$, and $\overline{T}_3 = \overline{T}_1$. Now Tolya's statement can be rewritten in the form

$$T = T_1 \cdot T_2 \cdot \overline{T}_1 + T_1 \cdot \overline{T}_2 \cdot T_1 + \overline{T}_1 \cdot T_2 \cdot T_1, \text{or}$$
$$T = (T_1 \cdot \overline{T}_1) \cdot T_2 + (T_1 \cdot T_1) \cdot \overline{T}_2 + + (\overline{T}_1 \cdot T_1) \cdot T_2$$

We know already that contradictory statements are untrue. Therefore, $(T_1 \cdot \overline{T}_1) = 0$. If one of the multiplicants is zero, Tolya's statement will assume the form $T = T_1 \cdot T_1 \cdot \overline{T}_2 = = T_1 \cdot \overline{T}_2$. It will be true and, hence, equal to one, if both of the multiplicants are equal to one.


Triode
NOT
not
Pentode
AND
and
Double
triode
OR
or

Therefore, $T_1=1$ and $\overline{T}_2=1$, or $T_2=0$. Thus we have obtained that the first statement of Tolya is true, and the second false. Since his words were: 1. I'm not guilty. 2. Misha's done it. 3. Dima is telling a lie saying I've done it—it's clear that the window had not been broken by Tolya or Misha.

This simultaneously proves the third of Dima's statements accusing Tolya of the crime to be untrue. Hence, $D_3=0$ and $\overline{D}_3=1$. So in the formula for Dima's statement the last two of the items will turn zero, and it will assume the simple form

$$D = D_1 \cdot D_2 \cdot \overline{D}_3$$

We have obtained already $\overline{D}_3=1$, hence, $D_1=1$ and $D_2=1$.

The first and the third statements of Dima are true, and this proves him to be innocent.

The third of Misha's statements controvenes the second statement of Dima. Let's write $M_3=\overline{D}_2$. Hence, $M_3=0$, and $\overline{M}_3=1$. Now Misha's statement is as follows:

$$M = M_1 \cdot M_2 \cdot \overline{M}_3$$

It will be true only if $M_1=1$, $M_2=1$. $\overline{M}_3=1$. Misha's second statement is true. The window was broken by Lenya. Thus the formulae of mathematical logic enabled us to find the culprit quickly and unmistakenly.

In the course of computer progress mathematical logic became intimately connected with computer mathematics and with all problems relating to the construction and programming of electronic computers.

The start was made when scientists initially suggested the possibility of constructing electrical circuits on the basis of mathematical logic. Next such circuits were assembled. Now computers are being built on the basis of all types of electronic circuits.

Now look. Suppose we agree to designate contacts closing a circuit in the presence of signals a and b by the same letters a and b and contacts breaking the circuit in the presence of these signals by the symbols a' and b' and, moreover, agree to designate the parallel and series connections of these contacts by the signs of addition and multiplication, then we will find that operations a', $a+b$, ab are performed according to rules of logical negation (NOT), addition (OR) or logical multiplication (AND). A closed circuit is in this case 1 (truth), an open circuit 0 (lie).

Imagine an electric circuit consisting, for example, of a voltage source, an alarm and two switches. In such a circuit to sound the alarm both switches have to be switched on. This is called the coincidence circuit, or the logical AND circuit.

An output signal appears only in case both signals coincide in time.

Let's connect both switches in parallel in another circuit. To sound the alarm one OR the other switch should be switched on. This is called the separation circuit. It performs the logical OR operation. The circuit allows voltages from different lines to be applied to one point without connecting these lines.

The negation, or the logical NOT circuit, can be called an inverted circuit. It has one input and one output. But the output signal appears only in the absence of the input signal.

There is, naturally, no sense in inserting circuits with switches into high-speed electronic computers. Here the job is done by electron devices. They perform the same logical operations, but at enormous speeds.

Here, for example, are three electron-tube circuits. The first NOT, the second AND, and the third OR. How do they work?

Let's make use of the analogy between the electric and water currents. See how the level of water in the vessels drops and you'll understand everything. If the slide valve is NOT moved, the level of water in the vessel will drop. If the first AND the second slide valves are moved, the level of water in the vessel will drop. If the first OR the second slide valve is moved, the level of water in the vessel will drop.

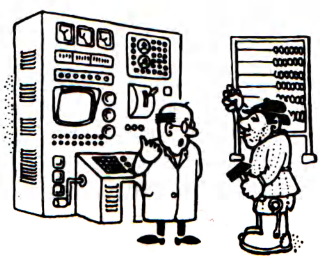
Something of the sort takes place in the electron tubes as well. The only difference is that electric current flows instead of water. Instead of water levels we have output voltages, and the circuits are controlled not by slide valves, but by current pulses.

Thus, we have obtained circuits for realizing the three principal logical operations: the omnipotent AND, OR, NOT, so to speak, materialized in the substance of wires and tubes. They enable the computer to "reason" in the course of its work: AND—to connect, OR—to choose, NOT—to negate.

If one recollects that the trigger in showing one and zero seems to say "yes" or "no", it will become clear: the computer language, despite its scarcity, enables all numbers and all words to be coded and logical reasoning to be performed.

The application of the calculus of statements in automata, in electronic circuits connects mathematical logic with cybernetics, on one hand, and makes this abstract science bring practical results, on the other. In plain words, mathematical logic is active everywhere, where electronic computers are at work, for every problem is solved by computers in compliance with its immutable laws.

But this is only one aspect of the problem. The other is that the computer circuits themselves, and their elements, are being analysed and developed with the aid of mathematical logic.



"Its answers are ambiguous, sometimes."

M

Where Is the Midget Moving?

MICROMINIATURIZATION

**A trend
in the progress of technology
aimed at reducing the dimensions,
weight and energy consumption
of equipment,
at improving its reliability
and facilitating the automation
of its production.**

If the designers of electronic computers were to have a song of their trade it would surely have the refrain "Smaller, still smaller..."

Judge for yourselves.

There is "Eniac", the one-time idol of computer operators—an intricate collossus weighing 30 tons and occupying a hall of 150 square metres and containing 40 separate panels, 18 thousand tubes, 1500 electromechanical relays.

Impressive numbers!

And the other veteran—"Tridag"?

It occupied a whole building housing transformers, electric motors, air-cooling plants and pumping stations. They all served 8 thousand tubes and 2 thousand relays.

In our time the fate of a computer somewhat resembles the fickle fate of many films. Barely has it succeeded in making the world gasp as it becomes a museum exhibit, a greater rarity than, say, a car made at the beginning of the century. Such was the fate of the first computers.

Why were those giants so short-lived? Why did those "mastodonts" of computer technology perish? Main reasons for this were their large dimensions and, of course, slow operating speeds. The operating speeds of those giants, though rather high for those times, were still slow—some tens or hundreds of calculations per second, not more.

Yet the problems put forward by modern science and technology were such that the mere thought of solving them could take the breath away.

The need arose of performing tens of trillions of arithmetical operations. Even with a speed of ten thousand operations per second it would take a high-speed computer over four years of continuous operation to do the job. For instance, the solution of a problem relating to planning and control of the economy requires 10 000 000 000 000 000—a number with sixteen zeros (10^{16})—calculations to be performed.

Three and a half million slow-speed computers would be needed to complete this enormous job. This is unfeasible. Only one alternative remains —to make the computers work faster.

Working eight hours a day you could count to a million in three and a half months. A billion would take you ... 500 years to count.

The computer does it quicker. But how much quicker? In a day, an hour, a minute?

How many times quicker—that is the question. And then: what should high-speed computers look like, what elements should they be made of, what will their dimensions be?

Now that computer engineering has its history we can glancing back perceive the changes that the computers have undergone from generation to generation, and follow the trend of their development.

The ancestors of present-day computers were the electromechanical sluggards into which all the ingenuity of the fourties was packed. Their time of operation was in the milliseconds range.

The first generation of modern computers announced its appearance by a steady hum of electron tubes in grey metal cabinets. Their life was not a very long one—from 1946 to 1957. The density of elements was 0.01-0.10 per cubic centimetre.

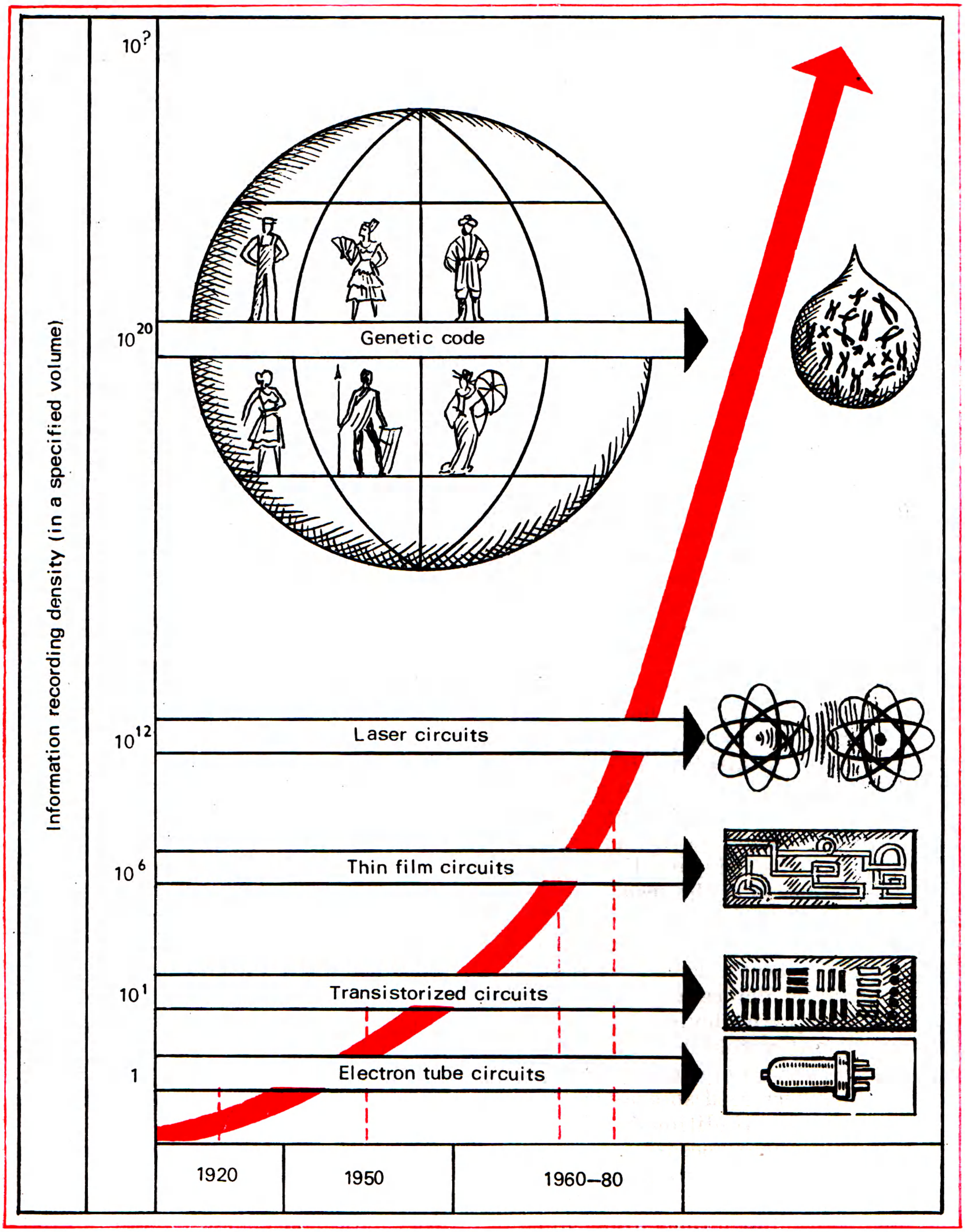
Operating speeds were already in the microseconds range. As soon as these computers began to display first signs of intelligence people hurried to brand them "thinking machines" and began feverishly making estimates as to what the dimensions of computers comparable to the human brain would be. The result was discouraging. The "electronic brain" would be as big as the biggest skyscraper. It would need a Niagara Falls to cool it.

The computers of the second generation began to take shape already within the first generation.

The main part in the computers of the second generation is played by semiconductors. The best electron tube works not more than 5 thousand hours, while a semiconductor device works 70 thousand hours. Alongside the envelope of a tube the semiconductor device the size of a match head looks quite a dwarf. It proved to have many valuable qualities: the reliability of the new computers increased, their energy consumption was low, and they could do well without cooling. Their dimensions decreased so drastically that designers began talking of table calculators to replace traditional arithmometers.

And what about speeds? A tenth or a hundredth of a second per operation? No, much faster—some thousandths or even ten-thousandths.

As the computers of the second generation appeared it became clear that the method to minimize their dimensions in future should consist not merely in dimi-



Information recording density (in a specified volume)
10?
10^{20}
Genetic code
10^{12}
Laser circuits
10^{6}
Thin film circuits
10^{1}
Transistorized circuits
1
Electron tube circuits
1920
1950
1960–80

nishing the volume of various blocks of the computer as a whole but should be based, in the first place, on minimizing the dimensions of separate components, on increasing their packing density with a simultaneous decrease in the number and length of all connections between the blocks. Now the designers went to any length to make a midget out of the computer.

And the simple transistor which recently was triumphantly marching through the entire electronics has modestly relegated to the background. Instead, new components took up the struggle for minimum dimensions and maximum speeds of computers. Great was their number: optotrons and cryotrons, high-frequency transistors and tunnel diodes, spacistors and twistors, biaxes and transfluxors, persistors and cryosars, parametric devices and technetrons. A tenfold decrease in the volume of various apparatus became at once a reality. And operating speeds shifted to the hundred thousandths and even millionths of a second range.

But even this colourful array of subminiature, ultra-fast, super-reliable components soon made way for thin films—the building stones of third-generation computers.

Three generations of computers in the spell of twenty years!

At the beginning of the fifties—tube computers, at the beginning of the sixties—transistorized computers, and at the beginning of the seventies—computers on integrated circuits (thin films).

With the aid of these new building stones it proved possible to build a world of tiny giants, to erect electronic cities of unusual architecture. Recently, the designer would proudly demonstrate a computing block of the computer the size of a tin of sardines. Now, engineers dream of packing 350 thousand circuits into one cubic decimetre.

Where do these magic qualities of the thin film stem from that allow engineers to achieve so much?

Usually films are produced by evaporation. The appropriate material is heated in vacuum under ambient pressure of a thousand millionth of an atmosphere. The material evaporates and condenses on a glass or a metal plate. This fine work is made much more intricate by the necessity of arranging the particles not arbitrarily but in accordance with a strict pattern. "Electronic stitching" is based on the process of condensation through the slits of a mask repeated many times. The structure of the layers of the film used in circuits—there may be ten, fifteen or more of them—must coincide exactly. To show the difficulty of this job it suffices to state the thickness of the film—it's only 100 Ångströms (one hundred thousandth of a millimetre thick). The right to use the word thickness with the film being thinner than a ten thousandth of the thickness of a safety razor blade remains in itself questionable.

This film circuits are complete electronic circuits. Thus we witness not the art of assembling circuits from separate blocks, from separate building stones, but a supreme mastery of matter when every particle of it in compliance with the wishes of the creator occupies a place allotted to it.

This is the quality that now assumes major importance for computer designers.

◀ The path of microminiaturization.

Millions of devices per cubic millimetre in conjunction with speeds of millions of operations per second.

Operating speeds of third-generation computers are expected to rise by about two orders of magnitude: 10^8 operations per second, that's what their speed is going to be. This is only an order of magnitude less than the limit set by the velocity of electric pulse propagation in solids.

And the fourth generation? These computers are still more advanced. Speeds up to 10^9 operations per second, a working memory store housing 10^8 bits of special inter-computer information units. This unit is equivalent to two decimal digits or one ABC sign. This amount of 10^8 bits is simply hard to imagine. Let us by way of an example translate the volume of computer external memory store exceeding 10^{12} signs into the "book language". The result will be millions of volumes of 500 pages each!

The fourth-generation computers boasting such parameters and such a structure are, in effect, real communities of the second- and third-generation computers. This trick was accomplished with the aid of a new subminiaturization instrument, the BIC. Big Integrated Circuits represent structural complexes of numerous elements. Just compare: the envelope of one semiconductor device houses only the device itself, of an integrated circuit—up to ten devices, and of a big integrated circuit—over a hundred. And this is not the limit. In the future BIC will, probably, grow to become GIC—Gigantic Integrated Circuits — containing several thousand elements.

GIC may be regarded as the building blocks for fifth-generation computers, or, to be more exact, of highly productive communities of entire computer systems with a total memory of billions of bits and operation speeds of billions of operations per second.

An absolute superiority of midgets over giants! The midgets won again, having succeeded in opening the doors of the kingdom, unseen and unheard-of before, of the kingdom the entrance to which bore the inscription "nanosecond"—a billionth of a second.

Such computer speeds, though it sounds like a paradox, can be neither seen nor imagined, but they can be attained and utilized.

This marks a complete triumph of technology: something has been made by hand that defies imagination.

However, as is often the case in technology, every new achievement creates a new problem.

The limit for the speed of operation of third-generation computers is set by the velocity of propagation of electric pulses in solids.

To overcome the problem one has to make a detour.

The way as the specialists see it is as follows. Microscopic devices have been designed for the conversion of electric signals into light signals, and vice versa.

Simultaneously fibre optics has come into existence. The latter makes use of thin transparent filaments, with the aid of which light can be transmitted along any straight or curved path connecting the elements of the circuit, in the same way as electrons are transported along metal wires.

As a result, in addition to the electron the particle of light—the photon —was, too, harnessed to the electronic cart. In opto-electronic systems information fluxes flow at the same time along electric and optic channels, whose joints are provided with opto-electronic and electric-optic converters. The use of optic connections and of optic methods of information processing has given electronics a new degree of freedom, has substantially increased its possibilities and opened up new horizons. Thus emerges the shape of computers of the following generations. Life will be blown into them not by electric current but by a ray of light. Now the phrase "the computer radiates thought" will sound quite real.

The principles of design of future optic computers will be quite different from those utilized in the design of electronic computers. Light pulses of a hundred billionth of a second duration switch a lazer system on and off practically without delay.

Fantastic speeds led to fantastic dimensions of the computer—they have reached the absolute minimum, the part of the calculating element in them being played by molecules and even atoms. The most acute problem here is reliability. Since repair work on such midget computers is not feasible they have to work without faults. This, the engineers decided, could be achieved. Such devices exist. For instance, nature has nursed the human brain. Its reliability is perfect. It works without repair or stoppage about 70 years, despite the fact that every hour of human life some 1000 neurons die—that makes some 500 millions during the whole life.

Then why not make use of nature's experience?

Isn't the idea of building a computer with the reliability of the brain too bold? Isn't this dream baseless?

It turns out not. Using fibre glass a laser device can be built that will operate on the principles of a living neuron. Light-conducting filaments will play the part of nerves transporting impulses. The pattern of operation of such a computer will imitate the action of the brain's neurons and the nervous system. This hybrid of technology and electronics will, in effect, make a synthetic brain.

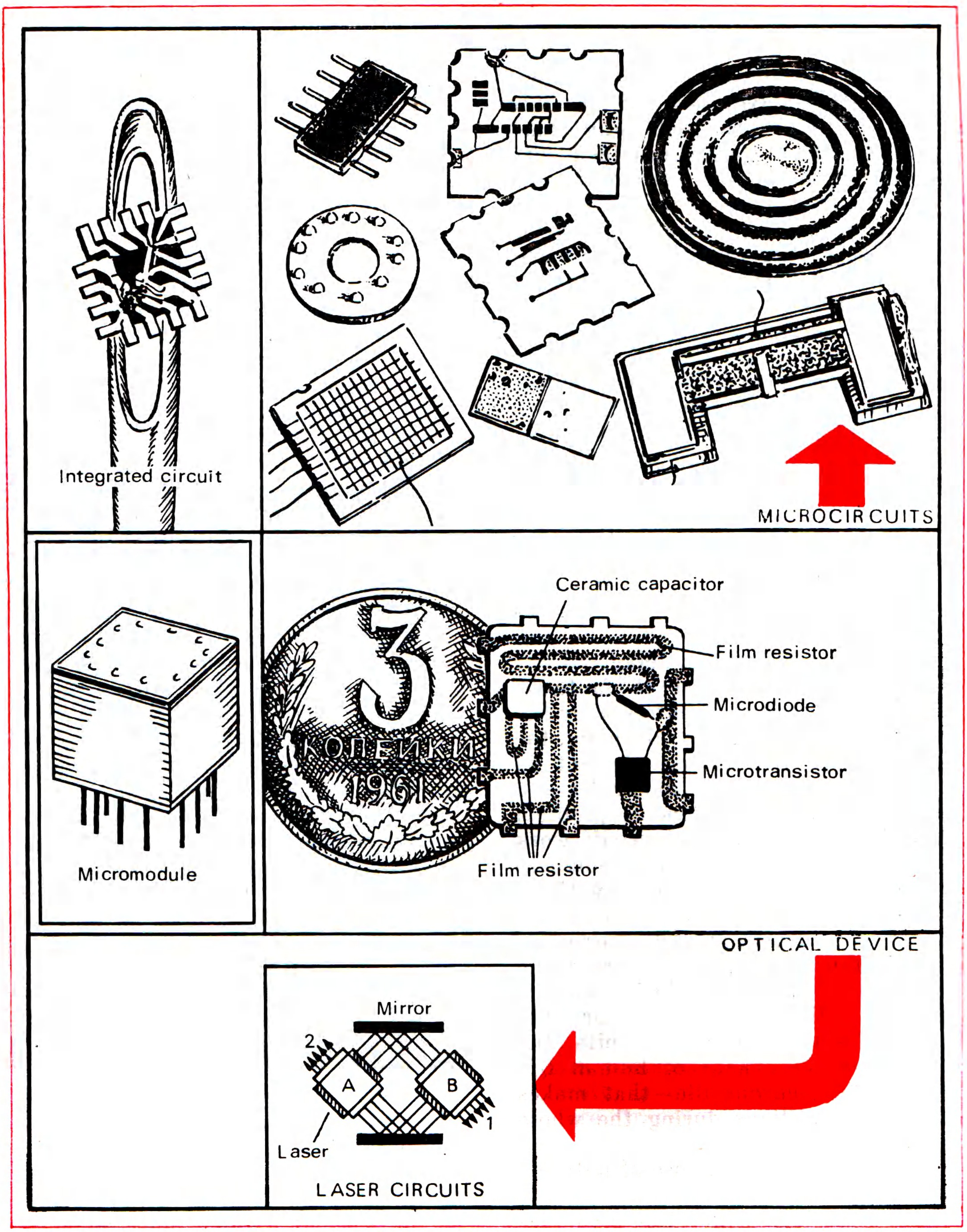
It would seem that everything that could be desired had been realized: speeds defying imagination, wonderful reliability and utmost compactness. But people with a foresight are already able to discern the dim contours of new machines.

An attentive reader, you have not failed to notice that the description is simply "such machines", without the customary epithet "thinking", or the rigorous definition "computing". Why?

New machines are expected to revolutionize technology in the same way as this was done some twenty years ago by electronic computers which replaced electromechanical calculators since their speeds will be no less than 10^{20} logical operations per second. Try and find an epithet for such a machine. Their operating principles will, too, be quite different.

Imagine yourself reading a book not line by line but whole pages at a glance.

This is the operating principle of the computer, and such projects already exist. They will be capable of processing incoming data en masse. The computer element will perceive not a line but a whole picture, nay,


Integrated circuit
MICROCIRCUITS
Micromodule
Ceramic capacitor
Film resistor
Microdiode
Microtransistor
3
КОПЕЙКИ
1961
Film resistor
OPTICAL DEVICE
Mirror
2
A
B
1
Laser
LASER CIRCUITS

ten thousand pictures at once, each of which will contain 10^{10} bits of information. In these computers you will be looking in vain for channels transmitting light and electronic signals.

They are strange, almost bodyless creatures.

Their principle of operation, to a first approximation, resembles that of the epidiascope, which instantly displays pictures on a screen and overlays them one on top of the other.

The computer's "memory", if it is based on "pictures", will be able to store a huge library of 500 thousand volumes.

The selection of information in these computers will not be based on the address principle when to get to the desired cell it is necessary to find the appropriate "street" and "house", but on the principle of associations.

Everything we memorize is interconnected, we memorize groups of information, not separate bits.

That's how our memory—human memory—works. This, too, will be the working principle of the new computers which have been even before their birth romantically christened "picture logic" computers or "picture arithmetic" computers.

We have just been introduced to several generations of computers. Have you noticed how rapidly their capabilities increase, and how at the same time their dimensions decrease at no less a rate?

The rate at which such machines depart from machines that we have been accustomed to and become something defying imagination is quite terrific.

Where does the road of microminiaturization take us? Is there a limit to computer advancement?

The history of the generations of machines gives a negative answer to this question. And what about the limitations set by the laws of nature to name, for one, the constant velocity of light?

There is no getting away from the fact that the rate of information transfer is limited by the velocity of light. Therefore, future optical machines must be designed so that light in them would have to travel minimum distances. It may be conjectured that they will be spherical in shape, since out of all bodies with an equal volume the sphere has the minimum surface area.

Going over from our usual world into the world of the atom we come face to face with new laws, new conventions. In our world the capacity of the computer is limited by the maximum density of information packed into the computer memory. In the world of the atom this is of no importance since one cubic centimetre of an absolutely condensed nuclear matter weighs 114 million tons. What an enormous amount of information could be packed into matter having such density! And what about living matter? Just think about it,

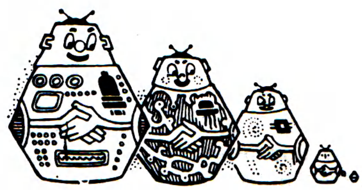
◀ The elements of microminiaturization.
Micromodules—blocks made of microelements operating as calculating cells. Integrated circuits—groups of elements. There are whole associations of them—the BIC—Big Integrated Circuits.
Absolutely new—opto-electronic—devices using lasers.

the material basis of genetic information of the whole population of the world—some three billion people—could be compressed into the volume of a rain drop.

It would be appropriate to remark at this juncture that the nerve elements of the human brain—individually—act quite slowly. The duration of the operating cycle is almost a second. Slow speed is made up for by an enormous redundancy, since the elements are great in number. According to theoretical calculations an element working at a rate of one millionth of a second does the work of a thousand elements each working at a rate of one thousandth of a second. Naturally the question arises, won't the designers turn back and start trading speed for quantity? Before there was an obstacle in this way—the dimensions of computer elements. This obstacle, as we have just seen, may disappear in the future.

Nature's ingenuity, its ability to pack information sparingly, point to the shortest road for the computer designer to take.

Today it is too early to try to define the place future machines will occupy in the life of man. What will be the job of intellectual automata that memorize and think quicker than the human brain? There is at present no answer to this question, and not because it lies in the distant future—it is not improbable that such machines will be our contemporaries. The point is, scientists at present have no clear picture of the future relations of the creator and its marvellous creation.



The investigation of various phenomena and processes with the aid of models. The model is a symbolic image (a drawing, a diagram, a description, etc.).

Different Is Identical

In 1870 the British Admiralty launched a new battleship the *Captain*. The ship went out to sea and overturned. The ship sank—523 seamen perished.

Nobody could have expected it. Nobody with one exception. The exception was the British scientist and ship builder W. Read who previously conducted experiments with a model of the ship and concluded that she would overturn even in mildly rough seas. But the Lords of the Admiralty refused to give any credit to the scientist who had been playing around with a "toy". And irreparable loss was the result.

It was not overnight that the model—this priceless and doubtless aid of engineers and scientists—found acceptance. See how little models were trusted not so long ago—only 100 years back. In a well-known publication—Granat's dictionary—even in its seventh edition, the term model merited only two words: "See foundry."

When one speaks of models nowadays, he least of all has in mind casting models. Airplanes, machine tools, hydro-electric stations, cranes, icebreakers, rockets, tractors, rolling mills—to enumerate everything that is made with the aid of modelling is a job in itself.

Scientists have made this apparently childish hobby their business. Rigorous scientific definitions for models have been introduced. Some models are called material or physical. They imitate on a lesser scale the existing "nature": real constructions, instruments, machines, etc.

These are the models we have grown so accustomed to. They facilitate in many ways the work of designers, draftsmen and engineers of various specialities.

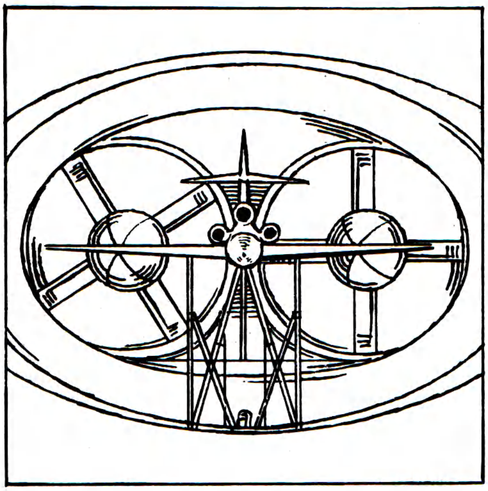
A model of an airplane being designed—an exact small-scale copy of it—is placed into the wind tunnel to measure with the aid of this "toy" such most important parameters as aerodynamic drag of the plane, lifting force, thrust, weight, etc.

Wind-tunnel tests yield altogether some 250 thousand numerical characteristics. All of them are of the utmost importance for the design of a new plane.

Another example of a model reproducing the physics of the process was cited by one of the authors of this trend in modelling, Lenin prize winner, Doctor of Technical Sciences V. Venikov.

"It was in the year 1953 that the construction of a gigantic hydro-electric station now bearing the name of Lenin was begun on the river Volga near the Zhiguli mountains.

"Power from the station was mainly to be transported to Moscow over an electric power-line about one thou-



A material or physical model is a small-size analogue of the real object.

sand kilometres long. Scientists and engineers faced many problems: that of controlling power output and transport, of guaranteeing its quality, of protecting the equipment from failures, etc.

"Since it was the first time that such powerful hydro-electric generators, connected to long-distance ultra-high voltage lines, were produced, it was necessary to design for them basically new control and protection devices, among them generator excitation regulators.

"In 1954 five prototypes of such regulators were produced. But where were they to be tested? How was the optimum prototype to be selected?

"Extensive tests entail reproducing extreme, i.e. breakdown, conditions, and a breakdown of a power system means idle tools, cold furnaces, dark windows of living houses. To avert breakdowns protective devices and automatic regulators are needed including those which were to be tested just under breakdown conditions.

"There was only one solution—to construct an artificial power system in which all processes of interest to power engineers would follow a course identical to that in the future power system. Such a power system, rather a miniature model of it, was constructed at the Moscow Power Institute."

The difficult thing is to get started. And hydro-power engineers from Moscow made the first step. After that all large hydro-electric systems of such plants as the Volga plant, the Bratsk plant, the Assuan plant were studied with the aid of physical models.

Today the extreme importance of physical models as an experimental tool in technology does not need proving. Everyone knows it. But there exists another world of models of quite different qualities and character—the world of mathematical models. They take the form quite unexpected for models—that of mathematical formulae.

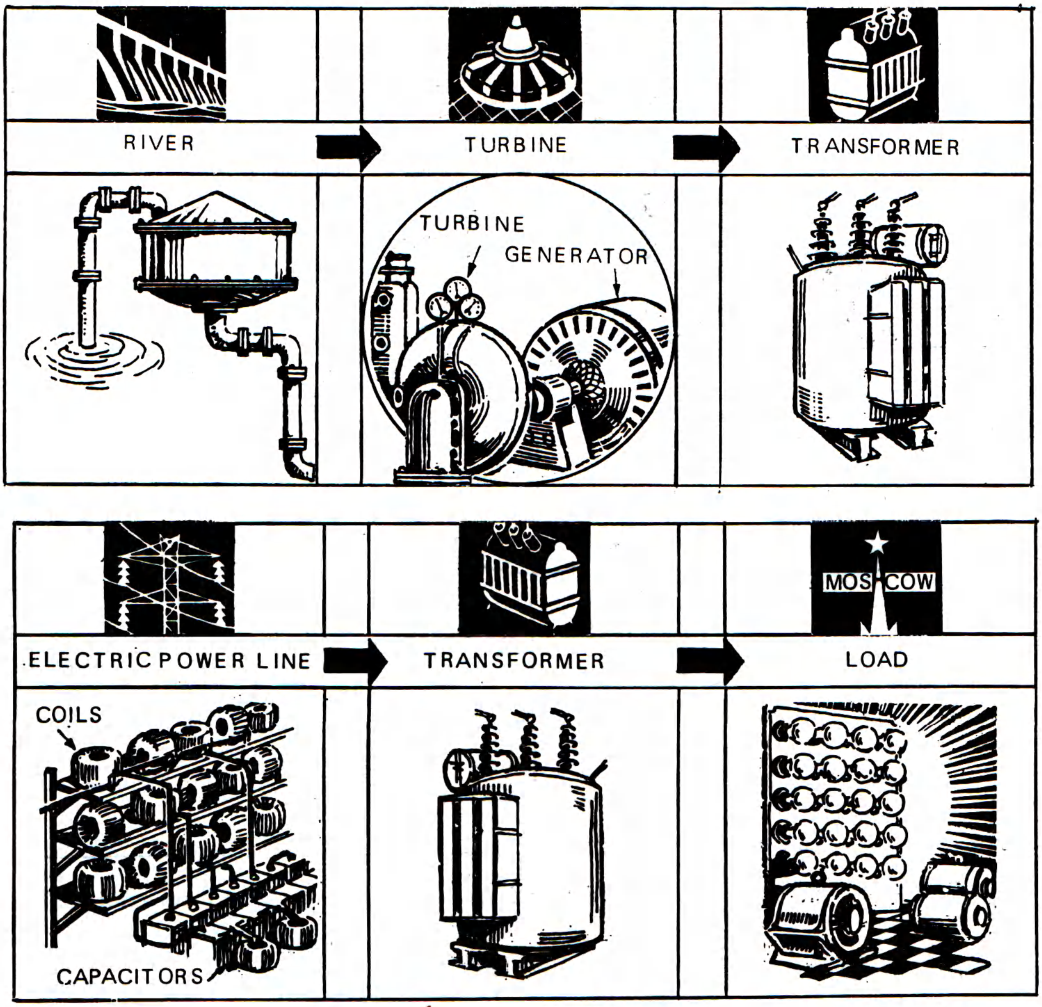
For instance:

$$a_1x_1 + b_1x_2 = c_1$$
$$a_2x_1 + b_2x_2 = c_2$$

What's the hidden meaning of these bare signs?

Let us ask the person who should know—the mathematician. Alas, the mathematician's answer will be couched only in the most general terms: "This is a system of two linear algebraic equations with two unknowns. But what its precise meaning is, I cannot tell."

Let's ask engineers of various specialities. Their answers will not coincide. "This is," the electrician will say, "an equation for voltages or cur-



A model for the reproduction of the physical processes—an artificial power system.

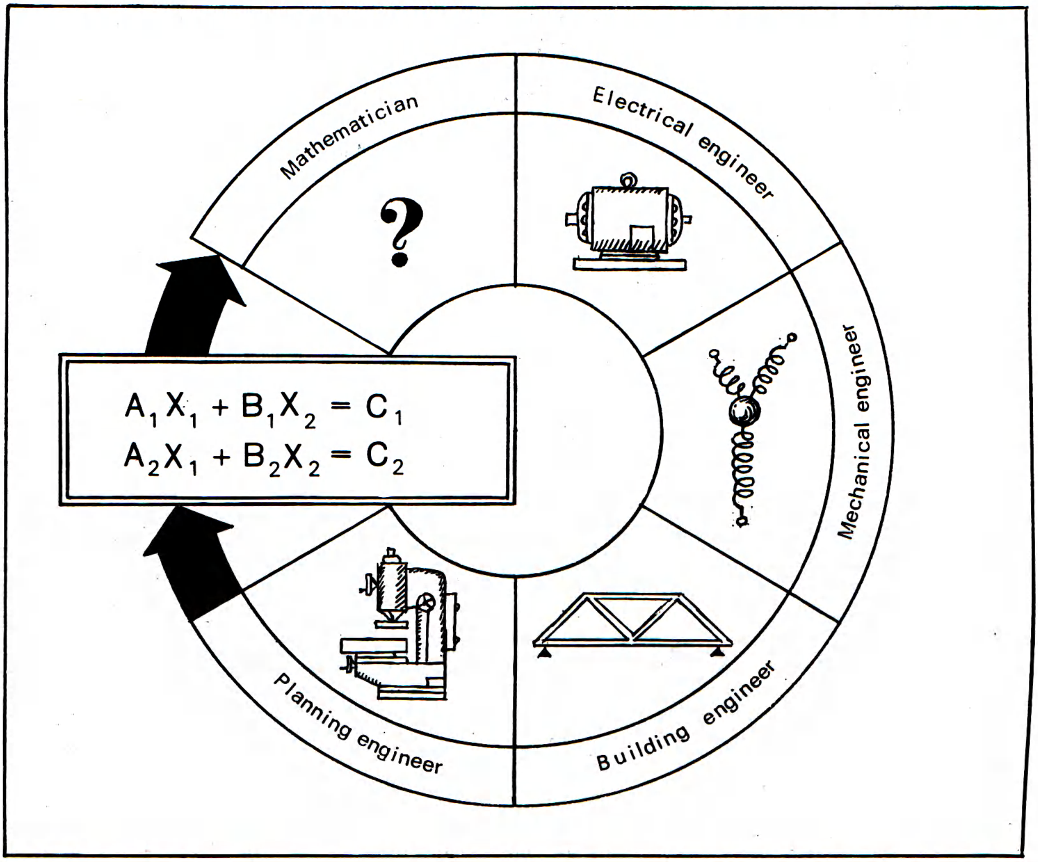
rents in a circuit with active voltages."

The specialist in mechanics is certain that the equations describe the equilibrium of forces in a system of levers or springs.

The building engineer will inform us that these are equations relating forces and deformations in some structure.

The specialist in planning will state quite authoritatively that these equations serve to calculate the working time of machine tools.

Five quite different answers. Which is the right one? You shouldn't won-



The model can assume a somewhat unfamiliar form as well—the form of mathematical formulae.

der—all are right. Yes, a single system of linear algebraic equations can describe the state of equilibrium in an electric circuit, as well as in a system of levers, or in a structure. All depends on the meaning of the constant coefficients *a*, *b*, *c* and of the symbols of the unknowns x_1 and x_2.

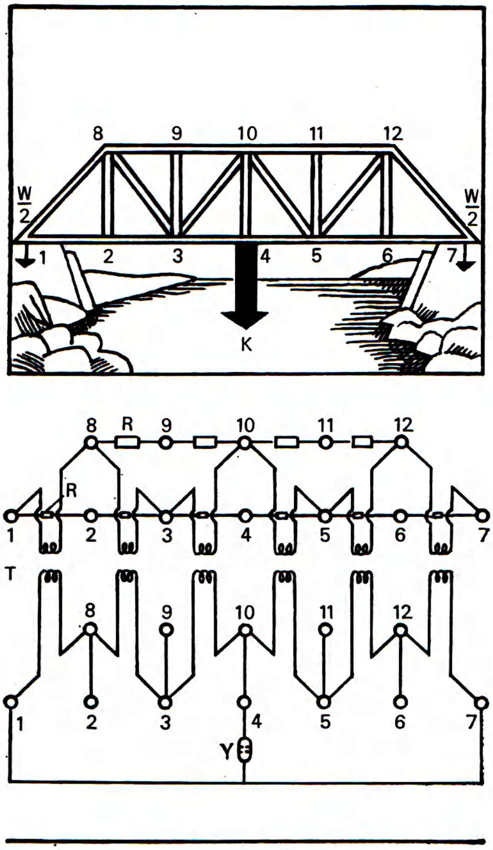
It is appropriate at this juncture to recollect the words of the famous Russian academician A. Krylov: "To think of it, what could be in common between the calculation of motion of celestial bodies and the roll of a ship. Yet, if only the formula and the equations without words are written, it is impossible to discern which of the two problems is being solved: the equations are the same in both cases."

The wonderful mathematical similarity of diverse phenomena presents tremendous opportunities. What's the use of a scrupulously exact material model of a bridge assembled from exactly the same materials and parts as the prototype? There is a simpler solution—the model of the bridge may be constructed in the form of an electric circuit. This circuit serves as a peculiar modelling balance. Electricity proved to be the most useful "balance" for "weighing" mathematical models. Modern electric equipment combines the qualities of great simplicity and reliability with those of accuracy and sensitivity. This enabled electric models of mechanical, thermal, acoustical and other phenomena, continuously varying with time, to be devised.

Electric models comprise capacitors, resistors and inductances. For instance, it is possible to assemble a circuit with currents proportional to stresses in the structure of a bridge and to measure voltages across the junctions of the circuit which are proportional to deformations of the girders. In this case the equations, in which those deformations play the part of unknowns, may be dispensed with.

And what if the need arises to calculate a new variant? One has only to change the value of the resistors and repeat the measurements to get the data. This method enables numerous versions of structures to be tested within tens of minutes.

Electric models are built, for instance, for the solution of problems relating to the flight of an airplane.



An electric circuit model of a bridge truss.

It takes seven months for ten calculators to calculate ten versions of the problem. With the aid of the electric modelling apparatus ten people can calculate a thousand versions of the same problem in only four days.

Let us now find out how the electric modelling apparatus, this "mathematical mirror" reflecting the regularities of the model, works.

Let's start with a simple example. We intend to study the stresses in a steel bridge truss loaded by a crane. What do we start with? First of all let's find the geometric image of the truss and its electric model.

This is done with the aid of unfamiliar "electric cubes" which specialists call resistor boxes. These "cubes" can be arranged to outline all sorts of figures: the body of a dam, the wall of a channel, the blade of a turbine, the wing of a plane, a rail, etc.

Each of these "electric cubes" consists of several coils of wire and condensors, connected to a single terminal. The required circuit is drawn along the terminals inside the "cube"—the so-called junctions. They are connected to current sources, and this initiates various phenomena in the "cubes". Electricity acting on each "cube" through its junction plays the part of water, heat source or mechanical force—i.e. of the active environment of the real prototype being studied.

But how should these "cubes" be assembled into figures corresponding to dams, parts of turbines, etc.? These structures or machine parts should, too, be subdivided into "cubes", so that a definite number of the "cubes" would correspond to a definite dimension of the object being studied. This can be done easily with the aid of the object's prints.

Let's return now to the calculations of the truss. Using the drawing of the truss we arrange the "electric cubes" to form a geometric likeness of it and make the measurements. There is no need of complicated switching and connecting of the ends of one "cube" with those of another. The mass of "electric cubes" is so arranged that any figure can be immediately "cut out" by simply outlining the object with a string on the "electric cube" set.

A universal electric model possesses the additional faculty of probing deep into the element. Is there any way to learn what happens 10 cm inside the truss? Let's make a "hole" in the electric model. We can make any "holes" we like, marking them appropriately on the print. After that we have only to disconnect a certain number of "cubes" in the corresponding place of the model. After the required hole has been made, any measurements may be made inside it, and they will give exact answers as to what takes place inside the beam. To probe to any depth into the "wound" inflicted on the model, one has only to connect a wire to this place. This is done automatically by pressing an appropriate button on the "electric cube" set.

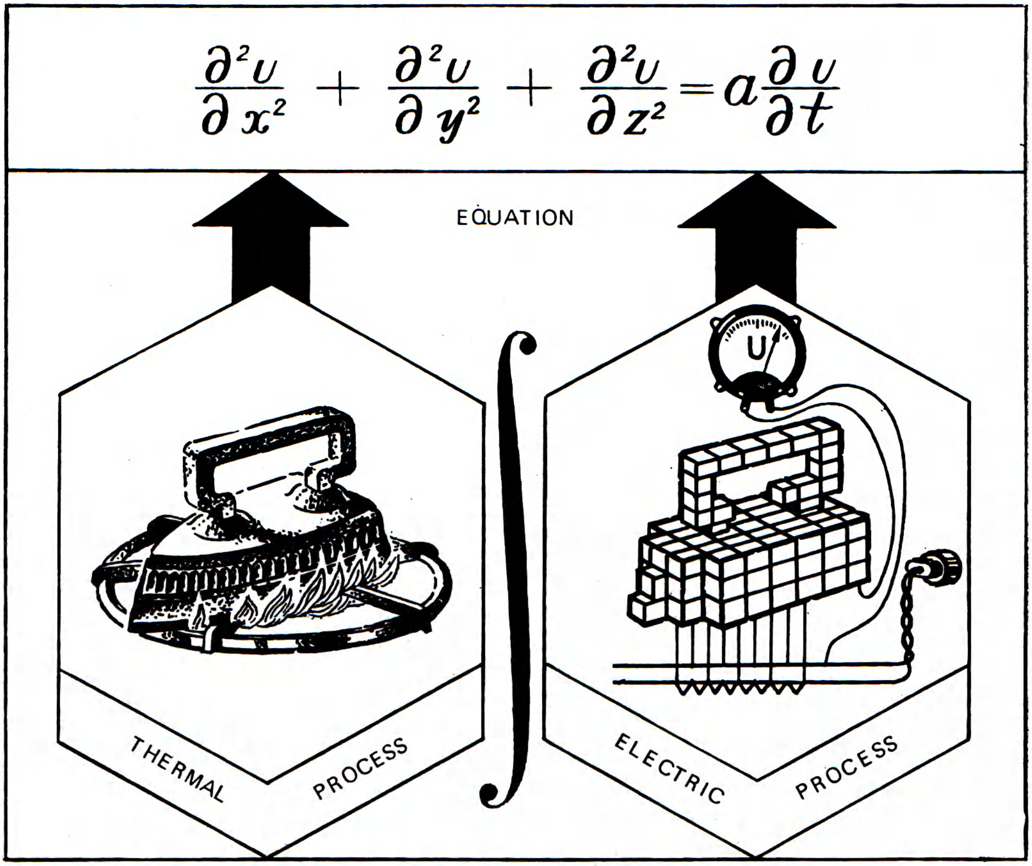
The stresses in the beam are studied on an electric model called the electro-integrator. It solves—integrates—with the aid of electricity complicated differential equations sensitive to the smallest changes taking place in the shortest intervals of time.

The integrator is one of the existing types of continuous-action electric modelling machines. Another name for them is analogue computers. Literally day to day their family is being expanded and modernized.

You have not failed to notice that the principle of operation of the analogue computers is quite different from that of the digital computer. One specialized book on modelling contains a very vivid and clear example to this effect.

A tailor who measures a man's figure in certain places makes use of numerical methods.

The shoe-maker, on the other hand, who outlines the shape of a man's foot on paper, makes use of the analogue principle, since his measurements are continuous. This, too, is the principle of operation of the analogue computer:



The analogy existing between thermal and electric processes enables the distribution of heat in bodies even of the most complex shape to be modelled.

continuous changes in numerical values are correlated with continuous changes in the value of the physical analogue.

For some research studies electric modelling sets play the part of the marvellous cure-all.

Let's again take the airplane studied in a wind tunnel. As a result of studies scientists arrive at the so-called flight equation of the airplane. To solve this equation means to predetermine the flight path of the plane. Despite numerous parameters its solution would present few difficulties if the forces acting on the plane in flight would remain constant.

But this is totally out of the question—the plane is subjected to alternate downward and upward air streams, it is thrown about from side to side like a ship on the waves. The forces acting on the plane change continuously, too. These changes take place every moment of time, and they are not repeated.

On an electric-modelling or an electronic set fast processes can be repeated any number of times. The mathematical model helps man to achieve mastery over time. With the aid of "electric cubes" it enables dynamic variable processes taking place in reality to be slowed down or accelerated.

The scientist has only to reduce the modelling rate to place himself in the position of a man watching a slow motion picture—he is able to learn things he would not be able to without the artificial slowing down.

By increasing the modelling rate it is possible to hasten a process which in reality proceeds at a snail's pace and takes years to complete.

Looking into the "mathematical mirror" one sees and quite quickly, too, what is going to happen to a dam, a lock, an artificial lake several years after they have been built.

This is the reason why the unquestionable advantages of mathematical modelling are adopted without reservation by scientists of various specialities.

Physicists occasionally find for the models quite fantastic, from the layman's point of view, fields of application. Just to cite physico-mathematical models of the plasma—of the object the direct study of which, as physicists themselves agree, is made very difficult by its peculiar nature and by the complexity and great cost of experimental installations.

A veritable hamlet in space envelops the earth—75 space stations. This is the place of destination of rockets fired from the Earth. Regular traffic by spaceships is maintained between the stations. They bring in foodstuffs, equipment and instruments, specialists for servicing and repair work. These results of studies carried out by American scientists using the method of mathematical modelling were expressed in concise formulae. That's modelling as applied to astronautics.

And what about chemistry? Here the usual practice is for a process after leaving the laboratory to be subjected to a protracted, multistage and arduous testing and development work. The journey from the test tube to an industrial installation often takes from ten to twelve years. Can mathematical modelling be applied here? Yes, and it is already being applied. For instance, at the Novosibirsk chemical plant factory tests have been completed of an installation which managed to "skip" all intermediate development stages and arrived at the factory direct from the laboratory. The "mathematical mirror" disclosed its true image. Mathematical models are also used to study the properties of new catalysts, as well as in some other chemical experiments.

In collaboration with biologists, chemists achieve promising results in modelling such exacting and unwieldy substances as enzymes, these marvellous catalysts of life.

You can learn about models in biology and medicine from a chapter of this book called "Cybernetics in Biology".

Something remains to be said about one more aspect of modelling, about its role in experiment. The modelling experiment differs from the usual one in that the experimenter experiments not with the object itself but with a model of it. The model "intrudes" into the experiment and draws attention to itself. This is a very important property of modelling, for models can be experimented with even when the objects themselves for some reason or other are beyond the experimenters' control—as the case may be, they may be too far away (the stars), or very short-lived (elementary particles), or too great (large industrial complexes). In these cases the model acting as an intermediary in assuming the role of the object widens the scope of the experiment rendering thereby invaluable service to the experimenter.

The story about where and when analogies between different processes and properties with an identical "mathematical image" are used can be continued indefinitely. Or it can be cut short with the words that have been born several hundred years ago.

"And, above all, I value the Analogies, my faithful instructors. They are in possession of all the secrets of Nature and should therefore be last to be ignored."

These are the words of the great German mathematician J. Kepler.

A musical piece produced by an electronic computer according to a programme describing the requirements for the work.

A Deaf Composer

We shall begin our acquaintance with "electronic composers" with a list of some of their most celebrated works.

These include the "Illiac Suite" for strings written by a computer at the University of Illinois, USA, and four thousand songs under the general heading "Bert's Button" produced by a computer belonging to the Dadatron Company of California. At Harvard University a computer is also a capable popular song composer. True, its operators have not assigned names to its compositions. Perhaps they were discouraged by the machine's strange habit of suddenly switching from one song to another for no apparent reason. In our country a "Ural" computer working in a different style has produced a series of musical pieces under the general heading "Urals Melodies".

Yes, electronic computers write music. How do they do it? Do they understand anything of the complex laws of composition? Can they be musically talented?

These are natural questions. Let us try and answer them. First, the latter question: musical talent.

It would seem that music can be written by non-musical methods. So talent is not all that is necessary... .

Two centuries ago, in 1751, an English musician, William Hays, wrote a humorous work called *The Art of Writing Music Employing an Exceptionally New Method Suitable for the Poorest Talents*. All that is needed, according to the instructions, is a stiff brush and some ink. You dip the brush in the ink, then drawing a finger over the bristles you spatter a sheet of music paper with ink spots. Then all that remains is to add the bars, note stems and other musical symbols to complete the work.

A few years later, in 1757, a German, Kirnberger by name, compiled a *Guide for Composing Polonaises and Minuets with the Aid of Dice*.

Unlike the former, this was a serious work. Before writing his composition the composer has to draw up a table of six columns, numbered one to six for the faces of the die, and eight rows, corresponding to the number of bars in the musical phrase. The next step is to compose 48 bars, one for each square in the table. Finally, the author has to cast the die. Say, it gives a "4", then the composer takes the first bar of his piece from the first row of the fourth column. Thus, by casting again and again, the first phrase of eight bars is completed.

In 1793, no less a composer than Mozart wrote a *Guide to the Composition of Waltzes with the Aid of Two Dice Without Any Knowledge of Music or Composing*. It also provided for

A waltz written by Mozart with the aid of dice.

a numbered table with notes to be randomly selected by throwing a pair of dice.

On learning these techniques, one is naturally tempted to ask why a machine couldn't "throw dice" and select random notes from a table. It certainly can, and much faster than a human being. In one experiment a computer was used to analyse 37 tunes. Then, after 6000 "dice throws" it produced 600 new tunes. True, it did not hesitate to take whole passages from one or several tunes, displaying a propensity for plagiarism, and could hardly be called a "creative" machine.

Paradoxically, it was Hays' method of spattering ink spots with a brush that proved most suitable for computer music, though with one important improvement: the erasal of unwanted blot-notes.

To operate on this principle, a machine's memory must be provided with a store of sounds from which it can extract combinations according to mathematical rules. As you may have guessed, the "sounds" in the machine are represented in terms of numbers. And, of course, a carefully compiled programme is needed.

But what is to be gained by this? Who needs this kind of primitive musical compilations? The answer is no one—at least no one needs them as music. However, they have proved to be the source serious and very promising work.

An example of such work is the "Urals Melodies" mentioned before. They are interesting as an attempt to construct not only chords, as is usually the case, but also that very important component of music, the melody. The author of the new method is Soviet scientist R. Zaripov. The essence of his method is contained in a paper entitled "On Algorithmic Description of the Process of Music Composition" printed in such a serious and highly esteemed publication as the *Proceedings of the Academy of Sciences of the USSR*.

R. Zaripov, mathematician and musician, had first to adjust himself to his electronic "co-author"—"Ural" computer—since a machine can solve only those problems which have been described mathematically, for which there is an algorithm and a firm guide for action.

Thus, it is first necessary to compile the laws, principles and rules of musical composition in terms of mathematical formulae and logical relationships. Is this possible? Certainly.

Men noted long ago that music follows certain mathematical laws. Cassiodorus wrote in the 6th century: "Music is a science that considers numbers with respect to phenomena observable in sounds."

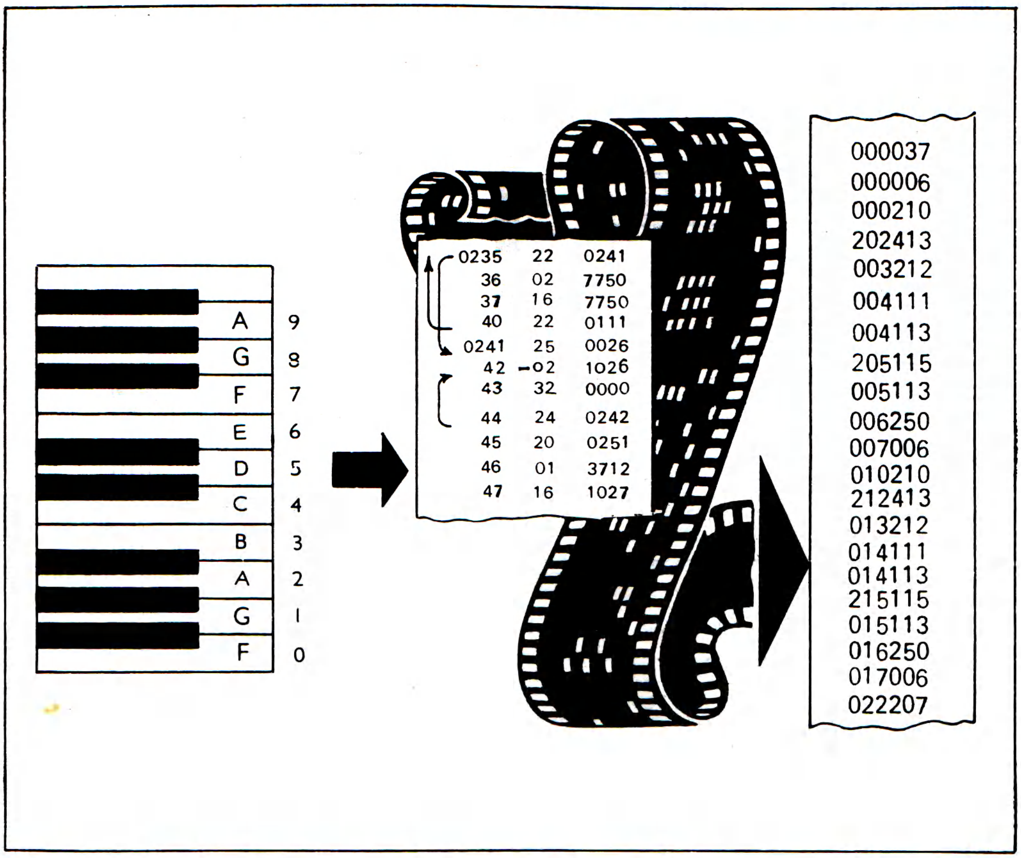
It is said that Pythagoras, once, on passing by a smithy, noticed that the hammers striking the anvil produced sounds with intervals corresponding to a quart, a quint and an octave. He walked into the smithy and asked the blacksmith to show him the hammers. He weighed them and found that the hammers that produced the octave, the quint and the quart weighed respectively a half, two-thirds and three-quarters of the weight of the heaviest hammer.

The relationship discovered by Pythagoras subsequently became the basis of the theory of music.

The simplest harmonious combinations of tones—chords—were studied long ago. It was found that the greater the simple fraction expressing the ratio of the sounds' frequencies (which correspond to the pitch of each sound of the chord), the "purer" the chord is and more pleasing it is to the ear.

Thus, a high C is produced by double the frequency of a low C, the ratio of the octave being $\frac{1}{2}$. The ratio $\frac{2}{3}$ yields a fifth (C-G), the ratio $\frac{3}{4}$ a fourth (C-F).

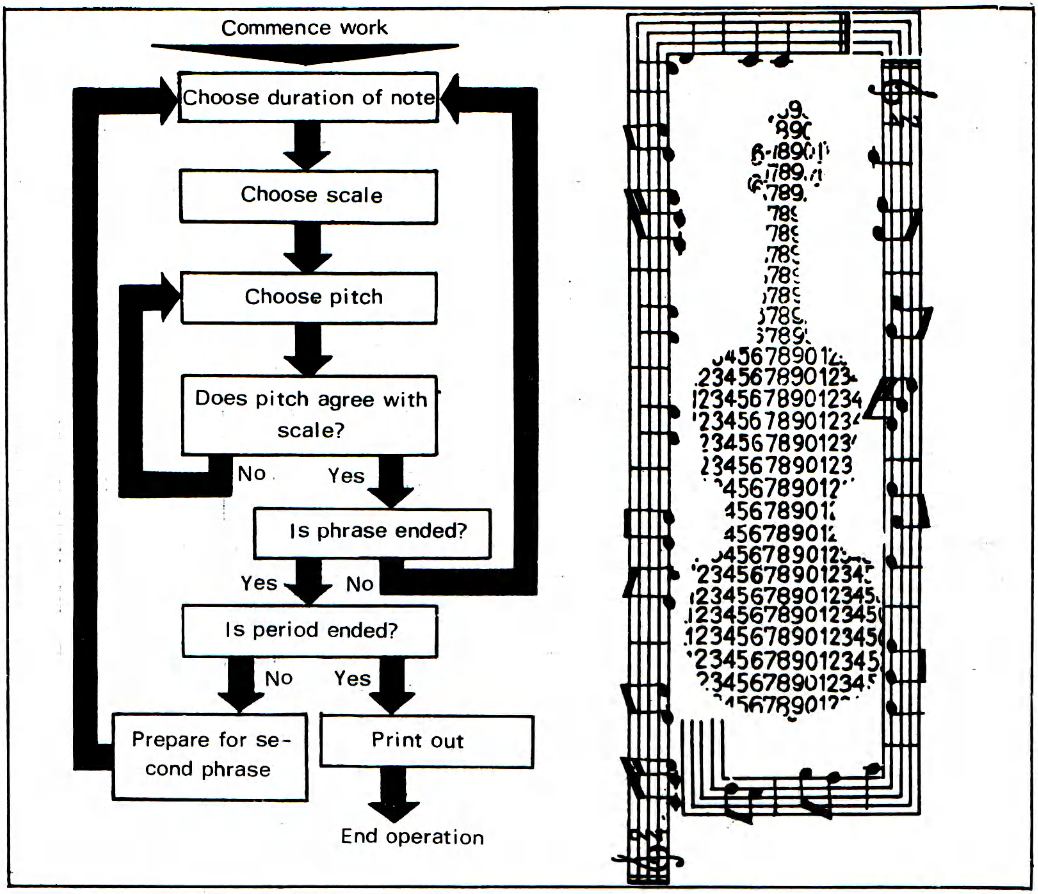
It is known that piano scales are associated with rational and irrational numbers, and that there are logarithms in music.



Several processes in the translation of notes and rules of music into machine language: a method of encoding pitches; a portion of a programme written down in number code; the same programme on punched tapes; the result of the machine's work written down on paper tape.

Mathematicians studying music found that popular songs are drawn from 35 to 60 notes. A statistical analysis of large numbers of songs revealed the following typical song structure: there is the first part, which we shall call *A*, covering eight bars and consisting of 18 to 25 notes. This part is repeated once and then followed by a part *B*, also covering eight bars but consisting of 17-35 notes, after which part *A* is repeated once more.

Other interesting rules were discovered. If five consecutive notes follow on an ascending scale, the sixth will always drop, and vice versa. Also, the first note of part *A* will usually never be the second, fourth or fifth minor note of a scale. Songs obey such long-established rules of composition as Mozart's rule which lays down that an interval between two neighbouring notes must never exceed six tones.



Schematic diagram of the steps in the production of machine music.

You may, on occasion, have listened to an unfamiliar tune and been able to predict the following note before it was played. This happens most frequently with lyrical songs. Specialists say that, in such cases, each subsequent note carries less information than, for instance, in music pieces by Prokofiev or Shostakovich which abound in unexpected inflections. Thus, the amount of information per note is a parameter, a quantity which can be used to judge the music.

The rules of composition deducted from analyses of musical works are used in writing music with the help of electronic computers. In addition, the "Ural" computer was provided with a special generator of random numbers, its purpose being to present random notes in a digital code. Each note was then examined under the rules of musical composition, and only when a note was found to meet the requirements was it entered into the score. If the screening reveals the note to be unsuitable it is rejected, and another candidate is investigated. This continues until the tune is completed.

It would seem from this description that computer music writing is not all that difficult, but it was quite some time before Zaripov finally worked out the programme for the "Ural" computer. His task was to provide a mathematical description of music for the machine and develop a system of codification for notes and other elements of music.

For writing the marches and waltzes that were later incorporated in the "Urals Melodies" Zaripov represented every note as a five-digit number. The first two digits denoted the ordinal number of the sound, the third indicated the length of the sound, the fourth and fifth, its pitch. The machine was not allowed to include more than five consecutive ascending or descending notes (remember the rules of composition), nor could it select adjacent pairs of notes of more than an octave difference. There were many other taboos besides.

Even so it occasionally got out of hand. Zaripov recalls that after he had taught the machine to write waltzes he decided to go over to marches. But the computer balked, refusing to write anything but waltzes, and then finally began to rewind the programme tape over and over again without producing any scores at all. It was only after a thorough recheck that Zaripov discovered that in one of the lines of the programme he had mistakenly recorded the number 1177 instead of 1777.

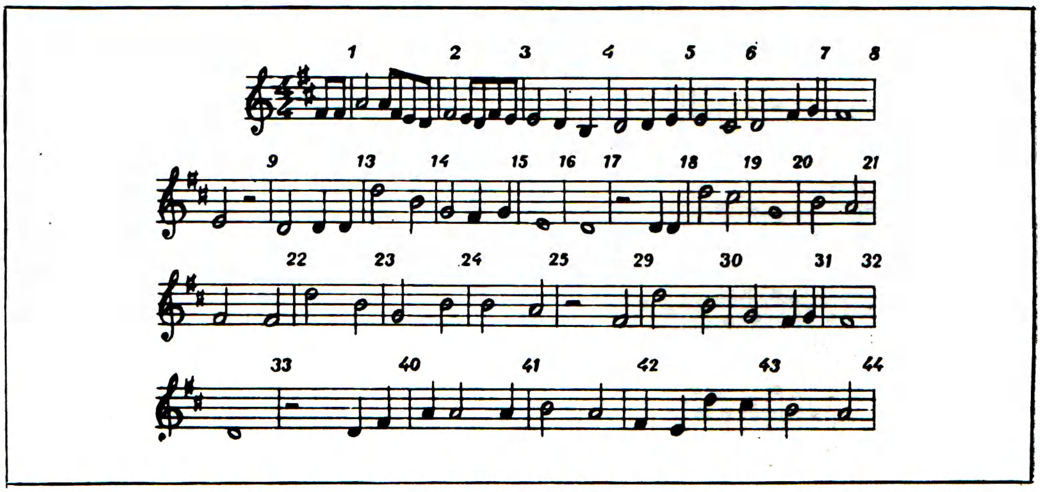
A considerable part of the machine's music-writing programme was devoted to a description of rhythmic patterns or meters. In this case two meters were required: four-quarts for marches and three-quarts for waltzes. The programme also provided for the number of parts in the future compositions and the number of bars in each part.

The programme, which incorporated more than two thousand instructions, utilized the total capacity of the "Ural's" working "memory". Each individual

note required an average of 800 machine operations, and a whole piece as many as 30 000.

A melody synthesis programme for a "БЭСМ-2" computer occupies several thousands of its "memory" cells.

When the computer, equipped with its programme, finishes its compilation of the tune its automatic printer feeds it out in code on paper tape. The record is deciphered and then transcripted into conventional musical script.



Let us now have a look at some examples of electronic musical composition.

On p. 219, is a fragment from the second part of the "Illiac Suite".

On p. 220, top, are fragments from two tunes written by the Soviet "БЭСМ-2" computer with the help of the Latvian mathematician Vilnis Detlovs.

The melody on p. 220, bottom, represents a sequence of 32 bars selected by American scientists Olson and Belar from 44 bars produced by a computer.

This is one of the first tunes produced by the "Ural" computer (before the "Urals Melodies") on top of this page.

And below is a passage from the "Urals Melodies".

Now that you have seen how computers compose music and have examined several pieces, it is time to explain why scientists devote so much time and effort to produce what is usually extremely simple melodies.

The thing is that computers deal with symbols. The elements of music are also symbols. The number of symbols in music is relatively small, which makes it convenient for computer experiments. A computer makes it possible to trace step by step, note by note how simple elements combine to produce a tune. Computer music offers an opportunity to study the very nature of music, investigating musical forms, chords, scales and sequences. A computer is a fine tool for analysing the creative process.

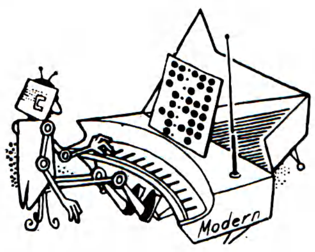
By teaching computers to write music scholars hope to penetrate the domain of art and investigate it through a new, cybernetic approach.

Hence the very specific role assigned to computers composing music: they are not intended for creative work but as man's helpers. A computer can, for example, easily cope with the rather laborious task of transcribing a score from one key to another, and it is sure to make no mistakes in the process.

A computer can be usefully employed in deciphering musical manuscripts employing the methods of quantitative analysis. In a similar way it may transcribe voluminous tape recordings of musical folklore.

"Electronic musicians" can be entrusted with such tasks as searching for new timbers, the importance of which can hardly be overestimated for instrumentation, as well as in the arrangement of symphonic music for individual instruments.

It is hard to say whether machines will ever be capable of producing anything like genuine works of art, and works of creative value. Obviously, a machine producing something like a work of art has no creative urge: it all begins and ends with the first and last bar assigned by the programme. A machine may grind out hundreds and thousands of tunes, but it will never say with pride, "This is my best work!"



An Advanced Programme

N

NUMBERS IN A COMPUTER

The recording of numbers and instructions in a computer— in its recording block or in the arithmetical block— with the aid of notation scales.

Two States

Everything made of 0 and 1—only two symbols, quite convenient, isn't it? Let's try and find ways of recording them mechanically, electrically or electronically.

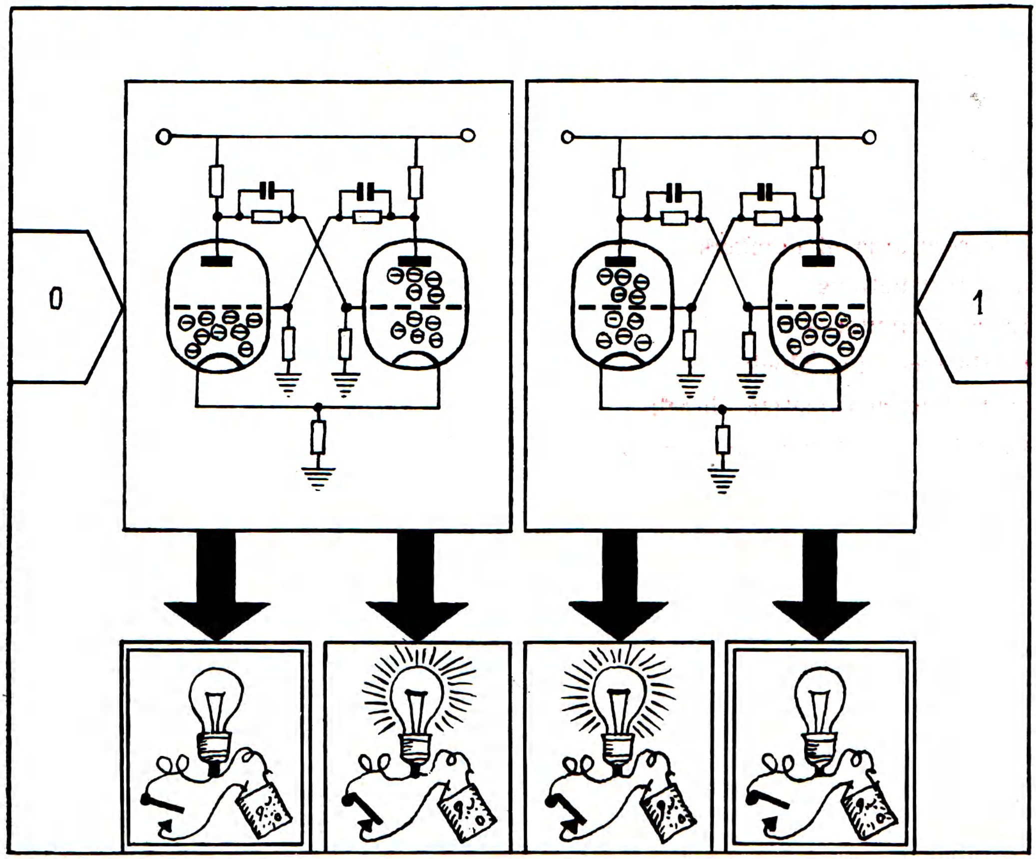
Let's start with the simplest. You've probably seen a simple village gate lock—a chunk of wood with a nail in the centre. This device can keep the gate either closed or open, there being no intermediate position.

And what's the electrical analogue of such a rotating lock? A simple push-button table-lamp switch—press the button to turn the light on, press the button to turn the light off. The switch remains in one position until we switch it into another. After it is switched into one position it will remain in it as long as necessary, providing for the memorization of this position.

The symbols 0 and 1 of the binary system can be transmitted and recorded with the aid of electric current, for example, by changing the time intervals of current in the circuit: a short interval—a dot, a longer one—a dash, as in the Morse code. Or by changing the polarity of the current: plus-minus. Or by changing the amplitude: one in the presence of a signal, zero in its absence. The last method is used in computers because it's reliable, and because the computer's devices easily distinguish the presence of the signal from its absence.

The main part of the high-speed computer is the so-called trigger. It, too, works on the "on-off" principle.

In a simplified form, the trigger



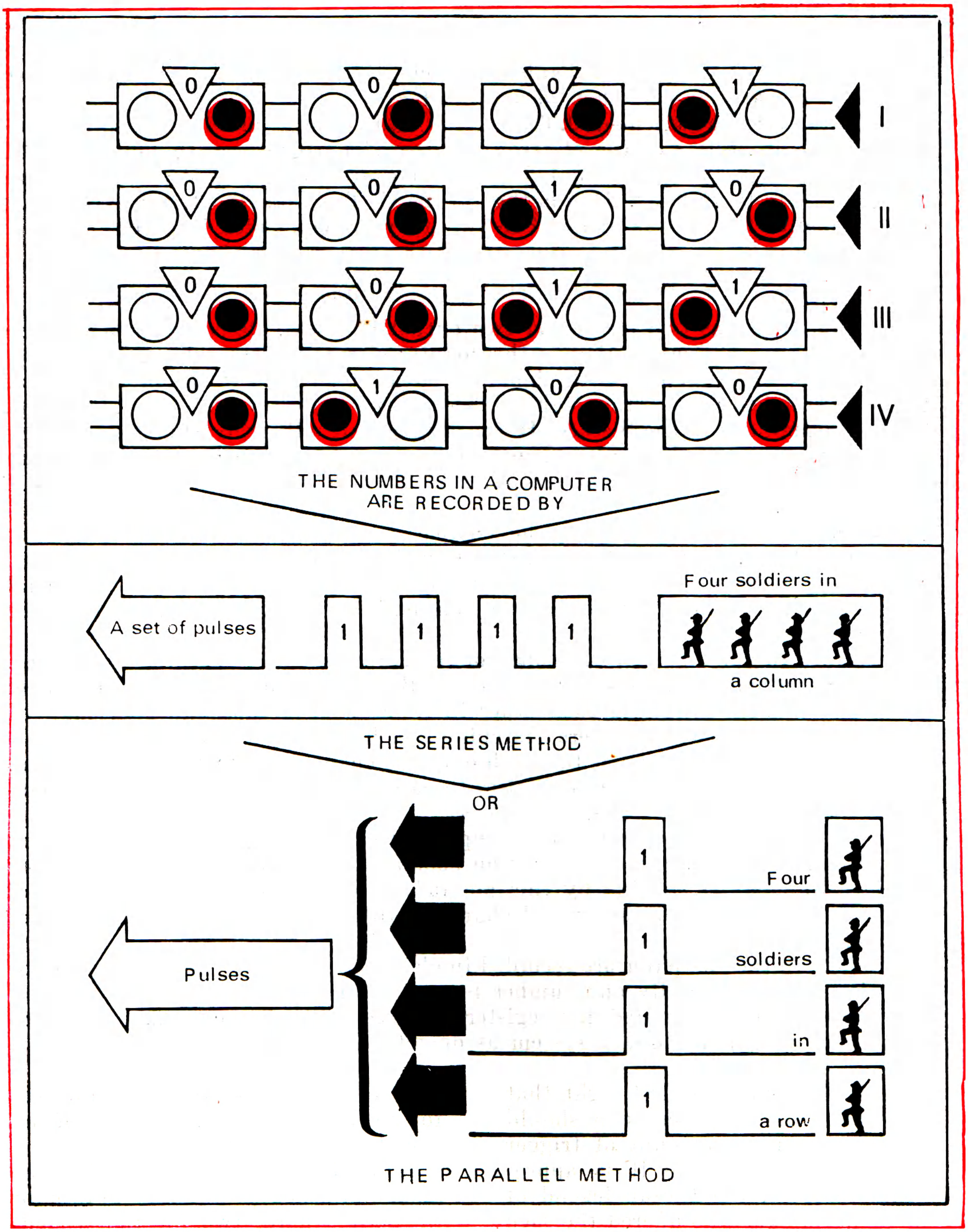
The trigger circuit. When the right tube is open and the left closed, the trigger registers 0. And vice versa, when the left is open and the right is closed, it registers 1.

consists of two electron tubes assembled in one bulb. They are electrically connected so that when one conducts current, the other blocks it. (One is open, the other is closed.) One of these stable states was taken to mean 1, the other 0.

Each new electric pulse applied to the input of the trigger simultaneously closes the open tube and opens the closed one. And in strict accordance with this pulse the trigger immediately changes its state from 1 to 0 and vice versa.

It remains in each state until a new pulse reaches it. So "overturning" from one state into the other the trigger enables pulses to be registered.

The recording of numbers in a computer by the series and the parallel methods. ▶


0 0 0 1 I
0 0 1 0 II
0 0 1 1 III
0 1 0 0 IV
THE NUMBERS IN A COMPUTER
ARE RECORDED BY
A set of pulses
1 1 1 1
Four soldiers in
a column
THE SERIES METHOD
OR
Pulses
1 Four
1 soldiers
1 in
1 a row
THE PARALLEL METHOD

The switching time of a mechanical device is usually 0.5 s, that of an electrical device—a switch—is 0.035 s. Due to the properties of the electron tubes the trigger "reverses" unbelievably fast—in 0.000001 s. This is the clue to one of the secrets of fast calculations by the electronic computer.

But then a justifiable question arises: if a trigger registers only 1 and 0 how are we to record all other numbers? To make the triggers calculate they are connected into circuits.

Here we have four triggers connected into a circuit.

Each of them has two input and two output contacts. Before work has begun the triggers record "zero", that is the counter circuit registers 0000.

Now suppose that an electrical signal—a pulse—is applied to the input contacts of the first trigger from the right. The trigger will "reverse" and register 1, the rest remaining in the 0 state. Hence, the circuit will register 0001.

Let's transmit another pulse. The first trigger will switch off and will return to 0 and transmit a pulse to the second. The latter will register 1. The circuit will register 0010.

Such a system of triggers may be compared to the abacus having only two beads to a string. When all beads on the string have been moved from right to left, one should move one bead on the next string returning the former to the initial position. What's done by fingers on the abacus, is done by electrical pulses in the trigger counters.

There are in existence two methods of recording numbers: parallel and series. The series method has been described above. By this method all the pulses travel along one channel following each other in time. This method can be visualized as a troop column with soldiers marching one behind the other.

In the series method one has to watch only one channel which carries the pulses. But then you have to wait for the pulses to pass one after another as on the crossroads you wait for the transport to pass.

The parallel method entails pulses appearing simultaneously but in different conductors. The parallel motion may be compared to troops marching in a row shoulder to shoulder. Acting by this method, to determine the combination of pulses it is necessary to observe all channels, to know what happens in each of the conductors.

Numbers in the computer are recorded in electronic circuits. The other name for them is registers. Usually one number is recorded in one register.

Here is a number recorded in a register. You see in the figure (p. 225) the orders of the numbers in the binary system as depicted by the pulses.

It would appear at first sight that to record large numbers one should have an enormous amount of trigger cells. At this juncture it is appropriate to recall the Indian legend of the Shah Sheram who offered the sage Seta to name a prize he would like to receive for his invention of an excellent game—the chess.

Seta laid the chess board before the Shah and asked for one wheat grain for the first square, two for the second, four for the third and so on, for all the 64 squares—that is, for each next square twice as many as for the preceding one.

The demand of the sage appeared quite modest at first. Still, Seta failed to get his prize.

The mathematicians of the Shah calculated that the number of grains for the last square is so great that it defies imagination: eighteen quintillion four hundred forty-six quadrillion seven hundred and forty-four trillion seventy three billion seven hundred and nine million five hundred and fifty-one thousand six hundred and twelve.

The grain would have filled two barns stretching from the Earth to the Sun. And this gigantic number the inventor managed to get with the aid of only 64 squares.

In the modern computer, too, the circuit of only 64 triggers is capable of counting the astronomical "chess" number 2^{64}.

Triggers have been in use as counting devices for a long time. Formerly they were used mainly to count atomic particles. Later their use was extended to computers.

In the Soviet Union the first trigger was made in 1918 by the prominent scientist, radio engineer M. Bonch-Bruevich. He started research on electron tubes way back in 1916 and was the first to organize the production of them.

Look Before You Leap

OPTIMAL CONTROL

Application
of mathematical methods
and of electronic computers
to evolve optimum
(best possible) decisions
for production control.

First, a problem. A factory that manufactures certain parts in serial lots receives orders for its wares several months in advance of delivery. It can manufacture the goods just prior to delivery; it can produce them earlier and keep them in the warehouse if this for some reason seems more convenient. But storage costs money. The question is how best to organize the manufacture and storage of the goods to reduce costs and overhead to the minimum.

Obviously, this is not a problem to be solved by rule of thumb.

Or take another problem: how to distribute workpieces among machine tools. This is not an easy one either. Thus, in distributing three workpieces among three machine tools there are 108 distribution variants. For four workpieces distributed among four tools the number of variants is already 8272.

These examples are cited not without reason: every day economists, planners, traffic controllers must solve similar problems to find the optimum variant for every given case.

Here an economist is confronted with a common, everyday problem: how to distribute orders for textile production among the mills most rationally. He must plan the utilization of the mills' capacities in such a way as to ensure the maximum output at the lowest cost; in other words, he must draw up an optimum plan.

Such a plan must answer the following questions:

Required daily supply of sand, tons

	I	II	III	
A	6	2	7	5
B	3	4	8	9
C	1	5	5	9
D	2	9	3	7
Cargo-handling capacity of each landing stage	8	11	11	30

What fabrics in what quantities and on what looms should be produced in each mill?

How many types of fabrics can all the mills manufacture? How will the quotas be met? Will they be surpassed or will output fall short?

What is the cost of the fabrics manufactured at each mill and averaged among all of them?

What looms are needed to fulfil the assignment?

Will new looms have to be installed?

It would take a long time to solve the problem even if we were to distribute three types of cloth among three mills (remember the example with workpieces and machine tools: 108 variants). However, let us try and solve a problem of a similar type to see what planners must deal with.

	I	II	III
A			5
B		3	6
C	1	8	
D	7		

	I	II	III
A		1	4
B		9	
C	8	1	
D			7

	I	II	III
A		5	
B	3	6	
C	5		4
D			7

Sand is delivered by barges to three landing stages. Let us denote the landing stages I, II and III. The sand is needed for four construction projects, A, B, C, D.

To solve this problem we will have to write several tables. In the first one the right-hand column gives the daily requirement of sand—30 tons. The bottom row indicates the cargo-handling capacity of each landing stage. The delivery quotas are balanced with the requirements. The numbers in the squares show the distance, in kilometres, between the landing stages and the construction sites.

Our problem is to distribute sand deliveries among the landing stages so as to keep the autohaulage, in ton-kilometres, down to the least possible minimum.

The garage traffic controller has distributed deliveries as shown in the second table (the numbers in the squares indicate the amount of sand delivered from the respective landing stages to the respective construction sites). All construction sites receive the necessary quantity of sand. But what about haulage figures? This is easily calculated: $1\times1+7\times2+3\times4+8\times5+5\times7+6\times8=150$ ton-kilometres.

However, a better distribution is given in the third table. The number of ton-kilometres is reduced by one-half: $8\times1+1\times2+9\times4+1\times5+4\times7+7\times3=100$.

But the best, optimum variant offers a 70 per cent cut of haulage as compared with the first. It is presented in the fourth table.

You see how much trouble is involved in the solution of a "simple" economic problem, a concrete problem with few variants and small numbers involved.

Today it is realized by all that it is hard to work out even a family budget for a month or two in advance to an accuracy of one rouble. The economic estimates for an industrial enterprise are a hundredfold more difficult. And what about calculations for a group of enterprises, a whole industry, or on a nation-wide scale?

After this try and imagine the tremendous scale of economic calculations for a national economy of the size we have in the Soviet Union!

See what savings have resulted from producing an optimum plan for a single industry on a country-wide scale. The optimum plan for the geographical distribution of cement mills throughout our country enabled a reduction of average haulage distance from 565 to 305 kilometres. This yielded a saving of 140 million roubles per year. Furthermore, it made possible the cancellation of construction plans of several mills in unsuitable locations. This yielded a saving of another 192 million roubles.

Such economic problems are solved by means of so-called linear programming, which was elaborated by Soviet scientist L. Kantorovich.

We shall try to explain the general idea of linear programming with the help of a simple example.

To function normally, the human body must receive a certain daily ration of nutrients: fats, proteins, carbohydrates, vitamins, mineral salts, etc. On the basis of comprehensive research, medical science has established the necessary ration for 15 types of nutrients. The substances needed by the body are contained in various quantities in different foods: bread, milk, fish, vegetables, fruit, cereals—in all some 40 or 50 groups.

The natural question is: what diet can fully meet the organism's physiological requirements at the lowest cost? In other words, what is needed is the cheapest and at the same time medically the most wholesome food.

Thus, the task is to choose from 50 groups of food products a diet containing the 15 nutrients required by the organism. The basic criteria for an optimum selection is the cost of the food. It should be as low as possible. The task, in mathematical parlance, involves the solution of a set of 15 equations with 50 unknowns.

Systems of simultaneous equations in which the number of unknowns exceeds the number of equations have an infinite number of solutions—and the task is to choose the one and only best one!

For the purposes of our example we can restrict ourselves to a more modest problem with only two foodstuffs—bread and milk—and two nutrients—proteins and calcium.

Here is a table showing how much protein and calcium there is in a kilogram of bread and a litre of milk:

	Bread, kg	Milk, litre
Protein, g	60	40
Calcium, mg	250	1200

The organism requires not less than 100 grams of protein and 700 milligrams of calcium a day.

Now we must recall what we know about systems of algebraic equations.

We denote the required quantity of bread by x_1, and of milk, by x_2; the coefficients a_1 and b_1 in the first equation denote the protein content of one kilogram of bread and one litre of milk; the coefficients a_2 and b_2 in the second equation denote the respective calcium content of bread and milk.

We know that the more bread and milk in the diet the greater is its nutrient content. Hence, we have a linear dependence involving a system of linear equations, viz.:

$$60x_1+\quad 40x_2\geqslant 100$$
$$250x_1+1200x_2\geqslant 700$$

The sign $\geqslant$ means "is equal to or greater than". This is a very important point. If the quantity of protein and calcium were rigidly defined (exactly 100 g and 700 mg, neither more nor less) everything would be clear.

Two equations with two unknown quantities. Such a system of equations has only one solution, and the question of an optimum choice does not arise. The trick, however, is that, according to the conditions of the problem, the body may get more than 100 g of protein and 700 mg of calcium a day. This leaves extensive scope for choosing. The number of possible variants becomes infinite.

Incidentally, this is easily demonstrated. The above expressions can easily be made into equalities. All we need is to introduce a new unknown quantity in each of them, that would make an equality out of the inequality:

$$60x_1+\quad 40x_2-x_3=100$$
$$250x_1+1200x_2-x_4=700$$

Thus, we have a system of two equations with four unknowns. It yields an infinite number of solutions, depending on the value we assign to the variables x_3 and x_4.

It remains to be said that, quite naturally, out of the multitude of solutions we are interested in only those where x_1 and x_2 have positive values: bread and milk can't be negative.

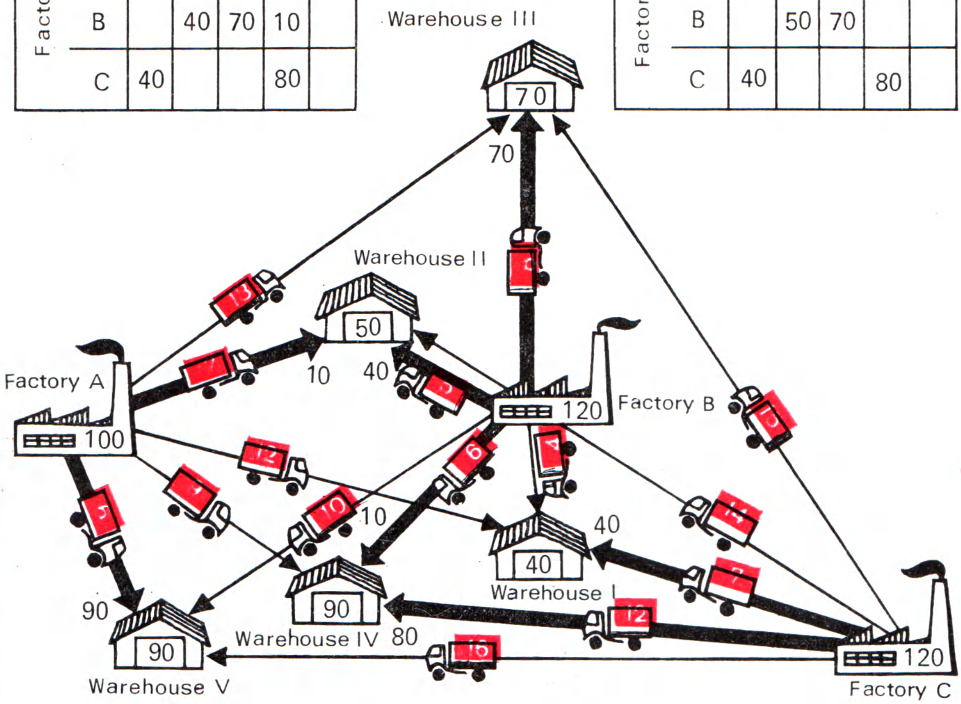
Suppose a kilogram of bread costs 21 kopecks and a litre of milk, 28 kopecks. Hence, the price of a diet consisting of x_1 kilograms of bread and x_2 litres of milk is

$$C=21x_1+28x_2$$

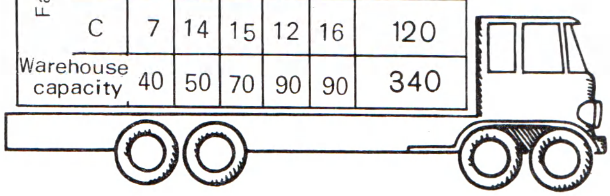
In linear programming this mathematical expression is known as the target function. It provides a precise quantitative characteristic of the goal we set ourselves in planning our actions. The function determines the criterion we use to compare various

Warehouses		I	II	III	IV	V
Factories	A		10			90
	B		40	70	10	
	C	40			80	

Warehouses		I	II	III	IV	V
Factories	A				10	90
	B		50	70		
	C	40			80	



Warehouses		I	II	III	IV	V	Volume of output of factories
Factories	A	12	7	13	8	6	100
	B	4	5	8	6	10	120
	C	7	14	15	12	16	120
Warehouse capacity		40	50	70	90	90	340



variants of the plan in the quest for the optimum one.

In our problem a clearly defined target function ensures the choice of the optimum diet at the lowest cost. The solution yields such positive values of the variables x_1 and x_2 which satisfy the conditions of the problem (as written down in the system of equations) and with which the target function has the minimum of all possible values. The methods of linear programming are designed to solve just these kinds of problems.

A computer is fed the conditions of the problem in the form of a system of equations and inequalities and the target function formula. The machine selects some initial variant and analyses it. The analysis immediately reveals whether this practically random variant approaches the optimum or not—something, obviously, highly improbable. If the variant is not the optimum one the analysis indicates how the next one should be chosen so that it is better than the preceding one and the target function is smaller.

The new variant is also analysed for optimum conditions and, if the answer is negative, another, still better, variant is selected. The quest proceeds step by step until the analysis reveals that the optimum solution, that is, a variant with the smallest possible target function has been found.

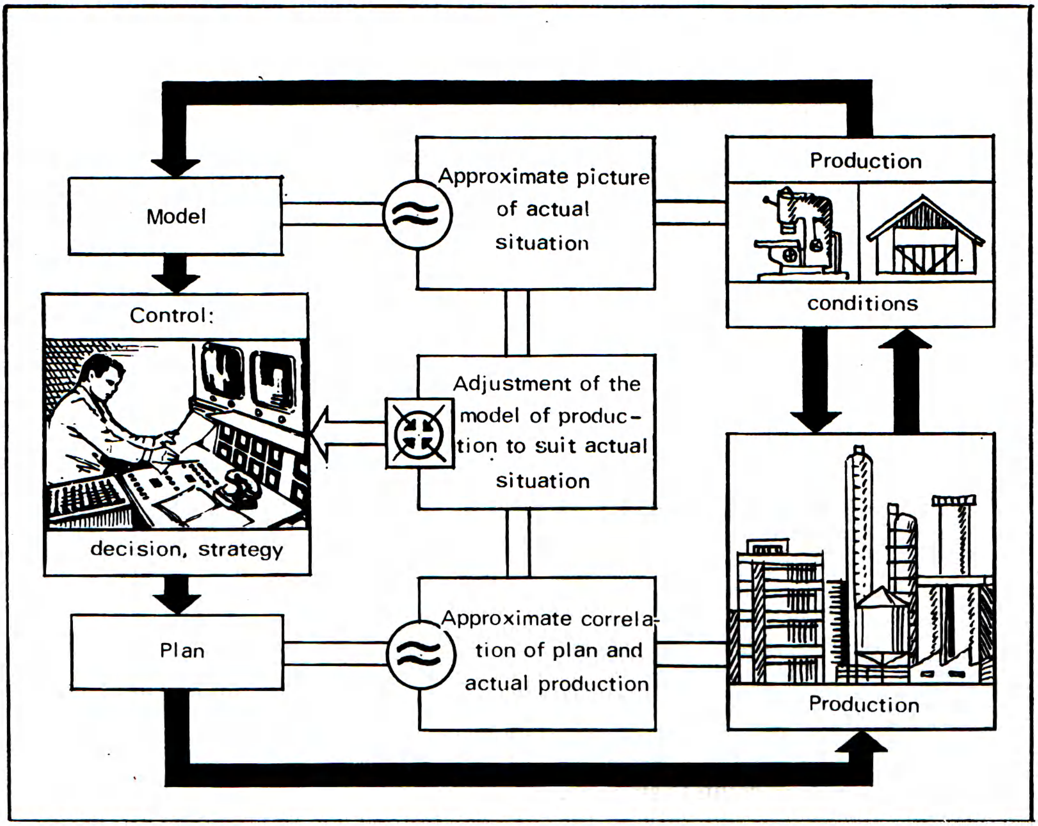
As you see, the method is based not on a random try-out of all possible variants but on a purposeful quest each step of which brings us nearer to the goal. When it is achieved, and the computer feeds out the optimum variant we can declare with full confidence that, given the stated conditions of the problem, nothing better can be devised—this is guaranteed by the methods of linear programming.

With the current high rates of economic development the components of the national economy interact faster and faster, and economic indices become ever more dynamic. In such circumstances planning must be carried out on a continuous basis, and all sections of the economy must be managed with the utmost efficiency. The smallest delays in planning and control can result in losses of no less magnitude than those due to inaccuracies in planning.

Until recently in our country more than two million persons were employed in administration and management. It may come as a surprise to the uninitiated that at the Gorky Motor Works alone a veritable army—more than five thousand people—are engaged in ensuring the factory's raw materials supplies and marketing.

The people responsible for economic management handle billions of papers annually. Nowadays simple desk calculators and adding machines are inadequate to cope with the flood of information, it is virtually impossible to calculate any great number of

◀ Study of transport operations by linear programming. The purpose is to obtain the lowest haulage costs taking into account the output of each factory, the storage capacity of each warehouse and haulage costs of a unit commodity from each factory to each warehouse. The tables at upper left and right present two optimum solutions. The numbers in the squares denote the quantities of different goods to be shipped to various warehouses to obtain the lowest overhead. The table at the bottom gives the cost of transporting cargo from factory to warehouse. The diagram in the centre presents the haulage routes with the costs presented on the vans. The thick arrows give the most advantageous routes.



Schematic diagram of production control.

plan variants and ensure optimal control of the economy.

Workers of the Cybernetics Institute of the Ukrainian Academy of Sciences have estimated that the volume of information involved in economic planning increases in proportion to the square of the volume of production. This means that in 20 years more than half the population of the Soviet Union would be engaged in management and administration.

The economists are justified in waiting for the day when complete automation of planning and economic calculations will become a reality.

Mathematical methods could be called the golden key that opens the doors into the mystery kingdom of economics.

Of course, solving economic problems is an extremely difficult thing. It has been shown that the higher the level of a nation's productive forces the more complex is the task of running its economy. The scope and complexity of calculations increase with the expanding volume of production, acceleration of growth rates, appearance of new industries, expansion of economic contacts. This is the reason for the extensive scale of work going on to use electronic computers to plan the economy of regions, republics and the Soviet Union as a whole.

In Byelorussia, for example, machines were used to calculate and introduce the most profitable plan of timber haulage. In Leningrad plans were drawn up of river and marine shipping for all of the main river and marine basins. The Computer Centre of the State Planning Commission of the USSR calculated the best distribution of suppliers and consumers of sheet metal and plate. In Turkmenia machines have been for several years carrying out a substantial portion of the economic calculations.

Many such examples could be cited. It is not for nothing that V. Glushkov, an eminent specialist in cybernetics, claims that soon "automatic systems will become as essential a tool of scientific research in the hands of economists as atom smashers are for physicists or electron microscopes are for biologists".

Electronic computers not only help to accelerate calculations, they also provide for a ten- and hundredfold reduction in the time needed to draw up plans. Electronic machines used for economic operations ensure centralized industrial management.

Economic management entails a kind of computer hierarchy. The "ground floor", so to speak, houses the "lower echelons" charged with the collection, storing and processing of information. They allow for planning the work of factory shops, departments and enterprises as a whole, providing a day-to-day picture of the state of affairs. Then come the peripheral units for data processing and storage. These are electronic machines connected by communications channels with the central "computer plants" of economic areas, industries or other amalgamations.

Further on, at the top, is located a system for receiving, handling and storing information designed to provide a comprehensive picture of the state of affairs in each specific industry and the economy as a whole.

Experts consider that the creation of a national network for gathering, storing, processing and transmitting economic information is a priority task the importance of which can hardly be overrated.

A planned socialist society should strive to attain the best possible, optimum results in each separate industry and in the national economy as a whole. It was this that V. I. Lenin meant when he said that only that construction can deserve to be called socialist which is carried out according to a comprehensive general plan aimed at the balanced utilization of all economic and financial resources.

V. I. Lenin repeatedly drew attention to the importance of scientific organization of administrative work, without which it is impossible to run the economy correctly. He wrote that people working in management and administration must pass the test of knowledge of the fundamentals of theory of our state apparatus, of the fundamentals of the science of management.

Nowadays mathematical methods are the basis of scientific management without which economic planning of industry, science, technology and distribution of resources, manpower reserves, and direct, concrete factory management and control are simply unthinkable.

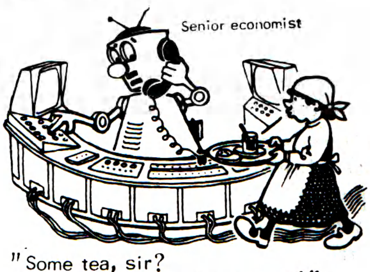
The best variant of a plan for the development of the Kuznetsk basin coalfields in the years 1962-1970 had to be worked out. It was necessary to take into account the number of collieries, the grades of coal, labour expenditure and a thousand and one other considerations. There are some 100 pits and cuts in the Kuzbas for which some 200 development variants had been provided. By using methods of mathematical planning the optimum variant for solving this complex problem was found. It turned out that the development of the Kuznetsk basin coalfields could be carried out with a capital investment 200 million roubles less than envisaged by the original "hand-made" plan. The computer-made plan proved 43 per cent more economical than the man-made one! Today economists increasingly reject "real-life" experiments and costly "trial-and-error" quests. They prefer the better tool of mathematical modelling. Such modelling was employed in the stupendous task of developing a scientific model of the national economic development plan of the USSR for the years 1971-1975. Practical recommendations were made on how to improve the development patterns for the economy as a whole and for separate industries, how to make the most rational use of material and manpower resources, on the questions of economic reform.

The new method makes it possible to forecast scientific and technological progress and its effect on the economy, assess natural resources, determine the optimum size of state reserves and optimize the structure of planning bodies themselves.

In conclusion, to show the whole importance of application of cybernetics in the economy, we should like to refer to a major component of socialist planning—to the work of drawing up the national economic balance.

This balance is a system of economic indices characterizing the principal correlations, proportions and rates of production, the sources and reserves for expanding the country's national wealth and popular income.

Mathematical methods make it possible to establish all the proportions and connections in the national economy with great accuracy and to study its efficiency. In other words, we can now determine much faster and more accurately whether our national wealth is being used correctly. And that wealth is great indeed. For example, the gross national product of the Soviet Union in 1968 was estimated at 500 000 million roubles!



"Some tea, sir?
You're overworking yourself!"

P

PROGRAMMING

The compilation of programmes for the solution of mathematical and information-logical problems on a digital computer: a chapter of applied mathematics dealing with the method of programme compilation.

Let's imagine the following situation. A construction engineer who wants to calculate whether a project of a railway bridge has been drawn up correctly comes to the computer centre. His problem is expressed in purely mathematical terms: it contains formulae, equations, calculations. Everything is at hand—take it and feed it into the computer.

But, alas, the problem is for the computer a thing beyond its understanding. The "electronic brain" cannot handle formulae, equations or calculations.

The computer does not understand what man asks of it.

How should the problem be adapted for the computer "mind", how should the computer be made to understand it?

That's what the programmist knows. The programmist is the connecting link between the computer and the problem it has to solve.

His job is very responsible—he has to visualize the problem from the computer's point of view. He has to subdivide any complex problem into a sequence of simple instructions that the computer could cope with.

Every problem, even the simplest one, contains numerous instructions. Naturally, the more complicated is the problem, the longer is the list of instructions.

This list, this set of instructions constitutes the programme for computer operation. As you, probably, understand, the compilation of programmes is a very difficult job requiring high qualification. This is because the programmist has first to visualize and then to realize in the computer all information transmission routes necessary for the execution of a definite sequence of operations.

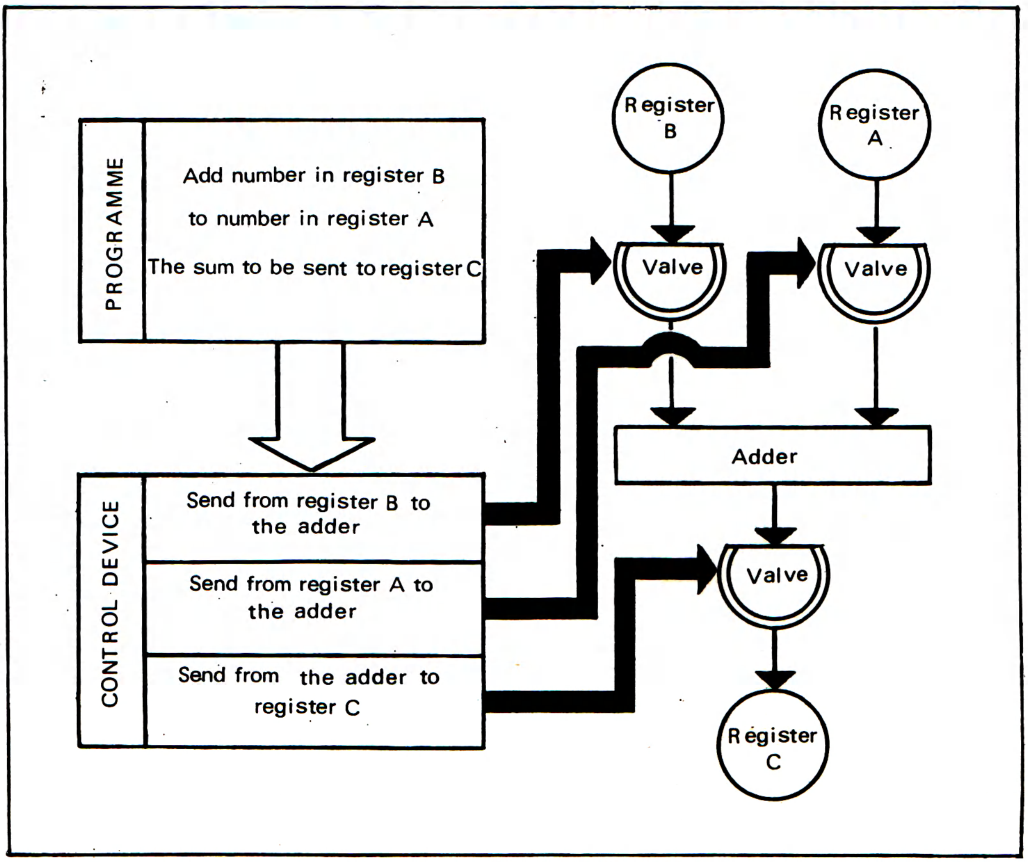
The programme has been compiled. The routes for the solution of the problem have been laid in the computer. Now the computer sets to work.

Since we speak of problem solution routes, this means that some communications, some channel is established between any two of the computer's elements. The communications channel must dispose of some sort of a "switchman" who either transmits information to a channel or blocks the way.

The elements playing the part of the electronic "switchman" in the computer are called valves. The purpose of the programme is to provide instructions for the opening of a certain group of valves while keeping the others closed.

The work of the computer is gover-

An example of the realization of a programme in a computer.



ned by the control block—the main element of this intricate electronic contraption. This block, like a conductor conducting an orchestra, exercises control over different parts of the computer, tells each part when it should go into action, what and how it should do. The control block, like the conductor, needs a "score"—instruction programme of the calculations. This device concentrates in itself all the internal communications and "processes" all commands which control such a complex automaton as the high-speed electronic computer. Let's take a look now at our "conductor" reading the "score".

So the control device works in close contact with the programme.

The operator switches on the computer and inserts a programme containing a list of instructions that have to be performed in sequence in order to solve the problem.

The programme in a digital computer is executed in sequence, as has been said before, in cycles, step by step, operation after operation. It is not to be wondered that this process is being compared to knitting: every part of the future product is made up of loops in different combinations. This is a very precise analogy, since existing knitting manuals, too, contain detailed instructions and calculations. And, like the electronic computer, programmes, these knitting manuals, are understood only by the adept.

An instruction has been received by the control device. It immediately "opens" the appropriate group of valves and makes the computer carry out the instruction. Suppose the instruction is: add the number in register B to the number in register A, send the sum to register C.

The computer should open the group of valves which transmit numbers over the adder. This will cause the following instruction series to travel along communications channels: "Send from register B to the adder", "Send from register A to the adder", "Send from the adder to register C".

Other valves will be needed for subtraction, etc.

Have you noticed that each instruction consists of two parts: it tells "what to do" and "where to do it". That's just how specialists term them: the operation and the address part, or, simply, address.

It must be admitted that in the computer the instructions look quite different from what's shown in the drawing. They assume the familiar computer appearance of number or sign codes.

Let's try to compile a computer programme for calculating the greatest common divisor of two numbers *a* and *b* according to the well-known algorithm of Euclid. For this purpose we should have a list of operations. Suppose we have them written down. Let's arrange them into a table and code each operation with a set of binary symbols. Besides, we'll designate every operation briefly by letters. This will facilitate the compilation of the programme.

Here's a short table of operations which will help us to compile the programme:

Operation	Brief designation	Binary code
Add number in cell No. to the number in the adder	Ad	0001
Subtract numbers in cell No. from the number in the adder	Sb	0010
Send number from cell No. to the adder having previously set the adder to 0	Ss	0011
Send number from the adder to cell No.	Sn	0100
Revert to instruction in cell No.	Rc	0101
If the adder contains a number other than 0, revert to instruction in cell No.	Is	0110
If the number in the adder is negative revert to instruction in cell No.	In	0111
Stop the computer	St	1000

To profit from the table one should keep in mind several important conditions.

The first—when a number from the register cell is sent to the adder it is retained in the register as well.

The second—when, on the other hand, a number from the adder is sent to the cell, the number which formerly occupied it is "erased", and the newly sent number is installed in its place. The number which has been sent from the adder remains there unchanged. Moreover, we'll have to remember that, if the numbers *a* and *b* are not equal, we'll have to

Cell numbers		Cell contents designated by letters	In binary code
Cells containing instructions	01	Ss—20	00110000010100
	02	Sb—21	00100000010101
	03	Is—05	01100000000101
	04	St	10000000000000
	05	Ss—20	00110000010100
	06	Sb—21	00100000000101
	07	In—10	01110000001010
	08	Sn—21	01000000010100
	09	Rc—01	01010000000001
	10	Ss—21	00110000010101
	11	Sb—20	00100000010100
	12	Sn—21	01000000010101
	13	Rc—01	01010000000001
	14		
	15		
	16		
	17		
	18		
	19		
Cells containing numbers	20	number *a*	
	21	number *b*	

find out which of them is the greater and which the smaller.

Man can do it easily just by taking a look at the numbers. The computer, on the other hand, always has to compare by orders. Therefore, the easiest way for the computer to find out which of two numbers is the greater is to perform subtraction.

The sign of the remainder will tell it which is the greater and which is the smaller.

Let's start compiling the programme.

We'll place the instructions in the working "memory" cells No. 1 through No. 13. The number *a* will be placed in cell No. 20, the number *b* in cell No. 21.

The addresses of the register cells will be written down in the decimal system.

Let's see how the computer works using the table as a guide. The computer is switched on, and an instruction is sent to the control device from the register cell 01.

This instruction will be carried out during the next step. The adder preset to zero will receive the number from cell 20—the first number *a*. This number will remain in the adder. Next an instruction from cell 02 is sent to the control device. The result is the subtraction of the number *b* from cell 21 from the number *a*. This, as we shall see below, satisfies the second requirement of the Euclid's algorithm concerning the comparison of the two numbers. Now it is the turn of the conditional instruction from cell 03. The control device checks the result of the foregoing operation.

If the remainder is zero, the numbers are equal, and each of them is the greatest common divisor. The computor prints the number, and the problem is solved.

If, on the other hand, the remainder is not zero, i.e. the numbers are not equal, the control device in compliance with the conditional instruction will turn to the next instruction in cell 05 and later to cell 06. In compliance with the instructions contained in these cells the number *a* from cell 20 will again be sent to the adder which has been preset to zero. There the number *b* from cell 21 will be subtracted from it.

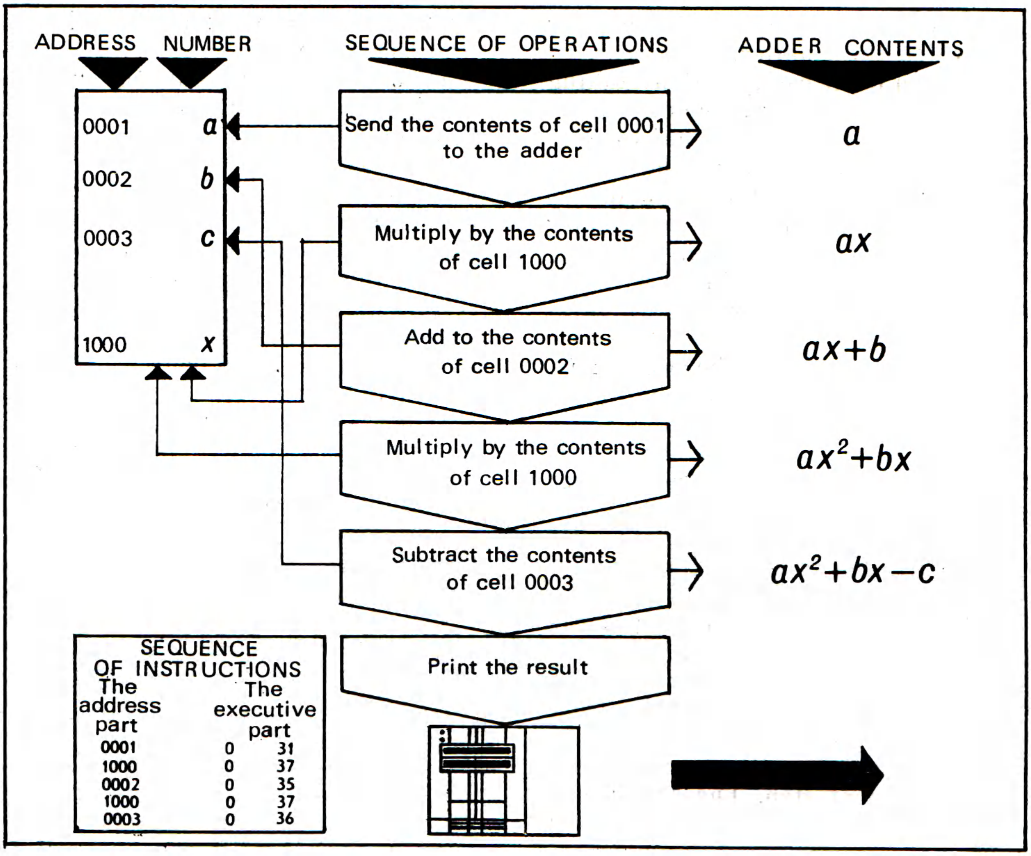
When a remainder accumulates in the adder, the conditional instruction from cell 07 is made to operate. If the remainder is negative, i.e. the second number is less than the first, they should, according to the algorithm, be made to change places.

The conditional transition instruction hands the control over to cell 10. The latter orders the second number *b* from cell 21 to be sent to the adder. Next the number from cell 20, i.e. the number *a*, is subtracted from it. The remainder which is positive is sent to cell 21 on the instruction of cell 12. Eventually the instruction of cell 13 again hands over control to cell 01.

The cycle will be repeated in compliance with the fifth requirement of the algorithm.

The number *a*, in this case the subtrahend (because it is the smaller of the two numbers), is sent to cell 20. The remainder which now occupies cell 21 will be subtracted from it, etc.

If, on the other hand, the remainder obtained after instructions 05 and 06 have been carried out is positive, the instruction 07 will be followed by the instruction from cell 08. The positive remainder will be sent to



An example of programming. The sequence of instructions is shown on the left below. The transfer of the number to the summator is designated by 31, 37 is the multiplication of numbers, 35—addition, etc.

cell 20, and computer control will be returned to cell 01 from cell 09. This, as in the case above, will be the beginning of a new cycle.

During this cycle the place of the two numbers is, in accordance with the Euclid's algorithm, taken by the subtrahend and the remainder.

In this way the process of searching for the greatest common divisor will continue cycle after cycle until the numbers in cells 20 and 21 are equal.

Thus, the whole programme is compiled from 13 instructions. It enables the greatest common divisor of any pair of numbers to be found. The number of instructions is always the same. But the total number of repetition cycles will be different dependent on the numbers a and b.

It's easy to verify that if $a=21$, $b=14$, the third cycle will yield the greatest common divisor equal to 7. In case of multi-digit numbers, on the other hand, the number of cycles may be tens or even hundreds.

Compilation of programmes for the solution of the more complex problems requires great experience and substantial effort.

It should be noted that without the programmes all electronic computers, even those capable of millions of operations per second, are, as a prominent computer expert Academician T. Marchuk once remarked, at best, merely items of furniture of institute and factory offices. The entire line of calculations in the computer, the so-called processing of information from input to output, is organized by the programme. It's the programme that ensures the execution of all operations assigned to the computer.

The programmists prepare whole series of standard programmes for the solution of typical problems. The greater the programme file provided for the computer the better it is adapted for its work, the easier is its contact with the user, the greater are the facilities for its use and the greater is its value.

Nowadays computer manufacturers spare no efforts and no resources to produce computers equipped with a complete set of standard programmes. For example, at the American computer production company IBM some one and a half thousand employees are permanently employed compiling programmes for the computers produced by the company.

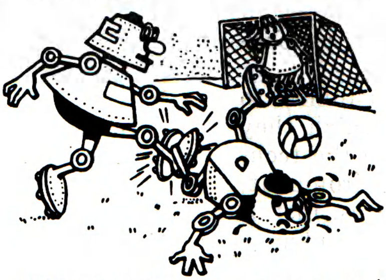
The programme library compiled for the "1900"-type computer alone comprises over 3.5 million instructions.

Programme compilation has become a sort of an industry for the mathematical provision of computers. More money is spent on this industry than on the production of the computers themselves. Thus, about one billion dollars were spent on the procurement of programmes for the IBM-360 computer.

Well then, what is this mathematical provision? It is a complex—literally a multitude — of programmes assembled in special libraries. They enable the computer to operate efficiently, to carry out the solution of problems. They, in the words of the experts, mean the same to the computers as college education means to people.

Our days witnessed the birth of a new profession—that of the mathematical provision systems engineer. So much attention is being paid to the education of programmists because without them the exploitation of electronic computers at present employed everywhere is impossible.

A qualified programmist must receive a serious mathematical education. Those who think of becoming programmists should study mathematics thoroughly.



"This rough has been malprogrammed again!"

The science which studies psychological aspects of man's labour activity to assess his supreme psychical functions (memory, thinking, attention, perception, etc.).

Man and Machine

It first came into the limelight during the Second World War. At the time a great deal of technical sinews of war were engaged in the conflict. The battles were fought by very mobile and very sensitive machines: airplanes, tanks, submarines.

The designers engaged in the process of development of certain machines often witnessed the seemingly inexplicable phenomenon: new military machines did not yield the expected results.

What was the cause of this? Special research, experiments and tests have demonstrated that new machines did not correspond to functional abilities of men who were to take charge of them.

This was actually the beginning of the new science of engineering psychology.

Men have grown so accustomed to the world of machines in which they live that they do not notice the technical character of their environment, all those automata, aggregates, installations, mechanisms, and the change in the character of work which took place in recent years.

The progress in technology has, however, greatly affected man's work. Several decades ago man in industry did everything himself. Nowadays he controls the process of work using for this purpose various "organs" of the machines in his service. Having liberated himself from physical labour man increasingly assumes the role of the commander giving orders to mechanisms which carry them out.

This, however, is one side of the relationship between man and machine. The machine, too, proved to be not indifferent to man, it, too, makes demands upon him. Modern machines, automata in particular, require attention, memory, wits, quick reaction.

The "demands" of the machines are so serious that a strictly scientific approach to their fulfilment is necessary. This is where engineering psychology comes in. As an engineering subject, engineering psychology studies machines, devices, instruments and mechanisms. But these studies are "unidirectional", from the specific viewpoint of demands made by man's mechanical aids on their creator. As a psychological subject the new science is called upon to study human thoughts and their peculiarities, the faculties of man. But, again, from a strictly definite point of view: whether the individual properties of a definite man are compatible with his profession.

In the rather short period of its history engineering psychology covered an arduous course interspersed with defeats and victories. At first it negotiated the more simple, to be more exact, the more noticeable, "technical stage" (the subdivision is purely symbolic). Scientists started work on engineering problems connected with the style design of instruments, with the disposition of work places, with the colouring of work premises. The result was that such "trifles" as the arrangement of switches, tumblers, the shape of handles and knobs, their colour, the change of the colour of walls, the disposition of furniture in offices and of machine tools in shops contributed to a sharp rise in productivity.

Wasn't that a success?

You bet, and no small one, at that.

The research methods of the second stage—the division being again symbolic—come closer to experimental psychology. Now scientists are working on problems of another type—they are assessing supreme psychical functions of man. Specialists in engineering psychology pay maximum attention to such fundamental problems as memory, attention, thought, perception.

What's their goal? The aim is to construct machinery adapted for contact, collaboration, "community" with man, compatible with his faculties and capabilities.

In the process of work man and machine are connected by a thousand strings, they are two links of the same chain. Therefore, one should know the facts both about the "machine" link and about the "man" link.

Engineering psychologists obtain precise and verified facts about the "man" link as a result of rigorous long-time experiments.

Let's take visual perception as an example. Studying its laws and specific properties engineering psychologists waste no time on exploiting them, on adapting them for practical purposes. The problem of optimum code for information to be displayed on the screen and on sign boards was solved in this way.

In the course of research into visual perception the generally accepted assumption that man sees more than he can reproduce was corroborated, too.

"What's here unusual or unexpected?" you're going to ask. "Was there any use in proving things that are obvious without proof?"

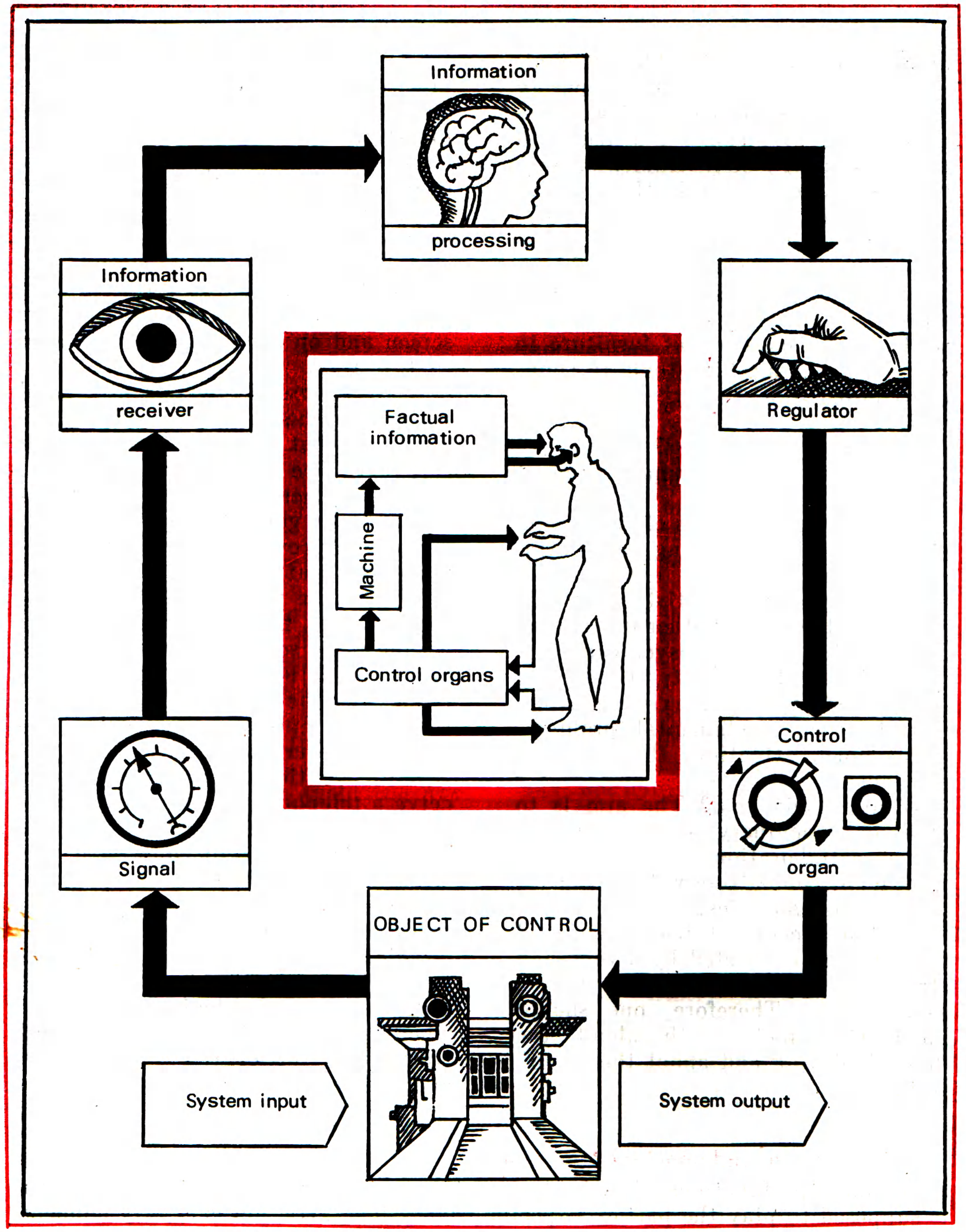
Well, there was. And for two reasons. Firstly, because the assumption, having been scientifically proven and argumented, becomes a fact. Secondly, because the situation "we see more than we reproduce" is very frequent in everyday life.

This situation arises when we perceive a telephone number in the telephone book and then dial it. The engineers, too, have to cope with this situation when choosing complex visual indicators adapted to man's capabilities.

This is a very important component of control of most intricate aggregates or technological processes, where man plays the part of the controller-operator of the united "man and machine" system.

Here's a "man and machine" system.

See how the functions of each block of this system are demarcated. In it man is supposed to play the part of a specific "subsystem". His job is clearly defined:


Information
processing
Information
receiver
Regulator
Factual
information
Machine
Control organs
Control
organ
Signal
OBJECT OF CONTROL
System input
System output

he receives factual information from the machine, processes it into command information and transmits it to the machine.

The machine, too, has its functions which are no less clearly defined. The machines on man's command perform technological operations.

True, the distribution of functions between man and machine may differ greatly from case to case.

What does it depend on? On the purpose of the system.

Here is a mechanized production system. Here man has to perform all functions of regulation and control.

Now we'll go over to a system of a higher type—to the automated production system. Here the major part of these functions is entrusted to the machines. Man's job is limited to planning operations as a whole. He makes important decisions, controls the work of the system in general, taking over the control in case of deviations from the programme.

What's the way of achieving best, optimum results of the combination of "machine" and "human" properties in the "man-machine" system? What's the way of attaining in the "man-machine" system maximum efficiency of the machine and minimum fatigue of man? The problem may be tackled from two opposite sides.

Firstly, the machine should be better adapted to man. Secondly, as it is being done by engineering psychology, man should be "adapted" to the machine in the best way possible.

Within the scope of engineering psychology come those links of the system where man finds himself directly connected to the machine, where the transmission of information takes place. Does that mean that man himself, in the first place, serves as such a link? It certainly does. He perceives the information by his senses. He processes information and transmits it to the control panel. When controlling the machine he translates instructions into a convenient code that can be easily understood by the machine.

Engineering psychology began very close studies of man's "capacity" as an "information channel", or "communications channel". Human "capacity" viewed from this angle turned out to be quite limited. This, at first glance, is a rather morbid conclusion. There's a limit beyond which man cannot reach. He cannot react to sound quicker than within the interval of 120-182 ms (milliseconds); to temperature changes—150-240 ms; to pain—400-1000 ms; to visual irritations—150-225 ms. These are rigorous objective figures.

But as scientists turned to "subjective" studies of various professions, it came to light that the human organism possesses enormous resources, that it, so to speak, tries to "outdo itself".

Experienced grinders discern gaps of 0.6 μ (micron), while man normally cannot see a gap below 10 μ. Textile

◀ The information flux in the "man-machine" system.

workers distinguish up to 100 shades of the black colour, steel workers distinguish a very wide spectrum of shades of red, up to several hundred. Painters are able to discern the difference in the proportions of two objects as little as 0.006 of their dimensions.

But here the legitimate question arises: is it always possible to "outdo oneself", to reach beyond the limit?

No, not always. High demands on the human organism in some cases lead to his resources being exhausted.

Let's take the example of aviation. According to American statistical data, 80 per cent of accidents are due to errors made by pilots or controllers because of excessive demands made by the "machine" link on the "man" link.

Soviet psychologists have discovered one of the most interesting and important phenomena: the time needed to find a solution is determined not by the volume of information, but by the number of "search steps", i.e. the number of visual fixations, the number of stops made by the eye. This means that in designing a machine, signals must be grouped in accordance with the properties of man's visual system, so that for the same amount of information the eye of the operator would have to make less stops, less "search-steps". For this reason specialists consider the rational arrangement of signals on the control panel to be of no less importance than the composition of a painting. In both cases good composition aids perception.

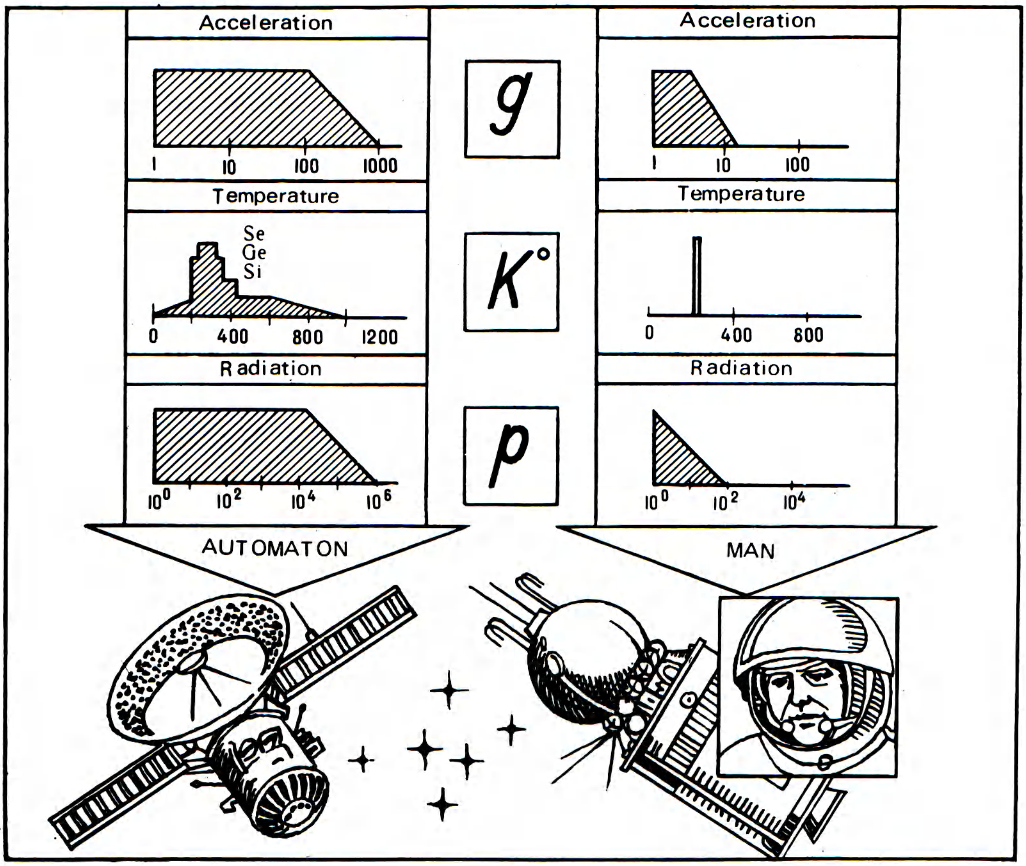
There is another very important field of action of engineering psychology: to assess and develop man's professional abilities, bring them up to the rising standards of modern technology.

During tests to this effect man is given problems of increasing complexity, and scientists with the aid of special instruments assess his so-called "progress coefficient", his "ability to develop his abilities". This method helps to find out whether a man can work in any of the professions requiring precise reaction, quick-wittiness, self-possession, orientation in an unforeseen situation.

There are different sorts of people. Some—the "hot heads"—fully display their abilities when unexpected decisions and quick actions are required of them, when they are prompted by danger. Others in such circumstances stand idle: they are unable to work, if they know that time is short, if they are disturbed by shrill noise, if something distracts them. In these circumstances they quickly become exhausted and forget habitual operations. But they are indispensable for carrying out observations or doing work entailing prolonged absence of information—the "hot heads" are unable to cope with such tasks.

This new interesting and important trend will help to find methods of speeding up the development of professional abilities, and man will achieve the skill of a great master not towards the end of his career, but in the prime of his life.

Take, for instance, technical hearing. It was commonly accepted that a keen ear had to be inherent or could be acquired by long years of practice. Remember stories told about the professional keenness of ear of the pilots—they are able to notice deviations of the engine rpm (revolutions



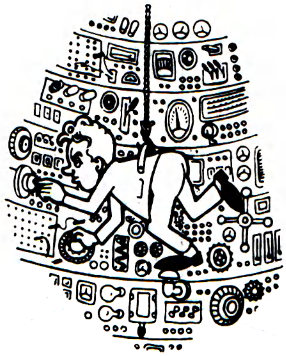
The comparison between the allowable limits of acceleration, radiation and temperature for man and automaton on a journey into outer space is not in favour of man.

per minute) from the normal as small as three per cent.

The scientists at the laboratory of labour psychology of the Academy of Pedagogical Sciences following meticulous research carried out into the properties of technical hearing developed express methods of training.

Workers at the Perm telephone plant, before being sent to shops, before jobs and duties are assigned to them, are examined by psychologists. Scientists assess innate qualities of every man and his ability to develop them. This enables to predict the job that will be to the man's liking, and to avoid wasting time and resources on teaching people jobs that they will not regard as fit for them.

Nowadays engineering psychology faces some very important problems. There is, on the one hand, the rapid process of liberating man, of facilitating his command functions. On the other hand, progress in bionics leads to new, closer ties between man and machine. Namely, machine control by means of speech and biocurrents is being considered. Biotechnical systems capable of receiving various signals from the human organism are coming into use. But these problems still remain to be solved.



Q

QUALITY CONTROL

The reception
and processing of information
which compares the parameters
of an object
with preset values.

The Sentry at the Border

Just imagine what would happen in plants and factories if the control of the quality of finished products, of technological processes would stop for a time. The factories would have to stop working, for no one needs products of inferior quality.

In modern industry quality control is one of the most important forms of control. It may be said that there's no production without quality control.

Evidently, the importance of quality control in automated production is much greater. Naturally, automated production requires automated control.

What is the job of a controller—be it a man or an automaton? It keeps an eye on parts being produced to ensure that they are of the right size, within the acceptable limits, on the temperature so that it should not rise above or sink below preset values, on a chemical process to hold it on the correct course. In this the controller is aided by information on the course of specific processes and about deviations from preset values. Without such information timely intervention in the course of processes is impossible.

It is easy to imagine the logic of a control operation: "If the event A has occurred, the operation B should be performed; if the event was C the operation to be performed is D."

The chapter "Automatics" deals at length with the "sense organs of modern technology": with sensors capable of penetrating anywhere, with amplifiers capable of million-fold amplification of the control signal, with specialized mechanical, electrical, and optical controllers, fast, compact, flexible, ensuring the necessary regulation procedure. There's in addition a vast army of tracking systems to watch over "law and order" in production shops. They dictate rigid terms to the machine tool or the production line, force them to operate in a strictly orthodox manner.

At this juncture it would be beneficial to show how the quality control is being accomplished and how multifarious this process is.

The control process usually consists of two stages. The first is the perception of information about the state of the object, and the second is the separation from the incoming information of that part of it which pertains to the quantity being controlled.

This is usually done in laconic language: "yes-no", "too much-standard-too little", "operational-nonoperational".

Everyone knows how important accurate measurements in quality control are.

Modern technology is able to produce automatic quality controllers with a memory. Such a controller will not only find errors, but will memorize them, make an analysis of them, draw conclusions and tell the machine tool what to do to avoid rejects.

Devices working in conjunction with automatic flow-lines may serve as an example of fully automated quality control.

There are even whole factories working on the "super-closed shop" principle without people and, thanks to automatic control, producing high-quality goods. This applies to hydro-electric stations and continuous process chemical plants. Here the centralized control embraces everything: quality of product, state of equipment, quantity and composition of semi-products.

The quality control (technological control) in engineering industry, on the other hand, is decentralized. It is carried out at principal operation stages, in the process of transportation and at special multi-operational control stations. There are special machines for sorting and filtering out rejects and for control of finished products.

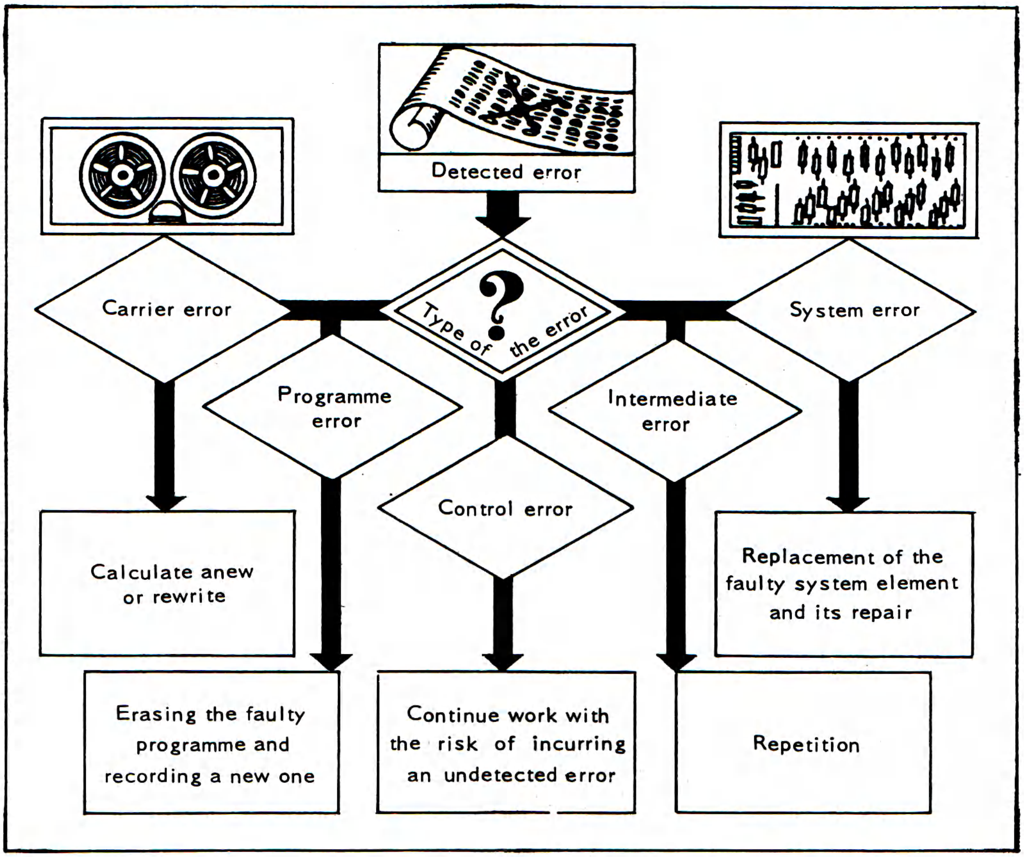
Nowadays, with the advent of automated production control systems the quality control is carried out by special devices coupled to electronic computers.

And what about the forms of control? They are numerous. Single parameter control, as its name implies, controls only one specific parameter with one gauge of the simplest type.

Multi-parameter control, as distinct from the single-parameter control, watches over numerous parameters with the aid of many well-coordinated instruments, machines or even whole systems. This control is, as a rule, centralized.

Methods of control are also subdivided into series, parallel and series-parallel. In the first, information is received, in turn, from several control sources. In the second, information is received continuously and simultaneously from many sources over multiple channels. The third, as may be easily guessed, combines both former methods.

There's also the logic control which entails the utilization of the result of mea-



These are the operations which have to be performed in case of computer errors of various types.

surements and control for self-tuning, for assessment of variations in conditions of some process.

Sporadic control is carried out as the need arises, from time to time, or in answer to automatic signals in case of rare but substantial deviations.

A more complex type of control, the multi-stage control, abides by the principle of hierarchy: the higher the control stage, the higher is the quality of machining or the accuracy of a process. Such control involves the collection of information from all the branches of the factory.

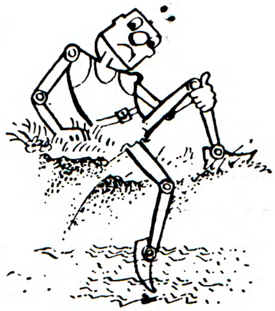
It's no easy job to effect quality control in industry. The above list was quite impressive. And still, it didn't mention local control, distant control, telemechanical control.

It must be said in addition that since the time electronic computers began to be used, the problem loomed of controlling the quality of their work. Now it is necessary to discourage the clever machines from making silly mistakes, to see that they do their calculations correctly. This is one of the principal problems of designing digital electronic computers. The problem is very complicated for even a dust particle on the magnetic memory tape may lead to an error. Try and find it afterwards!

Unhappily, existing methods of computer control do not guarantee absolute and continuous quality of calculations. A complete and detailed control procedure is, as yet, lacking, and the users of the ultra-fast and ultra-accurate electronic computers are still liable to suffer from their fancies —there are instances when the computer hands out an erroneous result.

There are various procedures for controlling the work of electronic computers. They are subdivided into the programme control and circuitry control methods. Each of the latter is subdivided, in its turn, into procedures of control in the process of problem solution and of control outside the operational cycle.

The simplest way of controlling the quality of computer operation, from logic considerations, would be to repeat specific cycles or replace the faulty block. It is also obvious that it is easier to control the information transmission circuits of the computer than the arithmetical operations. The problem of detecting and excluding all possible errors in the computer control system may, however, turn out to be insolvable.



"Brrr! It's too cold!"

R

RELIABILITY

Index of Trust

The probability for some device to operate without failure during a given time.

Don't look for the word "reliability" in *Encyclopaedia Britannica*, you won't find it there. Why? Because it is only recently that this word became a concept indispensable to science, technology and industry.

A few facts will do to explain how the problem of reliability arose. During the Second World War 60% of aviation equipment sent by the USA to the Far East proved to be deficient. Another 50% of equipment and spares deteriorated in storage. Tests showed that radar equipment remained inoperable for 84% of storage time, sonar equipment for 48%, and radio communication equipment for 14%.

Let's get down to business and, dispensing with introductory remarks, discuss the meaning of reliability. This will be explained by the prominent Soviet mathematician Professor B. Gnedenko.

Should we test the life of some electronic tubes from the same lot we would find that each of them worked for a different time.

It is impossible to predetermine how long any given tube will operate without failure. It is only possible to specify the number of tubes from a large lot which will, on the average, remain in operation after a given time.

In other words, the life of each tube as well as of any other product is a random quantity. And the job of scientists is to calculate the probability of failure-free operation of a device during its specified life-time. They call this probability the reliability.

Think of an interplanetary space-station. How complicated its work is! For this work to be successful the entire equipment of the station must operate without failure during the whole time the station is in orbit. In other words, all equipment of the station must display great reliability, i.e. the probability of failure of any element must be small.

To assess the importance of the term "reliability" we will have to engage in some trivial talk on the complexity of the world of modern machinery and instruments.

That will need some examples to illustrate the point.

A conventional electronic tube has some 60-90 parts. And the equipment on board the manned spaceship *Vostok* weighing 2000 kg (the total weight of the ship being 4625 kg) was made up of 300 instruments, which, in turn, contained 240 tubes, 6300 semiconductor devices, 760 electromagnetic relays and switches. All this complicated equipment had to operate during a long time in conditions of substantial overloads, vibrations and rapid changes of temperature and pressure. It was quite natural for the scientist-astronaut, Doctor of Technical Sciences K. Feoktistov to write: "Reliability became as important to astronautics as air to man—without reliability it could not exist at all."

Let's continue with our examples.

An electronic computer consists of tens of thousands of tubes, semiconductor diodes and triodes, resistors, connections and soldered joints.

The control system of the American intercontinental ballistic missile *Atlas* contains over 300 thousand elements.

And the reliability of such a complex depends on its weakest element—the one that's going to fail first.

Even in case every element is capable on the average of ten thousand hours of failure-free operation, every two minutes one failure, one fault is to be expected.

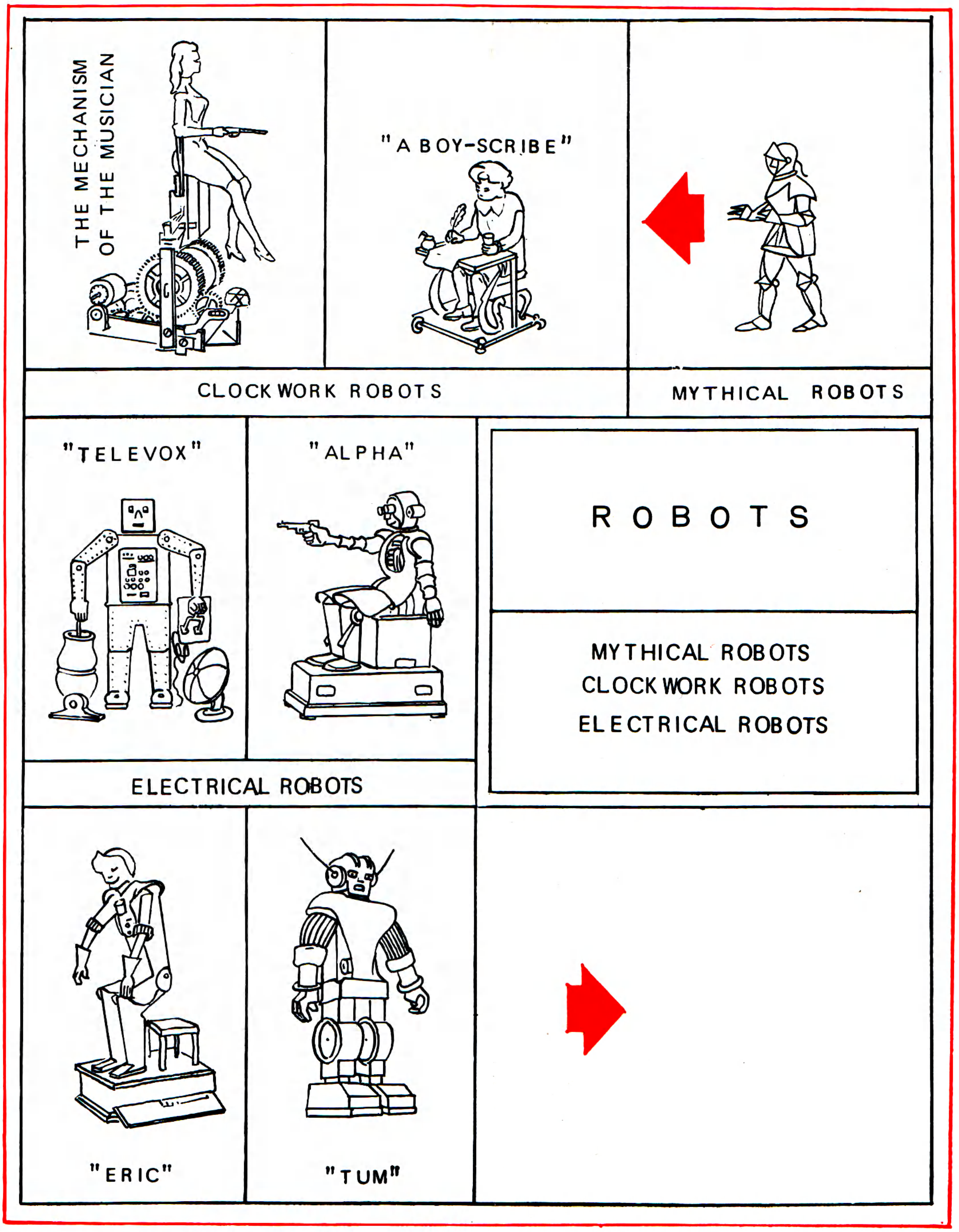
Does that mean that the more complex a system is the less reliable it is? As Academician A. Berg once aptly remarked, the stone axe was superior in reliability to modern installations—there was nothing in it that could fail.

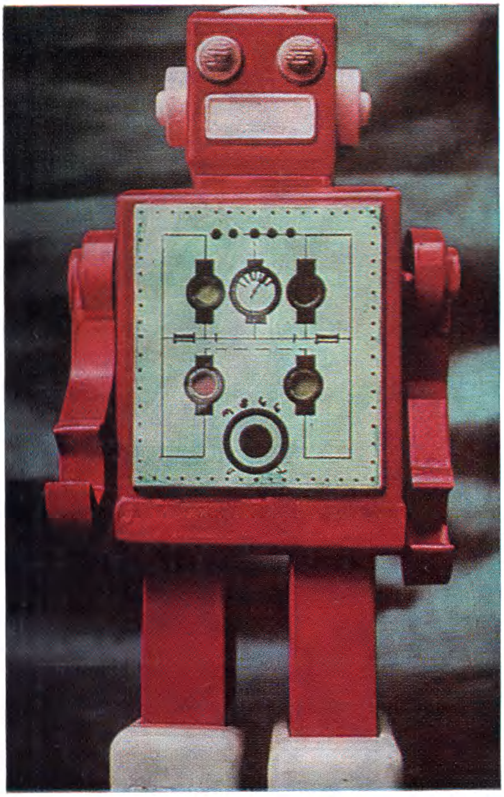
Academician Berg cites another example which demonstrates the influence of the reliability of individual parts of the machine on its reliability as a whole.

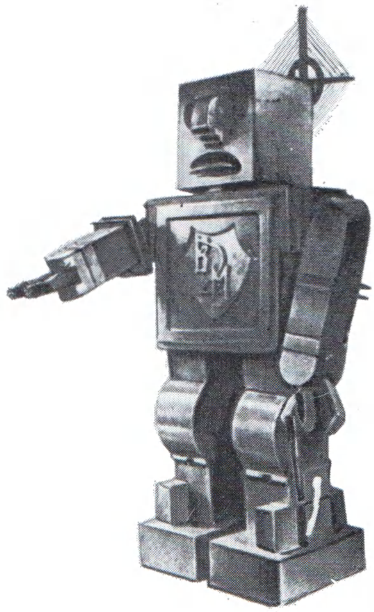
The results of tests of one computer prototype were little promising, it did not live up to reliability requirements. The investigation of the causes of it revealed that the reliability of the commonest parts—the carbon resistors—was unsatisfactory. This simple part is produced from nine materials: ceramics, brass, enamel, abrasives, etc. Each part goes through twelve technological processes, and each of them influences the reliability.

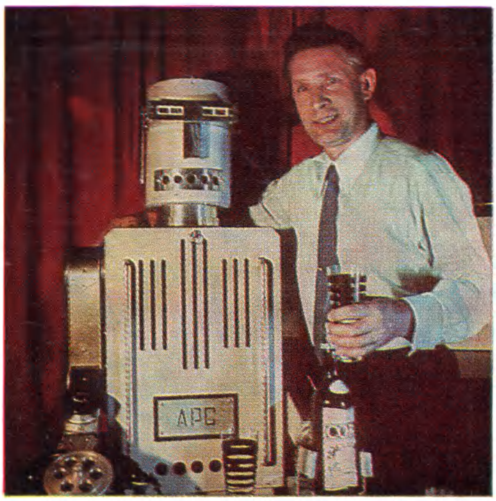
In the computer prototype which was subjected to tests there were some 600 thousand carbon resistors. Let's calculate now the number of factors which influence the reliability of this computer only through the medium of the resistors. The number will be $600\,000 \times 9 \times 12 = 64\,800\,000$! An enormous number! And the computer contains, besides, several tens of thousands of other parts.

The reliability of complex systems and machines in every field has its own criteria. In instrumentation it is


THE MECHANISM
OF THE MUSICIAN
"A BOY-SCRIBE"
CLOCKWORK ROBOTS
MYTHICAL ROBOTS
"TELEVOX"
"ALPHA"
ROBOTS
MYTHICAL ROBOTS
CLOCKWORK ROBOTS
ELECTRICAL ROBOTS
ELECTRICAL ROBOTS
"ERIC"
"TUM"

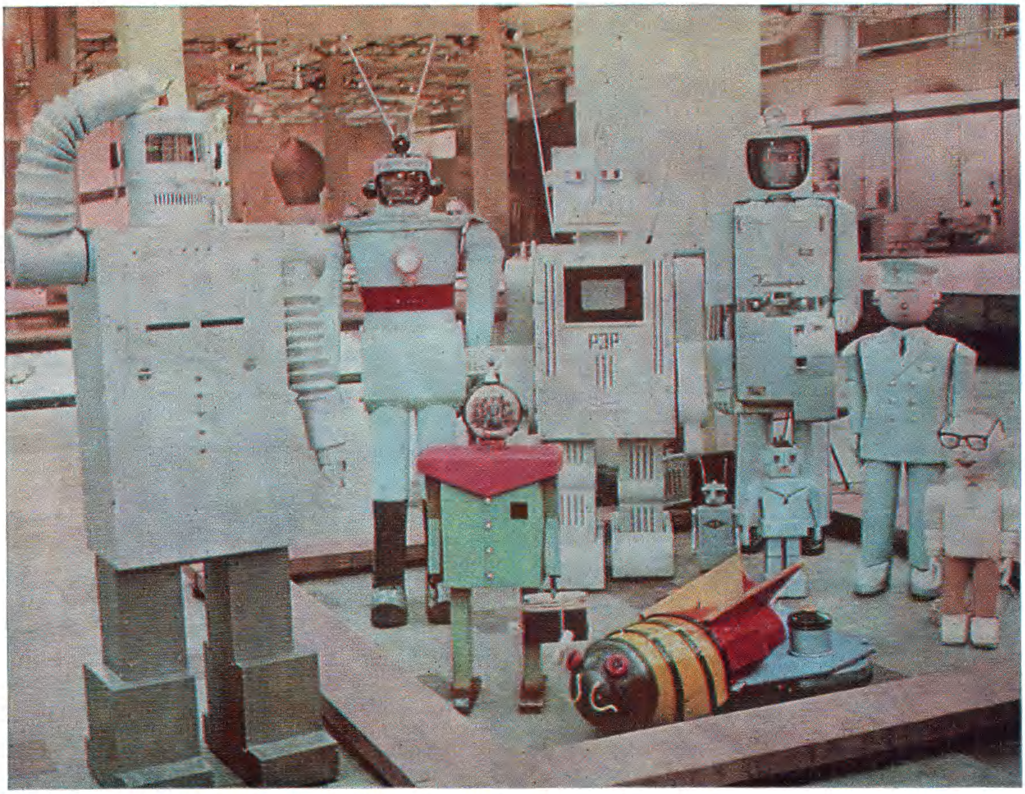


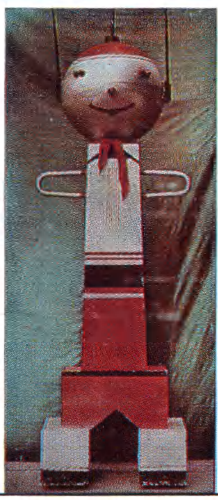


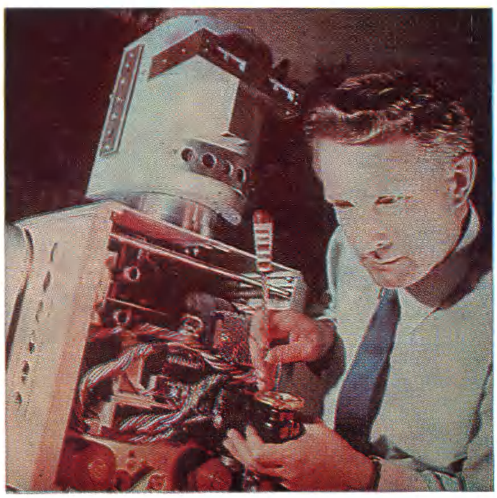


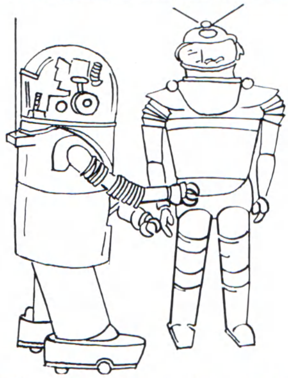
ROBOTS

ELECTRICAL ROBOTS

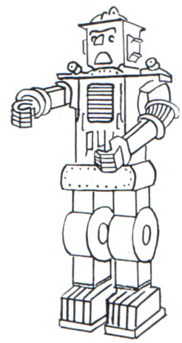








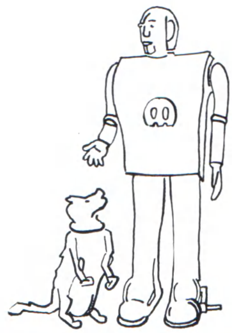
"TINKER" "NEPTUNE"



"RUM"

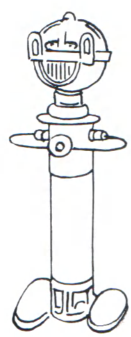
ROBOTS

ELECTRONIC ROBOTS

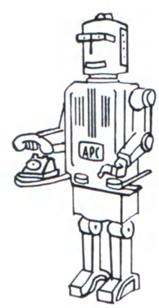


ELECTRONIC "DOG" and "MAN"

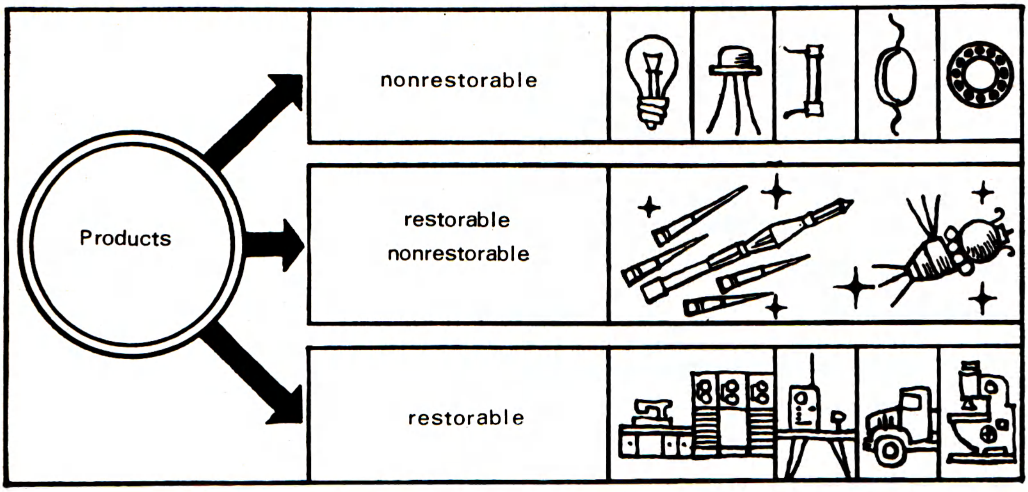
?



"GUIDE"



"APC"



The classification of products in the theory of reliability. Some products—the elements of radio-equipment, instruments, resistors, machine parts, bearings—are not regenerated. Others—electronic computers and control devices, cars, machine tools—are. Some, for instance, devices carried by rockets or satellites, are not regenerated in flight but are regenerated during storage or flight preparation.

the accuracy, in hydraulics the absence of failures in various operation conditions. The criterion of computer reliability is the accuracy of input, processing and output of processed information.

If a calculating device is unreliable, you have to expect mistakes and distortions. Some unreliability, even if it is extremely small, is common to all man-made products. Therefore, the problem of increasing reliability looms large before science and technology.

There are several means to achieve this aim.

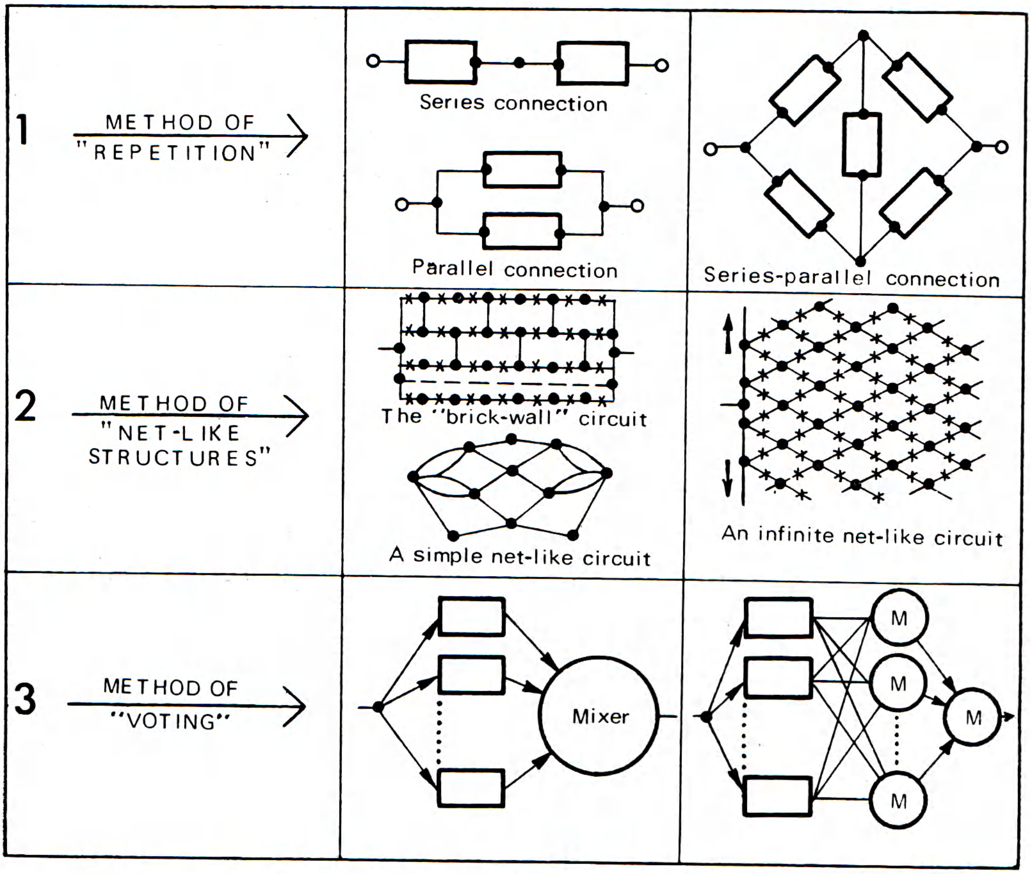
First and foremost it is the incessant improvement of the reliability of every element, every part of the unit, of the system. The more reliable a link, the more reliable is the chain as a whole.

But it is not always that this parameter should be improved by all means, for the costs may prove too high.

What should be done in such cases?

Having first heard of it you would't believe: build a reliable machine from insufficiently reliable elements. And the "unbelievable" method is being explored by scientists. This is how it is applied to logical computers on "relay elements".

Suppose the device consists of three relays the contacts of which may be open or closed. It is easy to calculate that the total number of contact states is eight in accordance with the number of various combinations of open and closed relays. Each state fulfils some function, for instance that of control. A defect in one of



There are several ways of creating redundancies. The method of "repetition" involves the assembly of a new circuit and the multifarious connection of it. The method of "net-like structures" helps when both the main and the reserve structures are liable to failure. "Voting" involves the replacement of the entire device or its block by an identical one and the connection of additional special devices—the mixers.

the states leads to another state. Since each state strictly corresponds to its own control command the defect will lead to a wrong instruction, and the system will make a mistake.

Can anything be done about it? Yes, it can. The number of relays should be increased, and out of the possible states only such should be chosen for control purposes which do not in case of errors coincide with some other state.

This is termed creating a redundancy and has an analogy in nature which is rich in excellent reliable systems made up of less reliable elements. For example, the human brain as a system is infinitely more reliable than its single element—the neuron: the organism operates even in case millions of neurons are put out of action. Try and find some technical device that would continue to function properly after the failure of only one of its elements!

Redundancy is a promising trend. Appreciable results have already been obtained, still greater results are expected. Yet specialists do not consider this to be the main road to high reliability.

Couldn't a system, machine or device be designed that would give automatic warning of a possible failure of a part, a unit or a block and that would, moreover, automatically switch a reserve block, assembly or part into operation? Like a living organism that sets in operation its reserve channels to preclude the possibility of stoppage.

Work in this direction has already started.

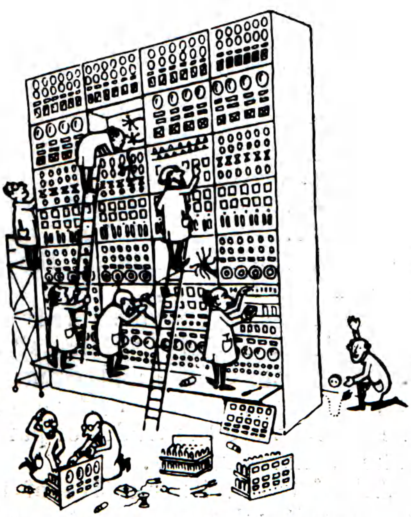
Today some machines control their own operations and give warning signals in case any defects arise.

Other machines are capable of testing their own electronic devices and of detecting 99.9% of tubes or other parts liable to failure.

At the Institute of Automatics and Telemechanics of the Academy of Sciences of the USSR a group of scientists headed by Academician V. Trapeznikov have built a digital computer which in case of failure hands out its own "diagnosis" immediately showing the place of failure of some block or part.

As a result of the application of such advances in modern technology the reliability of big computers rose to nearly 98%. This means that the computers work efficiently 85% of the time (with the exception of time reserved for inspection and maintenance). A case has been reported of a computer, consisting of 13 thousand micro-circuits, working faultlessly for 33 thousand hours. This is a great factor of reliability, though not the uppermost.

Scientists attack reliability along a wide front—they use every possible means to increase the computer's "index of trust". The battle for reliability has in effect only just started. But one should heed the warning of the experts that the problem of reliability, though satisfactorily solved today, will arise in a new form tomorrow and will never disappear as long as technical devices utilized by man are being developed and complicated.



"Look here, I think I've found why it doesn't work!"

A model or an automaton having the appearance of a man, often designed for practical work.

"Eric", "Tinker", "Siberian" and the Rest

Probably, no one now needs explaining what a robot is. We have grown used to these clumsy, slow metal likenesses of man, to their eyes of lamps, to their ears of aerials, to their monotonous, indifferent magnetic-tape-recorder voices. We are no longer wondering at them, we greet them as good old friends.

Do you know that robots have a long and interesting history?

The first mechanical man, the legend would have it, was built in ancient times by Ptolemy Philadelphus. His younger—by many hundred years—brother made history under the name of the "iron man". He was built by Albert the Great over 700 years ago. From that time onwards he has made his home on the pages of dozens of books.

Mechanical men "mastered" many professions, mainly "delicate" ones. Abundant were flute and drum players, dancers, scribes. Rare among the robots were the trades of painters, bakers, hair-dressers.

All of them, irrespective of trade, were built with the greatest craftsmanship .

The following story serves as a tribute to the art of their creators.

The famous French mechanic Jacques de Vaucanson decided to build a weaving automaton. The weavers of Lyons learned about it. The inventor's idea was not to their liking, and they decided to give Vaucanson a beating. Then to make fun of the weavers the brilliant mechanic built an ass who worked at a loom.

The enthusiasm for mechanical likenesses of man vanished at the beginning of the 19th century. From noisy reception halls of palaces, from royal castles the "mechanical men" moved to quiet museum halls. And here they rest to this day, these "unanimated men", which served to entertain the nobility. Is it only because of their strange "fate" that these artful dolls are of interest to us? Certainly not. The mechanical men are of interest to us, in the first instance, because they occupy a place at the start of the road which led to the development of automata.

New times brought new ideas. The era of electricity was marked by the construction of "electrical men". They had advantages over their mechanical "relatives" not only in the principle of operation but also in the number of man-like functions they could perform, since earlier artificial mechanical men were able to perform only one function each: the draftsman drew, the cittern player played the cittern, the scribe wrote, etc.

Meet the "electrical man".

His author, the American engineer Vansley called him deferentially "Mister Televox".

Clumsy, squarely built, eyes and

nose painted. His looks were very much inferior to those of his mechanical predecessors, but there was a lot he could do.

"Televox" worked as a permanent supervisor of the water tanks of one of New York's skyscrapers. He watched the water level, switched on water pumps.

Moreover, "Televox" had sound reproducing apparatus installed in him and could pronounce several phrases. He answered telephone calls about water level and pump operation.

This work is much more complicated than the work of a mechanical musician. Judge for yourselves: nowadays the work similar to that of "Televox" is being done by automated traffic controllers in numerous automated plants.

In addition to serious "professional" work "Televox" was employed in house work. He switched on the vacuum cleaner and the ventilator, lamps in the room, opened the windows and shut the doors. "My robot," said the inventor, "without its shell is actually an automatic telephone exchange, to which several electric motors are connected instead of telephone subscribers."

These electric motors performed all the actions of "Televox". In other words, "Televox" was a typical representative of "electrical men".

His counterparts of the time were in close affinity to him. Among them were the "Englishmen": "Eric" built by engineer Richardson, "Alpha", the creation of the professor of physics Harry May, the robot "Willy" of Westinghouse, and many, many others.

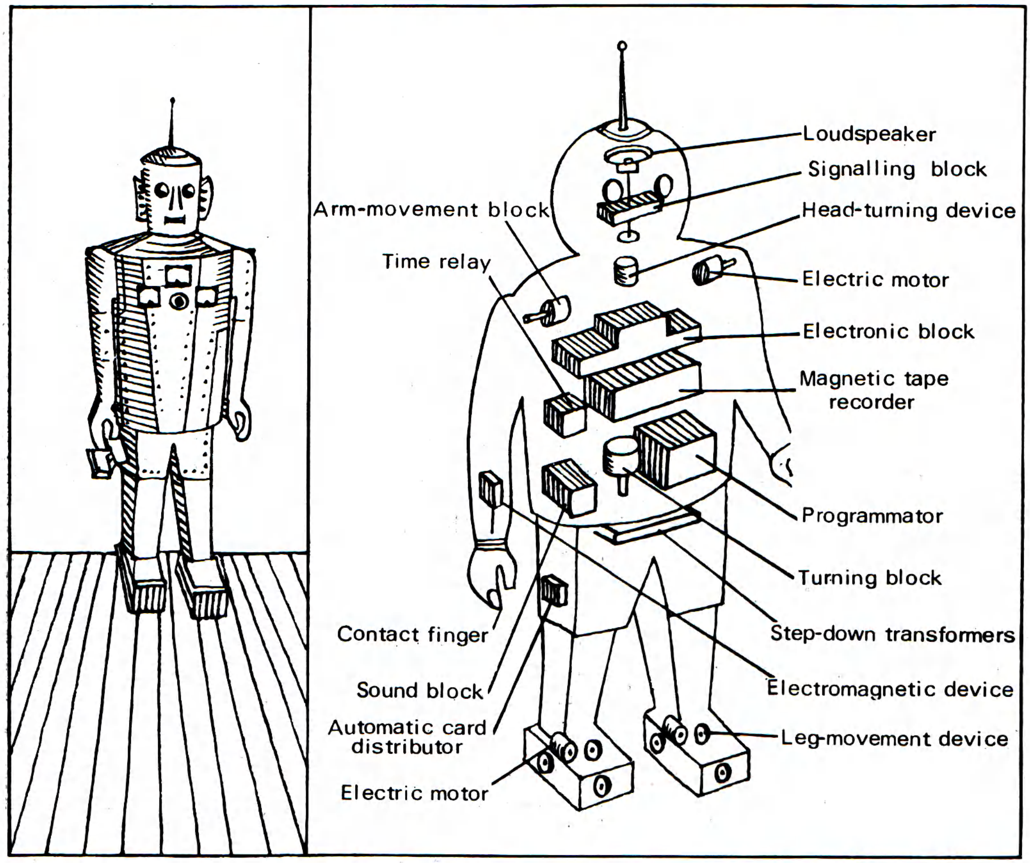
Robots of today are electronic creatures. One of them, an electronic citizen of Kaliningrad, says to this effect: "I have no heart. I'm doing well with transistors and intricate electronic blocks."

On p. 262 is the block diagram of the robot "Siberian-2". He can do the job of a guide to exhibitions, sell lottery tickets and books, advertise products and polish floors.

The robot consists of 19 blocks. The main blocks are the control blocks of the head, of the right arm, of leg action and of body rotation. A very important part in the "Siberian" is played by the programming device and time relay.

Here's a description of the robot by its inventors from the city of Omsk: "The robot draws power from the mains. The voltage of 27 V is applied to the programmator through the sound relay. There it is transformed into programme pulses. For instance, the 'leg' control block receives two programmes. The first sends the robot on his way forward. To change course or to turn back a second programme is needed. How does the robot turn a corner? An instruction is sent from the programmator to the control block, and the motor is switched on. After the corner has been turned a second signal is sent—this time to the stopping block, which switches the motor off. At the same time a tape recorder with recorded speech is switched on. As a result the robot turns and, for example, tells the visitors to the exhibition about some exhibit.

"The movements of the right arm are somewhat more complicated. Simultaneously with the motor a device is switched on which, say, hands out lottery tick-



The "Siberian-2" robot was built by boys from the Omsk municipal vocational school.

ets stored in the robot's pocket. Having clutched the ticket, the robot firmly holds it with his 'fingers'—contacts. As soon as a visitor takes the ticket the fingers are brought into contact, and the order 'return to zero' is sent. The arm motors are switched on, and the robot resumes its former posture."

These "electronic men" that have gone a long way from the superficial likeness to man can do a lot of the things we can do.

The first thing that meets the eye is the "wide range" of their professions and the compatibility of these professions in a single robot.

Some robots possess faculties peculiar only to them: for instance, they can have sense organs which are denied to man. For example, the robot

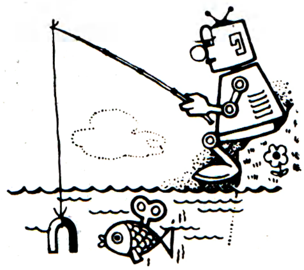
"ГПТУ" not only sees light, hears sound, feels heat, and notices obstacles and avoids them artfully, but reacts to radioactivity, as well. Several metres away from the danger zone it sends various warning signals.

Don't you agree that now the time has come to speak not only of robot toys? Real robot-assistants have made their appearance.

Nowadays "electronic dwarfs" are engaged in testing cars and planes, in shops with an unhealthy atmosphere; they sink to the depths of the oceans, rise in rockets to carry out cosmic studies.

With the aid of robots functions and behaviour of living organisms are being simulated with the aim of creating better engineering constructions and automata; biological processes are being modelled to gain insight into their essence.

Already now scientists are allotting serious scientific tasks to robots. How much more is in store for them!



S

SELF-ADAPTING SYSTEM

A system
whose method of action
changes automatically
to attain optimum control.

Imagine a comprehensive automatic system which responds instantly to any change in the mode of operation or of the ambient. A rise in temperature—an instant reaction follows. An unexpected drop of pressure—immediate action of the gauges, and it returns to normal. An unforeseen deficiency in the composition of a liquid—the system compensates for it the very moment it arises.

What a grand automaton, you would say; surely, it doesn't exist. But it does! It's the living organism. The living organism, we, human beings in particular, is this most advantageous, superb, optimum system, "whose method of action changes automatically to attain optimum control".

Self-adaptation is an invaluable quality of the living organism developed through the millions of years of its history, the ideal the designers of modern automata are trying to attain. The advent of cybernetics enabled a truly bold problem to be formulated: can the adaptation of living organisms to their ambient be regarded as an analogue for technical automatic systems subjected to changing influences?

Here we'll have to deviate somewhat from our main road in order to return later enlightened by knowledge that will help us on our way.

We'll have to get acquainted with such seemingly simple conceptions as a good and a bad organization.

At first glance it's perfectly simple: a good organization is the one that reacts correctly, a bad one that which always reacts wrongly. So it appears at first glance. An organization is described as good if it works faultlessly and operates within some strictly defined limits, i.e. operates well no matter what it is—a cat, an automatic pilot or an automatic plant.

Wait a little, says to this a prominent English scientist W. Ashby, inquisitiveness is a good thing, but just think of the many antelopes who died because they stopped to look at the hunter's hat.

There is no quality or faculty of the brain unequivocally accepted as desirable in one situation that doesn't become undesirable in another, maintains the scientist. And he cites some examples. Here's one.

Is it good or bad for the brain to have memory? It's good, if the ambient is such that the future often repeats the past. If the events in future would be opposite to those in the past, memory would be a disadvantage.

This situation occurs when a rat living in sewage tubes encounters a bait. The rat is very suspicious and accepts unfamiliar food only in small portions. But if delicious food appears in the same place for three days running, the rat learns it. On the fourth day it takes the bait boldly and poisons itself.

A rat devoid of memory (a bad organization by usual standards) will on the fourth day be as suspicious as on the first and will survive. Thus, in such conditions memory is a disadvantage. Does it follow that it isn't possible to distinguish "good" from "bad", that any organization can at the same time be good and bad?

At this point we return to our former road and arrive at the self-adapting system. Its trick is that it changes from "bad" to "good" by itself.

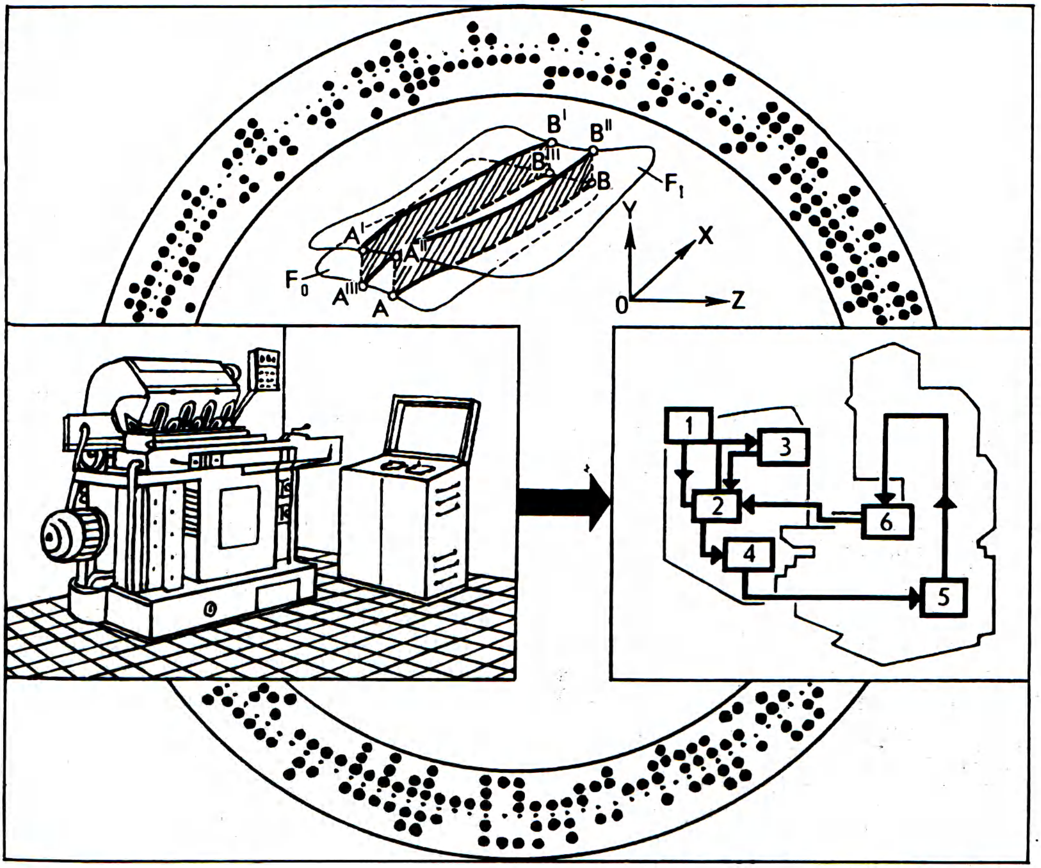
Let's take the well-known example of a child's brain. At first its working is such that the child is always attracted by fire. The organization is clearly a bad one. As a result of the experience obtained a new—"good"—organization comes into being: now the child avoids the fire, the brain as a system had adapted itself.

Is such self-adaptation possible in a technical system? Just think how wonderful it would be! The automaton would function satisfactorily not only under normal conditions, but under break-down conditions as well, could "level out" in any operating condition, would work like a man.

Self-adapting systems are classified by their behaviour. The simplest self-tuning systems choose optimum operating conditions with regard to ambient conditions. Such systems are increasingly being used in technology.

For instance, it is possible to build a self-tuning machine tool controlled by a programme. In this case the controlling device must mark the deviations in the dimensions of parts being produced and automatically effect changes in the programme. In this case an initially deficient programme will be improved in the course of the tool's operation, and rejects will be minimized. Scientists term this tuning for better operating conditions "self-improvement by the machine tool of its algorithm", of its working programme.

If the system can improve the algorithm of its operation, it can improve the algorithm of its behaviour, as well, make it "flexible", "searching", adaptable to the ambient. Such a



A self-tuning machine tool: *1*—programme block; *2*—self-tuning block; *3*—"memory" block; *4*—control block; *5*—actuator; *6*—measuring system. The process of self-tuning consists in searching for better results on the basis of results previously obtained. The tool itself works out an improved programme which takes into account former deficiencies in machining.

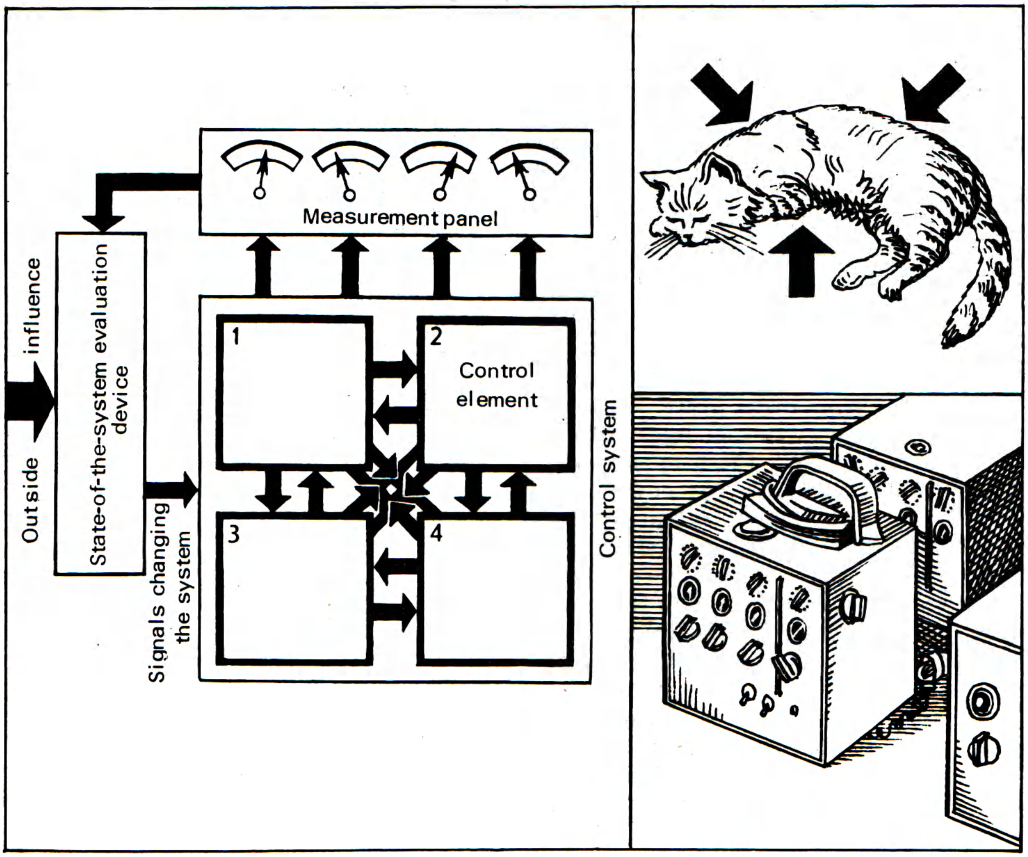
system, which changes its mode of action in unforeseen circumstances, is usually described as self-organizing. It occupies a position one step above the self-tuning system.

A Classical Example of a Self-Organizing System Is the Homeostat of W. Ashby. Here is a description of the principles of operation of this device.

The homeostat consisted of 4 electromagnets. The motion of their cores displaced the contacts of rheostats. The electromagnets were fed through these rheostats. Maximum displacement of a core caused an arbitrary switch-over of connections of the rheostats and electromagnet windings in the circuit. The positions of all four cores were thus interrelated since the current in each solenoid was dependent on the position of all four rheostats, and the position of each rheostat was dependent on the current flowing through the respective solenoid.

As soon as power was switched on all cores and rheostat contacts began to move. The resulting situation could be twofold: after some transient process the cores could occupy a stable intermediate state—in this case the system became stationary; in another case the system failed to find for itself a stable state, and as a result one of the cores exceeded the range of normal displacement and reached the limiter. This led to arbitrary connections in the circuit, after which the search for equilibrium was continued. After several switchings leading to arbitrary connections in the circuit of the homeostat the system ultimately attained a state compatible with equilibrium and then found this equilibrium.

Ashby's homeostat is a device which it isn't easy to put off balance.



Altogether 400 thousand combinations of switch positions were envisaged in the system. Various operations to which the homeostat was subjected, such as displacement of the limiters, changes in connections, petty failures, did not destroy its ability to find the equilibrium state.

The "behaviour" of the homeostat can be compared to the behaviour of a cat. If you push it, it'll make itself comfortable and fall asleep again. The same with the homeostat: when it's being pushed—displaced from the state of equilibrium—it "makes itself comfortable", tries various connections, and then "falls asleep" again, again finding a state of equilibrium.

The experiments with the homeostat were highly praised by Norbert Wiener. He considered Ashby's brilliant idea of a purposeful, arbitrarily chosen mechanism capable of attaining its ends through the process of learning to be not only one of major achievements of modern philosophy but an achievement leading to very useful technological results in the solution of automation problems, as well. He thought that we were in a position not only to make the machine follow its purpose, but, for the most part, a machine designed to avoid certain break-down situations would find aims for itself that it was capable of attaining.

Here's another example of a self-organizing system—the modelling of the process of survival on an electronic computer.

Imagine a computer the memory of which contains the numbers from 0 to 9 quite arbitrarily mixed. In this computer all numbers are multiplied by pairs, and the number on the right end of the product takes the place of the first multiplier. Let's put the computer to work. We know that an even number multiplied by another even number gives a third even number. Odd, multiplied by odd, also gives odd, and odd multiplied by even gives even. The conclusion can be drawn that after mixed encounters the number of even numbers in the "memory" of the computer will grow—the even numbers have greater chances of "survival". Gradually they will take the places of odd numbers in the computer "memory". The computer has "organized itself" for "survival". In time the practice of this purposeful behaviour will lead to the eradication of all odd numbers from the computer "memory".

This "wise" class of self-adapting automata includes yet another species. It bears the name of self-educating. To merit the name the automaton must first of all be capable of searching. Having been trained in this faculty the automaton must be given a "memory" to enable it to accumulate information in the process of searching. Next a system of prizes for successful ventures and of punishment for the unsuccessful ones should be devised. This method of self-education is termed the trial-and-error method. and it's being used in some programmes for solving educational problems.

Here's an example of a programme for a self-educating computer.

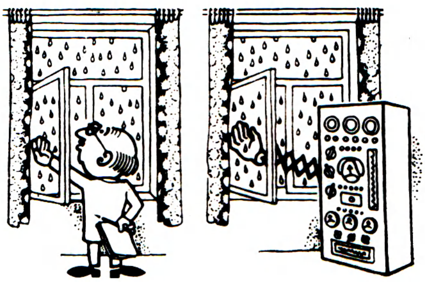
The computer was divided in two. One section played the part of the "pupil", the other of several "shops" with varying goods assortment. The task of the "pupil" was to learn to find the necessary goods quickly.

At first the "pupil" roamed the shops in search of the goods. In one shop he was in for success—he "came across" the goods. He "remembered" the "shop"—for this he was given a "prize".

The goods were changed. Out he went shopping again. New searches, followed by a new success, for which a prize was due. And, of course, a new "knot" in the "memory". This was repeated over and over again. The training resulted in self-education of the "pupil". He unmistakingly chose the right shop for specific goods.

Needless to say, automata capable of acting in this manner are rightly called "clever", for they are very much like real live pupils. It is not without foundation that scientists call such mechanisms "brain-like".

It should, however, be kept in mind that research in this direction is actually just beginning. There is as yet no general theory of self-adapting systems. This field of research may be likened to a great field touched here and there by the plough of research. But should this field be properly cultivated, a generous crop will be the reward for the time and labour spent, a crop of all kinds of self-adapting systems, true servants of man.



A complex of scientific theories dealing with the properties of sign systems.

Attention! Signs... .

Here's a rather odd complement,
- spoken language,
- symbolics of chemistry,
- street traffic signs,
- the "language" of the dolphins and bees,
- mathematical formulae,
- the Morse code,
- artificial computer "languages".

Enough for the present. What do you think such different concepts relating to quite different spheres of life have in common? All of them are examples of sign systems, they all are made up of signs.

Well, what is a sign, what can be termed a sign? Everyone of you gave out a sign when you for the first time pronounced the word "mom". And the signs used in games.... Or the familiar school bell. This is a sign to begin a lesson or a recess. And the important part signs played in the activities of underground organizations! A curtain drawn in some peculiar manner, or a flower placed on a window-sill served as a warning.

The "language" of animals, too, is a sign system. You, probably, had the chance to observe the difference in the sounds hens make. When a hen rallies her chicks it cackles. To warn of danger it cries out alarmingly. Scientists distinguish about ten command signs in the "hen language."

Insects use specific signs to transmit various, often quite complex, information. Ants, for instance, "speak." the "language of odours". And bees in their "monologues" resort to "dances". With the aid of the "dance" the bee tells about the whereabouts of the sweet nectar, how to find the way to the hive and so on.

Scientists are at present carefully studying the "language" of dolphins

However, the distinction between these "languages" and the human language lies not only in poverty of means of expression, in the small number of available signs, but in quality, as well. For animals, as distinct from man, the sign is always relevant to actuality, its meaning is always concrete, it is valid only at the moment it is emitted.

Various "finger languages" are also signs. A broken twig of a tree, smoke from the fire—all can serve as signs if there is an understanding as to their meaning: a warning, a landing sign for a plane, a meeting place. In general, as you have probably noticed, a sign is a symbolic signal with a definite meaning. The concept of a sign is very wide. But it always amounts to an object of substance, whether it is a happening, a phenomenon or action. And always this object manifests itself in intercourse —concretely or symbolically. A sign (as you have also noticed) always serves the purpose of storage, transmission or processing of information.

Signs are always part of a system. For instance, the identical sign "P" in the Latin ABC means the letter "P"; in the Russian ABC it corresponds to the letter "R", and as a traffic sign it denotes a parking place.

With the aid of sign systems people communicate with each other, such systems enable them to study nature, to work.

Scientists divide the sign systems into two categories: natural and artificial.

Animal "languages", "odour languages", "finger languages", etc., are natural systems. The most advanced natural sound system is the human language. It's a very fluid, flexible, well-developed system. Having been born out of communication, the human language serves as a means of communication between people. Our language helps us to express thoughts, wishes, to transmit the nuances of feelings. V. I. Lenin had a good reason to pronounce the language to be the main means of human communication.

The higher mankind rises in its social progress the more new sign systems come into being. For this reason their number is continuously growing. And for the most part this is due to artificial sign systems. Mathematical and physical formulae, the symbolics of chemistry and traffic sign code mentioned above can all serve as examples of such systems.

As a rule the role of artificial systems is auxiliary: they express things that can be expressed with the aid of natural signs, but more concisely, precisely and economically. They at once reflect the ultimate result and the way that leads to it.

Thus, if anyone would like to "translate" a familiar formula into words made up of ordinary letters, he would need several textbook pages to express the result of a simple mathematical calculation.

Try and add the number one million seven hundred thirteen thousand five hundred and one to the number twelve million one thousand three hundred and ninety-nine, written down in words. It's no easy job.

And it's so easy with the digits!

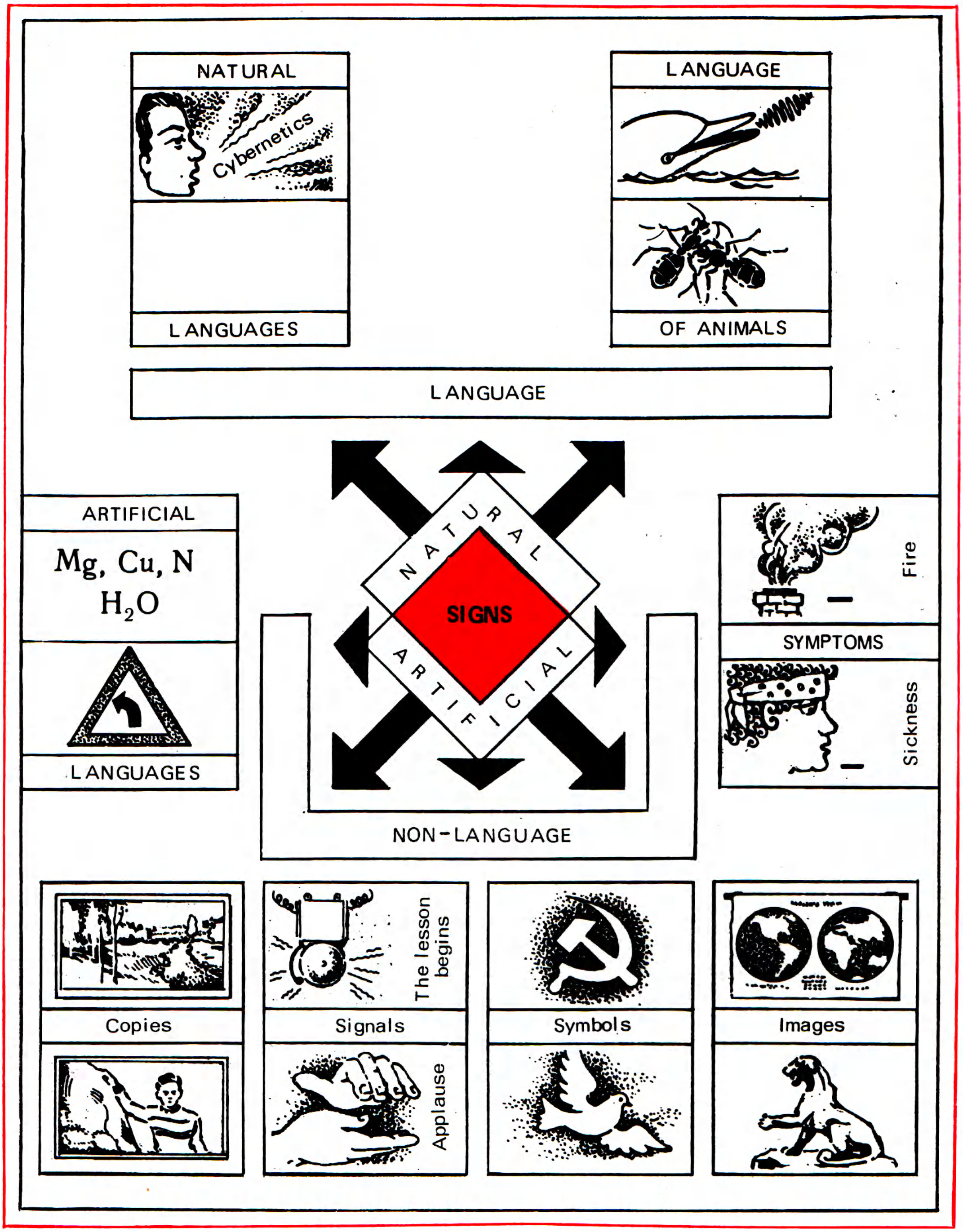
$$\begin{array}{r} 1\,713\,501 \\ +\,12\,001\,399 \\ \hline 13\,714\,900 \end{array}$$

There are "independent" artificial systems as well. Such systems in increasing use nowadays include first of all languages serving as intermediaries in computer translation and logical calculus.

There exists also another subdivision of signs. They are classified as language and non-language signs. This classification is easy to perform. It, so to speak, lies on the surface. Evidently, all natural and artificial languages are language signs. Various schematic diagrams, blue-prints, drawings, signboards, maps, illustrations, diagrams, dances, pantomine, music, sculpture, etc., are non-language systems.

Signs and sign systems are studied by a special branch of science—semiotics. It derives its name from the word "semios", the Greek for "sign".

Obviously, signs attracted the attention of scientists. Since signs appeared as soon as men began to think, their studies date very far back. Al-


NATURAL
Cybernetics
LANGUAGES
LANGUAGE
OF ANIMALS
LANGUAGE
ARTIFICIAL
Mg, Cu, N
H_2O
LANGUAGES
NATURAL
SIGNS
ARTIFICIAL
Fire
SYMPTOMS
Sickness
NON-LANGUAGE
Copies
The lesson begins
Signals
Applause
Symbols
Images

ready Aristotle and other Greek philosophers gave a thought to the gnostic value of signs. As man's experience extended and science thrusted deeper into the secrets of nature, regularities common to various sign systems became clearer. But primarily the ideas of semiotics won a place for themselves in the mathematical logic with its symbols and precise definitions. Here signs were more in evidence than in other branches of science. Achievements in this field are connected with the names of the German scientist G. Leibnitz and the English philosopher J. Locke.

Next linguistics fell prey to semiotic ideas. The need for communication between people leads to the establishment of a system of symbolic signs, maintains the French scientist F. de Saussure. He cited ceremonies, etiquette, war signals as examples.

Among all systems he attributed the major importance to the language.

The main principles of the science of semiotics were formulated by the American scientist Charles Peirce. In the thirties they were extended and developed by scientists from many countries belonging to many scientific schools. A leading place among them and the most important results belong to the Polish and Russian schools.

Didn't it appear to you that semiotics tries to grasp what's out of reach? That the field of interests which it is trying to "invade" is too wide? No, is the answer of the experts. Semiotics tries to tackle many fields of human knowledge but only from one point of view: different objects of research are studied unidirectionally, only from the point of view of their value as signs serving to express some context.

This is the reason for the exceptionally wide range of action of semiotics. To support this claim let's cite the proceedings of such an authoritative assembly as the first Soviet symposium on semiotics. It took place in December 1962 in Moscow.

The scientists considered from "the semiotics point of view" diverse problems, sometimes quite unexpected and strange for the layman.

Of course, much attention was paid to the natural language in its capacity as a sign system.

The description of etiquette is of interest from the point of view of semiotics. It turns out that fortune telling with the aid of playing cards presents attractions to semiotics, for the reason that "this relatively simple semiotic system can be of interest to general semiotics". Similarly, street traffic control "facilitates the establishment of certain regularities common to sign systems".

Climbing step by step the ladder of "establishing certain regularities", semiotics reaches the heights of quite "unearthly" subjects. It provided the specialists with an intricate tool enabling a language to be constructed for communication with civilizations of other planets. Yes, that's right. On the Earth a special language has been developed for the intercourse with our "brothers in intellect". Its author, the Dutch scientist Hans Freudenthal, has given it the name "lincos"—langua cosmica, the cosmic language.

◀ Classification of signs.

Lincos is based on the unity of the laws in the Universe, specifically, on the unity of mathematical laws. It's on the basis of these laws, which reflect the reality of the world, that Freudenthal builds his multi-stage lincos structure. This language has hierarchical organization, it contains an intricate system of relationships, complications, "advancement stages".

Obviously, appropriate means must be chosen for cosmic communications—a radio signal or a light pulse. To begin with, primary mathematical concepts should be coded with their aid: digits, equation signs, the essence of the binary system. Next a more advanced stage is reached: the exposition of the rules of arithmetic. Then comes the turn of algebra, and so on, up to higher mathematics. Finally, with the aid of abstract mathematics Freudenthal turns to evaluating human behaviour, starts telling the story about us, the inhabitants of the Earth, about our life, about the Earth—the home, where we were born.

You may accuse semiotics of being a purely theoretical science, for even the creation of lincos does not dispell this view. It's true, semiotics is a theoretical discipline, but it is still of some practical value. Think, for example, of the artificial sign systems—intermediary languages for cybernetic machines. Moreover, semiotics, together with psychology and physiology, studies the location of speech centres. The results of these studies proved to be of undeniable practical value: the achievements of several Soviet scientists aided in the construction of a special language for deaf persons. This is an example of help given to medicine.

Another example is from the field of pedagogics.

The pedagogues are paying an ever increasing attention to signs. This is not to be wondered at, since education entails, to a considerable degree, the mastery of signs.

And those who are not convinced by the examples should not forget that it's only recently that the marvellous faculties of semiotics began to be displayed. For this reason it's natural to expect from this science new discoveries and new successes in the future.

T

TEACHING MACHINE

A machine to teach people knowledge and skills.

An Automaton Decides upon a Mark

Belgian urchins wrote in the testimonial book of our pavilion at the Brussels World's Fair: "Please, build a machine which could help us not to study."

This wish will, certainly, never be fulfilled—no one's going to build a machine which would help not to study. But a machine which helps to study has been built.

Everybody has grown accustomed to the idea that whenever, wherever or whatever is being taught, the teaching is being done by man. Yet suddenly teaching has entered the realm of machines, and furthermore is being done perfectly well.

What does a teacher do during a lesson? He discusses a topic. To this end he chooses appropriate material and compiles questions. Subsequently he checks how the topic has been learned.

The process of education can be represented by a system of interaction between the teacher and the pupil. The result of the operation of the system should be the acquisition of knowledge by the pupil. This system, though it might appear to be quite simple at first glance, is a very complicated one. Direct coupling and feedback are established between the teacher and the pupil.

The direct coupling is represented by the channel through which the teacher transmits information over to you: lectures, laboratory work and practice.

The feedback is the route from the pupil to the teacher. It is necessary for self-control, to help the pupil understand how he succeeded in mastering the subject.

It so happens that the lesson, the common lesson at which you are present, is, as a rule, a process characterized by deficient feedback. The teacher sometimes doesn't know how his pupils are mastering the subject. And without this knowledge he cannot organize the educational process correctly, in accordance with the situation prevailing at the moment.

It has already been established by experts that for the educational process to be effective it should provide for every pupil, say, in the course of a native language lesson, to receive up to 100 reinforcing influences in the 20 minutes that the teacher explains his lesson.

In a class of 30 the number of such influences from the teacher would have to be equal to 3000 in the same 20 minutes. Thus, the teacher, like an automaton would have to exercise 150 reinforcing influences per minute. This is practically impossible.

What's to be done under the circumstances? The solution lies in the nature of the educational process. It is open to so-called programming, whereby an entire lesson or an appropriate paragraph from a textbook can be set out in detail together with precise instructions as to how and in what order the material is to be presented. Within such a detailed programme there is no difficulty in utilizing electronic computers to do the job of providing pupils with the information necessary to master certain subjects and asking them questions and assessing their knowledge on the spot.

To understand the principles of operation of educational machines let's see how the simplest of them work.

A tape with questions rotates in the machine together with blank paper for the answers. The pupil having answered a question must turn the handle. The answer moves under a transparent plate and can no longer be corrected. The correct answer, together with a new question, appears on the tape.

And now let's meet the electronic "Coach". It helps in the study of foreign languages. The pupil presses a button and a phrase in a foreign language appears on the screen. One word from the phrase has been omitted, and it has to be found and inserted into the phrase. If the pupil makes a mistake, the machine signals with a red lamp. This means that the button with the tempting word "Prompting" should be pressed. But don't place too much hope in it. You won't get a crib. Actually, what the machine does isn't straightforward prompting. You'll be asked a leading question to help you remember the material you have been studying.

A machine of the same type successfully teaches, independent of teachers, all the mathematical operations that can be executed with a slide rule.

The machines are provided with other buttons, as well. There may also be other luminous signs: "Correct", "You've made a mistake". If, for some reason, you have exceeded the time limit for the answer, the machine warns you politely "You think too long". The machine "educator" can mark the answer, measure the time spent on its preparation, consult the academic record card and in some cases ... send for a re-examination.

Isn't that a perfect examiner? There's a machine that can check 1025 examination papers, practically for all disciplines.

The number of machines used for education is continuously growing. Isolated experiments are making way for wide application of educational machines. For several years now programmed education has been practised at hundreds of colleges and vocational schools. Over 1000 schools have specially equipped classes. There is every reason to suppose that in the future such machines will be employed universally.

Well, and what's going to happen to the teacher, to the man who does the teaching now?

With the introduction of the most perfect automata his role will not abate, but, on the contrary, will grow in significance because of new duties. These duties will include the compilation of the programmes and their constant improvement. The teacher will, as before, play the most important part in the entire educational process, especially in fostering. And the machine will be his reliable educational assistant.

How does an educational machine operate?

The pupil receives a paper. It consists of the theoretical part, followed by two examples in the form of problems, one solved, and one to be solved. As soon as the pupil solves his problem he sets the number of his paper and the answer on the switchboard and presses the button. The machine instantly answers with a "right" or a "wrong". If the answer is correct, the pupil proceeds with the following paper. His task becomes more complicated with each successive paper. No paper can be learned unless all the preceding papers have been studied.

See how many connections there are inside an educational machine?

They all terminate in the control block. As soon as the pupil "introduces" his answer it is at once "attacked" by several devices of the educational machine. The comparison block compares the answer with the correct answer recorded in the "memory". If the answer is correct, a signal is sent to the assessment block. If it is wrong, a signal is sent to the block which analyses wrong answers. The information output block will function only after the machine has thoroughly studied your answer. This is a strict and exacting "teacher".

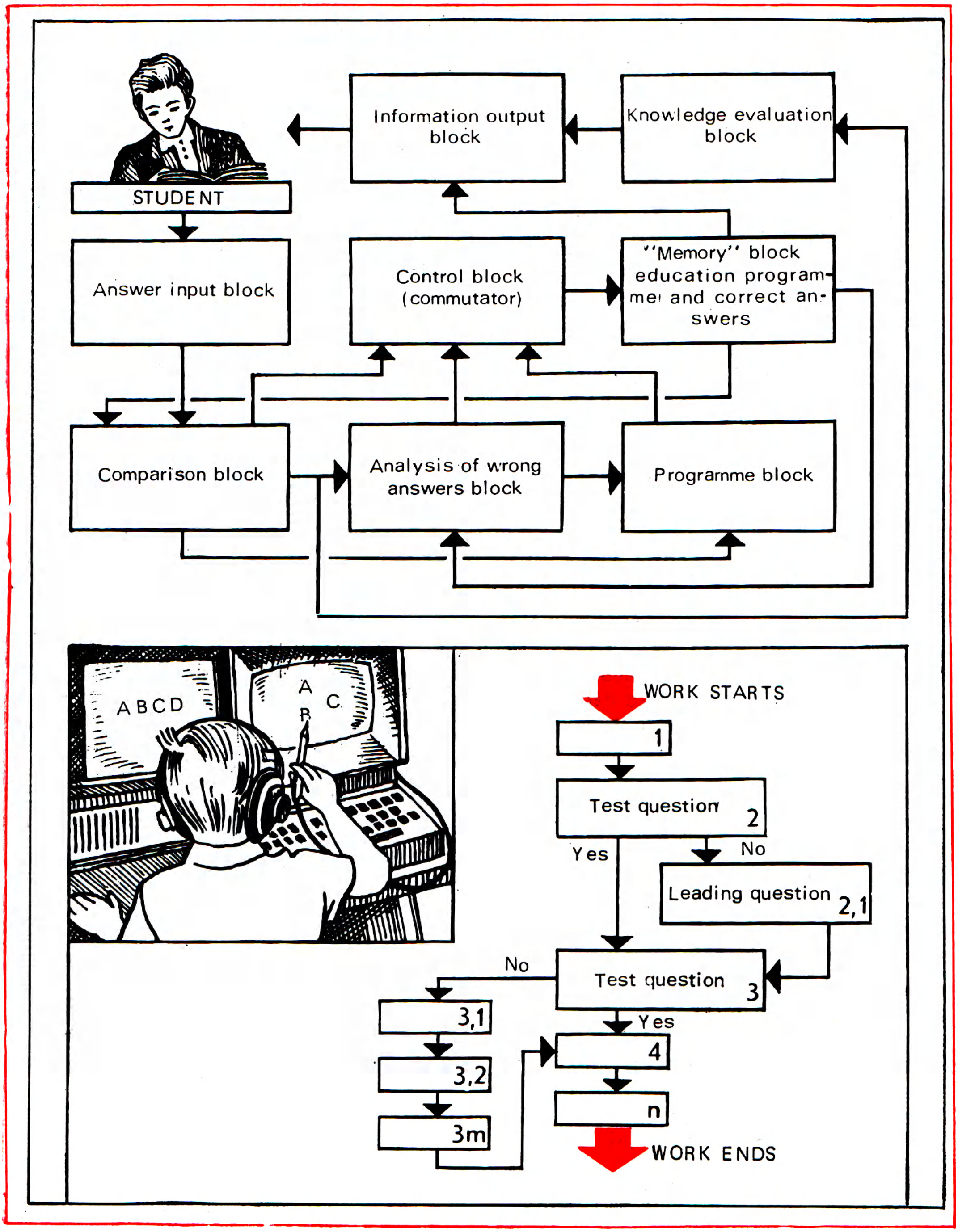
Not one but several hundred types of teaching machines have already been built, some simple, others complex, among them midget "examiner-teachers" the size of a cigarette case and large machines occupying whole rooms. The teaching machines are subdivided into groups in accordance with their purpose.

The first group is made up of simple mechanized devices.

The second group embraces training machines.

The third—testing and teaching machines. Among this group the majority is made up of examining machines used to test the knowledge of the students. The most widely used is "The Swallow".

As a rule, their names speak for themselves: "The Lecturer", "The Consultant", "The Trainer", "The Coach",


STUDENT
Information output block
Knowledge evaluation block
Answer input block
Control block (commutator)
''Memory'' block education programme and correct answers
Comparison block
Analysis of wrong answers block
Programme block
A B C D
A B C
WORK STARTS
1
Test question 2
Yes
No
Leading question 2,1
Test question 3
No
Yes
3,1
3,2
3m
4
n
WORK ENDS

"The Tester", "The Examiner". There are universal "machine educators", as well: they test, consult and examine.

The fourth group of educational devices is the most complicated of them all. It consists of classes for programmed education.

Let's learn about one of them, "The Accord". It has nothing to do with music. The name is made up of initial letters of its Russian designation meaning an "automated class for controlled education with ramified dosage". Let's enter it.

There are thirty tables. On each table there is a small control panel with lamps and levers. The big control panel of the teacher is connected to the small panels.

Every student has a chapter from the "educational programme" in front of him which he must learn. The chapter ends with questions. When the student thinks he has learned his lesson he operates an appropriate switch.

If the answer is correct, the signal "continue" will light up, if not—"repeat".

Now, note the following. There are, as usual, thirty students to a class, and there is, as before, one teacher to teach them. The educational process is, no doubt, collective: and, at the same time, individual. Here the students are not "reduced to the average".

There is a single programme, but everyone can learn it in his own way adapting it to suit his nature. A capable student will make quick work of the material and proceed further. The weak student, on the other hand, will be able to work slowly, not getting nervous and not trying his utmost to catch up with the class. In this way the principal doctrine of the old "unprogrammed" educational theory, that had been very difficult to put into practice, is realized: the doctrine of individual approach to every student.

Programmed education that will have to absorb the best achievements of our educational system will not only make life easier for the student, but for the teacher-programmist, as well. The teacher-programmist will be able to transmit the knowledge of his subject to any group of students irrespective of their level of knowledge and of intellectual development. By placing accent on individual work the teacher makes every student not only study, but learn, as well.

Much has been done in this country to develop the new educational method.

Special educational programmes are being compiled, the efficiency of various methods of programming is being studied, models of the educational process based on the theory of probability and methods of controlling this process are being designed, the search is on for a universal educational algorithm (i.e. rules).

However, scientists and educationalists endeavour to look farther ahead. They would like to build educational complexes and compile educational programmes that would take into account the individual propensi-

◀ **A block diagram of the educational machine "The Coach" and the route of education process from the start to the end of its work.**

ties of students as well. The new methods are being applied in specialized education: in sports, in music, in medicine.

To teach the blind and deaf a method of reading hand-written texts as they are written is being developed and tested experimentally. Such a machine will be able to correct dictations as they are written.

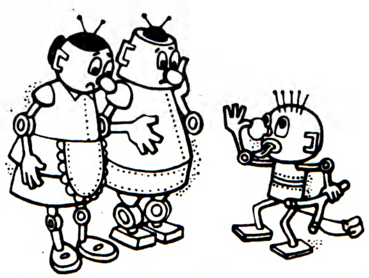
A design of a machine capable of talking and understanding human language has been developed. Such a machine will be able to teach hundreds, and in the foreseeable future thousands, of students. To teach various subjects and with an individual programme for every student. The machine will read what the student has written, hear him speak, in short will react to everything the student does in the process of education, and this without any control panels, levers or push-buttons!

The problem of employing big electronic computers in mass education is being considered, too.

Even the use of electronic teaching machines in flats is envisaged. They will be connected to the state educational machine network. In fact, two or three electronic machines can almost simultaneously provide educational information for hundreds, or even thousands, of consumers. This will enable permanent controlled education to be conducted from class work to home work. This may be supplemented by an educational television network.

Recently Soviet scientist O. Belotserkovsky read before an international conference an interesting paper with the title "The Effect of Space Research on the Development of General and Specialized Education". The paper dealt with the employment of communications satellites equipped with transmitters to transmit educational radio-television programmes to wide expanses of the Earth.

The scientist envisages the time when powerful television transmitters of the Earth's satellites "hanging stationary" at a height of over 30 thousand kilometres will start a new school year in the vast school, the desks of which will be strewn over not only towns and villages, but over the boundless expanses of jungle and plateau, over islands lost in the ocean and over the oases of the deserts. In this way a wide coverage of various sections of the world's population from the little ones to the grown-ups could be achieved. This, too, would, of course, increase the efficiency of education.



"Didn't I say the street will spoil him."

Translation from one language natural or artificial) into another language (natural or artificial) with the aid of electronic computers.

"The Horse [Called] Charley"

On January 7, 1954 in New York the first public demonstration of an electronic computer in its novel quality—that of a translator—took place. The computer translated Russian phrases into English. In all, 60 sentences were translated.

The computer translated. It did the job like a man ignorant of the language: with the aid of a dictionary. Man finds unambiguous words and arranges them into a sentence according to the rules of grammar. Needless to say, such a translation is far from perfect, yet, it caused great difficulties to the computer. The first difficulty can be defined as technical. Judge for yourselves: the special programme containing rules for the translation consisted of 2500 instructions, which is much more than for solving complex mathematical problems.

There was, too, another side to the technical difficulty. The computer could read 1 800 000 letters per minute, but to provide it with a corresponding number of punch-cards 12 thousand typists working at a speed of 10 thousand signs per hour would be needed. Even if magnetic tape was used instead of the punch-cards, this would require a huge number of dictators. Moreover, it would take, literally, an army of editors to read and edit the text.

Aren't those difficulties formidable? You bet! Yet, those are not the most serious. The main difficulty lies in the large volume of the vocabularies of modern languages. This leads to inaccuracies in translations from one language into another. An elucidating experiment of French linguists, who tried to assess the degree of precision attainable in translation from one language into another, brought the result that reminds one of the faulty telephone game. Fourteen experienced translators took their seats at a round table so that each knew the language of his right neighbour. The first translator—a German—wrote on a piece of paper: "The art of brewing is as old as the history of mankind", and handed the piece to his left neighbour. The latter translated the text from the German into his native Spanish, wrote it down and in his turn handed it over to his left neighbour. The sentence went on its way round the table, everybody translating it into his native language. At last it returned to the German in Hungarian. He translated it and read with surprise: "From ancient times beer has been the favourite drink of mankind."

Idioms present great obstacles to computers. The English words "charley horse" the computer will translate as "horse [called] Charley", when actually it means a "cramp in the calf of a leg". "Foolproof"—"proof against adverse influences"—translated literally means "proof against fools".

The French phrase "absorption comfortable des vibrations"—"a comfortable absorption of vibrations"—really means "the attenuation of vibrations to achieve a comfortable ride". "Dos d'ânes"—"elevated road irregularities"—is literally translated as "donkey backs". "Coups de roquettes"—"vibrations in the vertical plane"—means literally "rocket firings".

If the computer stumbles over phrases, what will it do with a text like the end of N. Gogol's story "The Nose"? "But, however, everything considered, though this, and that, and the other can, of course, be assumed, perhaps, even ... well then, can inconsistencies be avoided anywhere? Still, however, to meditate upon it, there is really something in it all. No matter who would say, and what he would say to the contrary, such happenings do come about in the world: rarely, but, still, they do."

It's too early yet for computers to take on sophisticated texts. What a lot of mistakes they make even with the simplest translations! Once computer mistook "one" for "two". And, instead of "two" gave out "ones". The electronic computer has made a mistake that would make even a mediocre pupil blush. In the course of a grammatical analysis of the sentence "The general's daughter was reading a book" the computer classified the word "general's" as a verb, not forgetting to mention its tense. The incident occurred because the computer "saw" a widespread verb ending in the combination of sounds which made up the noun.

An interesting incident occurred when a computer was translating an article from the English newspaper *The Times* dealing with computorized translation. The computer came upon the words "the iron curtain". It "stopped to think", and then having omitted this incomprehensible term went on with the translation.

Here's another incident. An American computer, while translating the title of the paper by the Academician S. Vernov "To Know the Secrets of Outer Space" has distorted it beyond recognition: "Let's Open the Secret Outer Space."

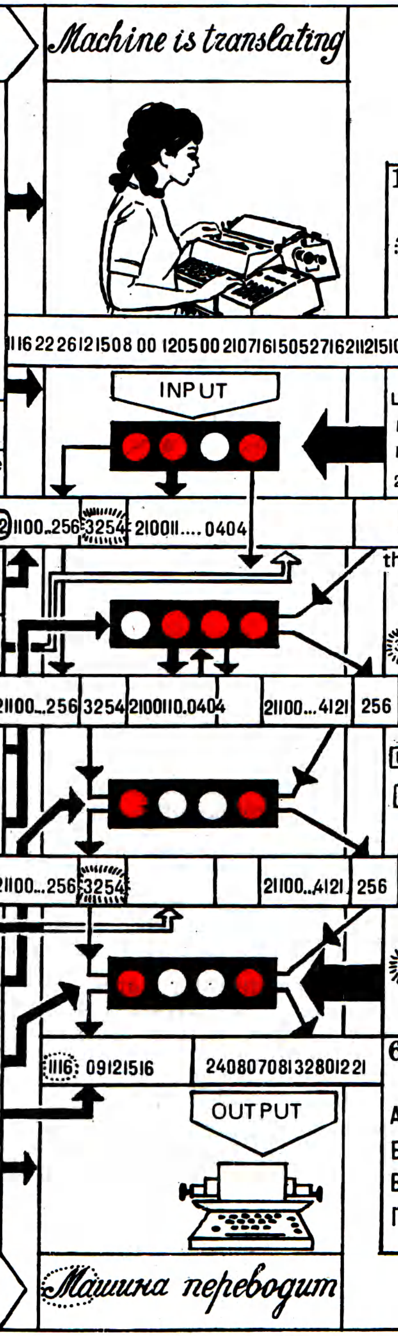
And still the computer translates. Let's see how it is being done.

Let's follow the stages of computer translation. To begin with, a reel is inserted into the computer with tape carrying the English text. The inscription is, however, not in signs but in perforations, as in punch-cards. This is the code of the text being translated. Placed next to this reel is a reel with narrow magnetic tape carrying the computer programme for translation operation. The computer "memory" stores in its cells Russian words arranged in strict order next to corresponding English words.

The computer translator, like man, makes use of the dictionary. The only difference is that in its dictionary words are "written" not in signs but in digits. The English "a" became 16, "b"—06, "w"—13, "m"—11, "n"—15, "x"—09, etc. Russian letters, too, became numbers: "а"—16, "б"—06, "в"—13, "м"—11, "н"—15, etc.

The technology of computer translation. ▶

THE ENGLISH TEXT IS GIVEN



The operator at the letter keyboard automatically substitutes numbers for letters (see Table 1), for instance A–16, M–11

Punched tape with numbers is fed into the computer

Translation programme is switched on

Subtract the codes of the words of the left column of the dictionary from the codes of the words, in turn, until the remainder is 0. When this is done, put the code of the right column (for its meaning see Table 3) in place of the word in the memory device

WARNING! The third word hasn't been found in the dictionary

Check the word using Table 4. Does it end on "s"? No! Does it end on "e"? No! Does it end on "ing"? Yes! Delete the ending and look up the dictionary again. Is there an "e"? Yes. Is there an "is" in front? Yes.

It's clear: this is a verb in the present continuous tense. It is translated as present. The verb "is" is not translated (there is nothing in its place)

Arrange the words according to the right-column codes in compliance with the rules of the Russian language

Subtract "Russian" word numbers in turn from the left-column codes of the dictionary 5 until the remainder is 0.

When this is done, place the right-column code (for its meaning see Table 6) in the memory device

The codes are transmitted to the automatic printer which prints the Rissian text

RUSSIAN TEXT

1 Table of English letter codes

A - 16	M - 11	U - 20
B - 06	N - 15	V - 29
C - 22	O - 20	W - 12

2 The English part of the dictionary

Left column	Right column
1622612 1508 - 121100	2563254
1205	2100110 .... 0404...
2107161508 27162108	21100...4121256

3 The meaning of the right-column codes

1 Nouns

2 Feminine gender ....

3254 Number in the Russian part of the dictionary

4 The diagram of the stages of checking the unidentified word

Dictionary → no → "S n" endings → no → "s" → "ing"; yes → delete "s"; yes → delete "ing"

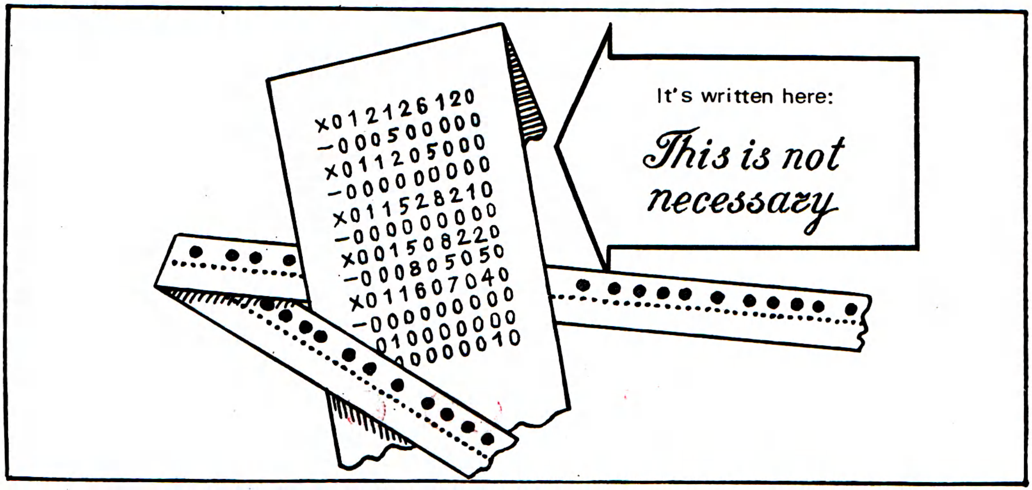
5 The Russian part of the dictionary

3254 — 1116 09121516

256 — 24080708132830 12

6 Table of Russian letter codes

А - 16	И - 12	О - 28
Б - 05	К - 19	П - 24
В - 13	Л - 27	Р - 07
Г - 10	М - 11	С - 05



These pieces of tape have been taken out of the computer after translation. Here is the literal translation: "Это не необходимо."

The translation starts with the computer searching in the dictionary for the words recorded on the tape. The computer has found a word. Hasn't it made a mistake? How could this be checked? The arithmetical device will subtract from every word-number found in the dictionary the word-number recorded on the punch-tape. If the remainder is zero, the word has been found correctly. Such comparison takes about one ten thousandth of a second. The computer can look through a dictionary of a thousand words in less than a second.

Next the computer turns its attention to the index number of the English word found in the dictionary. The corresponding Russian word bears the same number in the dictionary. And this word, too, is written in digits. If we now translate these numbers into corresponding Russian letters, we will get the Russian word—a translation of the English word introduced into the computer. The words have been translated, but the computer cannot, as yet, construct a Russian phrase. First it has to analyse the grammatical form of the English and the Russian words: the gender, the number, the case, the declination, etc. In the computer these characteristics, too, have the appearance of numbers and are stored in the "memory". Word parts such as suffixes, endings, prepositions and articles of the English words have been translated into the language of the so-called digital information that is acceptable to the computer.

Only now does the computer start analysing the English phrase as a whole. Subsequently it constructs the Russian phrase. This is done on the basis of the translation programme which contains the paragraphs: "verbs", "nouns", "adjectives", "numerals", "syntax", "changes in the word order". The computer constructs the Russian phrases from the words translated from the English in compliance with the rules of the Russian grammar.

The computer translator, as you already know, has made its appearance in 1954. Up to 1958 there were only three electronic computers adapted for translation of technical texts in the whole world: the Soviet, the American and the English. The most advanced—the Soviet—had a word reserve of 952 English and 1973 Russian words.

Here's an example of translation made by the computer in the form it was produced without editing:

When a practival problem in science and technology formulation, the chances are rathner goud *that* it leads to one on more differencial equations. This is true certenly of the vast category of problems associated with force and motion, so that whether we want to know the heavens or the path of an electron in an electron microscope we resopt to differencial equations...

Если практическая задача в науке или технике допускает математическую формулировку, шансы довольно велики, что это приводит к одному или более дифференциальным уравнениям. Это верно безусловно для обширной категории задач, связанных с силой или движением, так что, хотим ли мы знать будущий путь Юпитера в небесах или путь электрона в электронном микроскопе, мы прибегаем к дифференциальным уравнениям...

Later another Soviet electronic computer, "The Arrow", made a translation from the French into the Russian. Seventeen programmes containing 8500 instructions were compiled for this purpose. The computer translated the text by separate phrases. Even for a phrase of from 8 to 10 words the computer had to make 45-50 thousand cycles. True, this took only 20-25 seconds.

Recently a specialized English journal carried an article on computers that have from 1963 onwards been translating into English Russian technical texts in the field of aviation at a rate of 100 thousand words per day. Presently translation speeds of up to a million words per day have been achieved. All this suggests that computer translation will in due time, probably, become practical.

Intertreter: "He transmits Martian greetings!"

U

UNIVERSAL ELECTRONIC DIGITAL COMPUTER

A computer
based on electronic devices
and controlled by programmes.
It is capable of performing
a definite number of operations
per unit time with quantities
expressed in numbers.

Calculation with Lightning Speed

Most of you can't, presumably, even imagine what myriads of numbers surround the modern man. It wouldn't be an exaggeration to compare the number of arithmetic operations performed per month all over the world with the number of drops contained in the sea or stars in the Galaxy.

A hundred years ago relatively small groups of people handled all the calculations. Nowadays all sorts of professions—scientists, designers and engineers—are engaged in calculations, not to speak of accountants, bookkeepers and cashiers, who spend their whole lives struggling with numbers. Incidentally, nearly all calculations are made with the aid of various calculating machines. Without such machines, using only paper and pencil, one half of the population of the world couldn't perform all the calculations needed for the other half employed in productive work.

Without calculating machines normal life of modern society and continued progress in science and technology would be impossible.

But even with the aid of mechanical, non-electronic calculating machines people nowadays are no longer able to deal with extremely complicated problems posed by modern life.

This led to the appearance some twenty years ago in several countries of electronic computers which took over the struggle against numbers.

Having focused in itself the achievements of physics, radio-electronics and production technology of electronic and magnetic elements, the electronic computer became the most powerful and the most flexible calculating instrument ever to be built by man. A high-speed computer can perform over a million operations per second.

Calculations made with lightning speed. Yes, that's right, electronic computers do deal instantly with a flood of numbers. In one second the computer performs many times the number of operations performed by an experienced calculator with an arithmometer in eight hours. In the time of several hours the computer makes as many calculations as a good mathematician is unable to make in his lifetime.

Unbelievably high speed of count is only one of the extraordinary properties of the marvellous machine, which can extract roots, integrate and solve the simplest algebraic equations as well as most complex differential equations.

Now the electronic automaton can cope with everything. The machine successfully enters fields which until quite recently were considered to be the exclusive privilege of man. Machine tools, shops and factories are controlled by computers. Computer control of production processes appreciably increases the productivity of labour and makes work easier for the worker.

And the control of factory economics? The computer "economist" took over from man many functions of planning and analysing various economic parameters. Here, too, advantages are obvious: the control becomes more operative, the number of people employed in the control sphere decreases.

The fields of application of the electronic computer are much wider. There are computers that do the work of designers, translators, teachers, meteorologists. How do these electronic craftsmen work? The chapters of our encyclopaedia tell you about it, as well as about the principle of operation of the electronic digital computer.

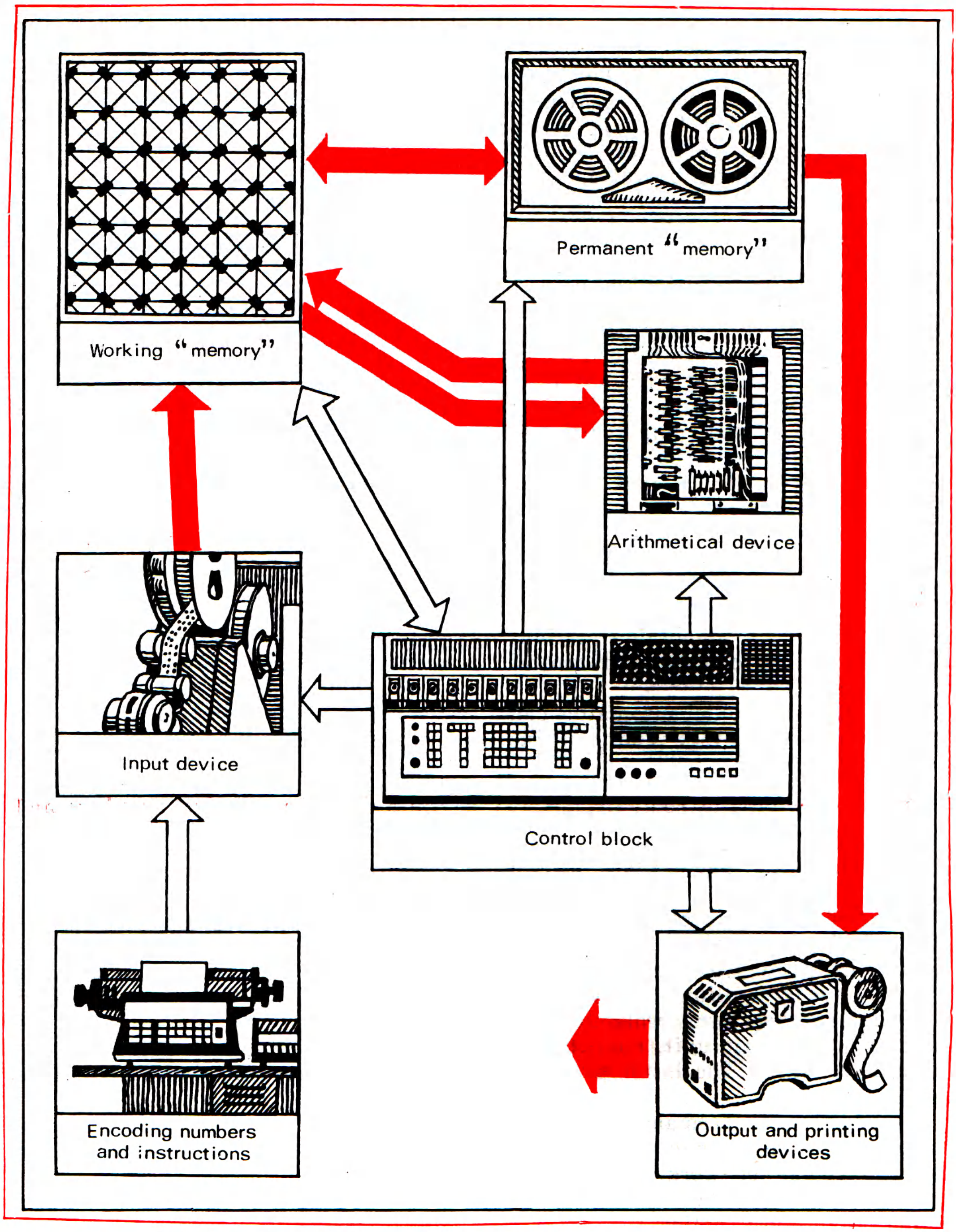
Numbers enter the computer by way of the coding device. Here numbers and instructions undergo transformations and assume the form suitable for computer operations. Next they are fed into the input device and into the working memory store.

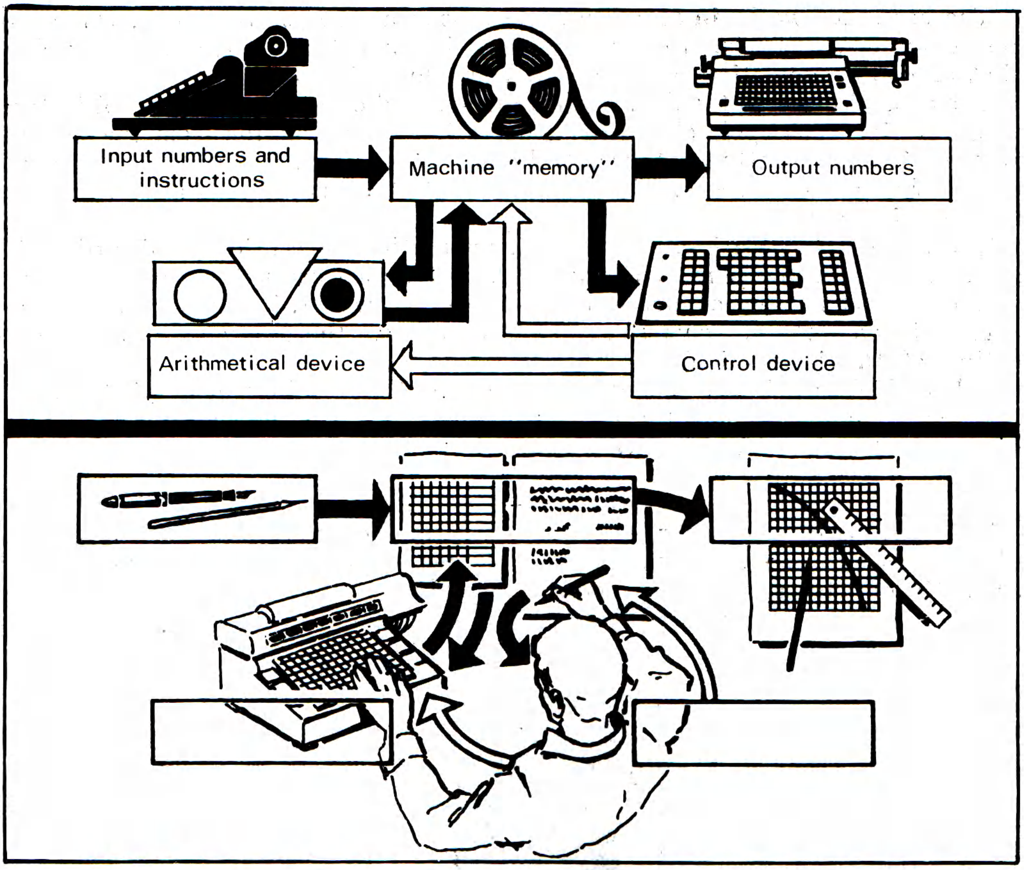
Some of the numbers remain here for the time being inactive. For the others the working store plays the part of a transit station. Through it some numbers reach the permanent "memory", a sort of computer's "notebook". Numbers are stored here by millions, the time of storage being unlimited.

Other numbers are needed for immediate processing. They are instantly fed into the arithmetic unit, consisting of adders, multiplication, division and subtraction circuits. The latter perform all arithmetical operations with the aid of addition.

In addition to permanent, long-time "memory" the electronic computer possesses a working "memory" as well. This is needed to record data frequently used in the course of work.

The capacity of the working "memory" is not large, but it hands out numbers quickly at short notice.


Working "memory"
Permanent "memory"
Arithmetical device
Input device
Control block
Encoding numbers and instructions
Output and printing devices



Man and machine carry out calculations in almost the same manner. The arrows show the paths of control signals.

The ultimate results of the calculations—the finished product of the computer—enter the output block and are typed on paper tape or on blanks of a specified form.

The arrows in the drawing show the general path of numbers and instructions in the computer. Red arrows indicate the path of numbers, white—the path of instructions.

If we looked, from a great height, at thousands of trains running in different directions along steel tracks we would perceive a similar picture. The motion of the trains, disorderly at first glance, is governed by a single plan, a single timetable.

◀ Block-diagram of a high-speed electronic computer. Red arrows denote the routes of digits, white ones—the routes of instructions.

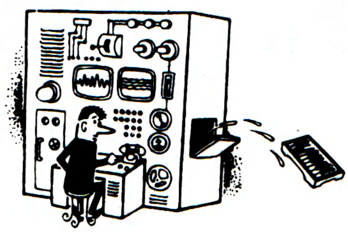
The computer works in separate cycles. Look at the control block. Out of all the computer parts it is, of course, the most important, for it is due to this block that automatic operation of the calculating blocks is possible.

The control block in the drawing has ingoing and outgoing blue lines of instructions. During each cycle of computer operation an instruction from the working "memory" is transmitted to the control block. It is recorded here and carried out during the next cycle. A special counter counts the instructions after they have been carried out.

The process is repetitive: choice of an instruction—execution; choice of an instruction—execution. The execution of the prescribed computer programme consists of a great number of such repetitions, each of which, in short, makes up one automatic cycle (1—the choice of an instruction from the programme, 2—the execution of the instruction).

All the highways in the computer pass through the working "memory" store. This is understandable, for it is the receiver of the calculating process programme fed from punch-tape or punch-cards.

The working of a universal electronic computer is, of course, much more sophisticated than has been shown here. However, now you have some idea of the basic principles involved.



V

VIDEO DISPLAY

Devices
used with the computer
for the input of data
presented in visual form
and the output
of data in visual form.

Open, Sesame!

Before we begin the story of the brand-new methods of effecting the output of information from electronic computers the reader should be made familiar with the problem of introducing data into the computer. The processes are closely interrelated.

Many machine-tool designers are confronted with the problems of effecting input to the machine: how best to feed workpieces or raw materials. And for the designers of electronic computers this problem assumes great proportions.

A computer may be utilized only if it is able to exchange information with man, with the outside world. Until the electronic computer receives input data and a programme of operations it remains speechless and thoughtless. Hence, to start working in collaboration with the computer man must provide an entry to it and must make himself understood. This is no easy task and it is made no easier by comparisons involving the opening of the door of a furnace to throw coal into it or the filling of a mill with grain to be milled by mill stones into flour.

The computer input, as we have said before, serves to enable man to cooperate with the computer and thus to make the work of both man and computer efficient. It may be said simply that in each approach to the computer man poses problems for the computer to answer. It is, however, a fact that man and computer speak different languages. Therefore, before you fill the computer with "grain", you must make it "understand" what sort of grain it is. And, secondly, it should know what to do with it.

When man begins working with the machine he provides initial data in the form wholesome for the machine and instructs the machine to carry out specific actions. The machine reads the data, processes them, records the results obtained and transmits them to man in a form understandable to him.

Previously man transmitted the information to computers with the aid of keyboard devices, this is still being done. The underlying principle has long been used in printing for setting the types of newspapers, magazines and books.

Imagine a standard printing machine which transforms symbols shown on the keyboard into a definite sequence of pulses and intervals between them. You press one key after another, and pulses corresponding to the information enter the machine.

But you won't be quick in introducing a mass of data into the computer manually, "by the fingertips". Even a typist of the highest grade cannot type more than six signs per second. The electronic computer, on the other hand, handles several million bits per second.

To make this discrepancy more evident imagine the operating speed of the computer to be a million times less. Our slow computer will operate at speeds convenient to man—one operation per second. The corresponding speed of the keyboard printing device will in this case amount to one sign per day!

The operator awaiting an answer from the computer could in these circumstances be compared to a man receiving a telegram at a rate of one letter-sign per day. Naturally, such speeds of information output are unacceptable.

What's the solution to this problem? How could the disparity between the capabilities of man and computer speed be avoided?

Special high-speed input-output complexes have been designed for computers. Usually, they consist of punch-card reading devices, several magnetic-tape data accumulators, a teletype and a high-speed printing device.

As you know, the punch-card reading device introduces into the computer information contained in perforations of the punch cards. The magnetic-tape memory devices—accumulators—enable the intermediate results of computer operations to be stored. They can also serve as longtime information store. The teletype is used for short messages, for instance to transmit an instruction to the operator to install a definite magnetic-tape bobbin. The operator, too, uses the teletype to send a signal to begin calculations. The printing device is used for the output of the results.

Modern input-output devices operate at the highest possible speeds. They "swallow up" some 1000 punch cards per minute and hand out data quicker than man can read them.

And even the teletype, this apparently most sluggish block of the computer, types much quicker and much more accurately than a qualified typist.

However, even these high-speed implements do not enable the possibilities of the reading devices of modern computers to be fully utilized.

Suppose you would like to feed into the computer not numbers or letters, but prints, diagrams, graphs, drawings? What would you do?

Previously, the user of the computer recoded all the graphical information into numerical coordinates himself and only then transmitted them to the computer. Now the computer has been taught to accept and hand out graphical information in the form to which man is accustomed. This substantially speeded up the "exchange processes" between man and machine. Formerly it took fifteen minutes for a teletype to print the coordinates of a thousand points of a straight line. The screen of a video display depicts a straight line in a millisecond, or two!

Visual images are introduced into the computer with the aid of a combination of photocells and an electron-beam tube. Each photocell is so arranged as to receive light only from a definite point of the screen. The computer identifies the image displayed on the screen by the pattern of signals from the photocells.

A combination of a pen and a photocell enabled the so-called "luminous pen" to be designed. This is a small hollow cylinder housing a photocell. This pen is used for the input of drawings, prints, diagrams drawn by hand on a screen resembling the screen of a television set.

Some 50 years ago the electron-beam tube was a rarity. Now it's a permanent resident of practically every home in town and country. The tubes live in our television sets, and it's their screens we watch.

Of course, the sphere of application of the electron-beam tube is not limited to domestic use, its range of action is exceptionally wide and manifold. Suffice it to name, besides television sets, measuring instruments, radar, computers, radio, automatics, X-ray instruments, electron microscopy—this "electron device utilizing one or several electron beams" works everywhere.

Nowadays there is a whole family of electron-beam tubes, consisting of near as well as distant relatives.

Let's trace the line of kinship of interest to us in this family.

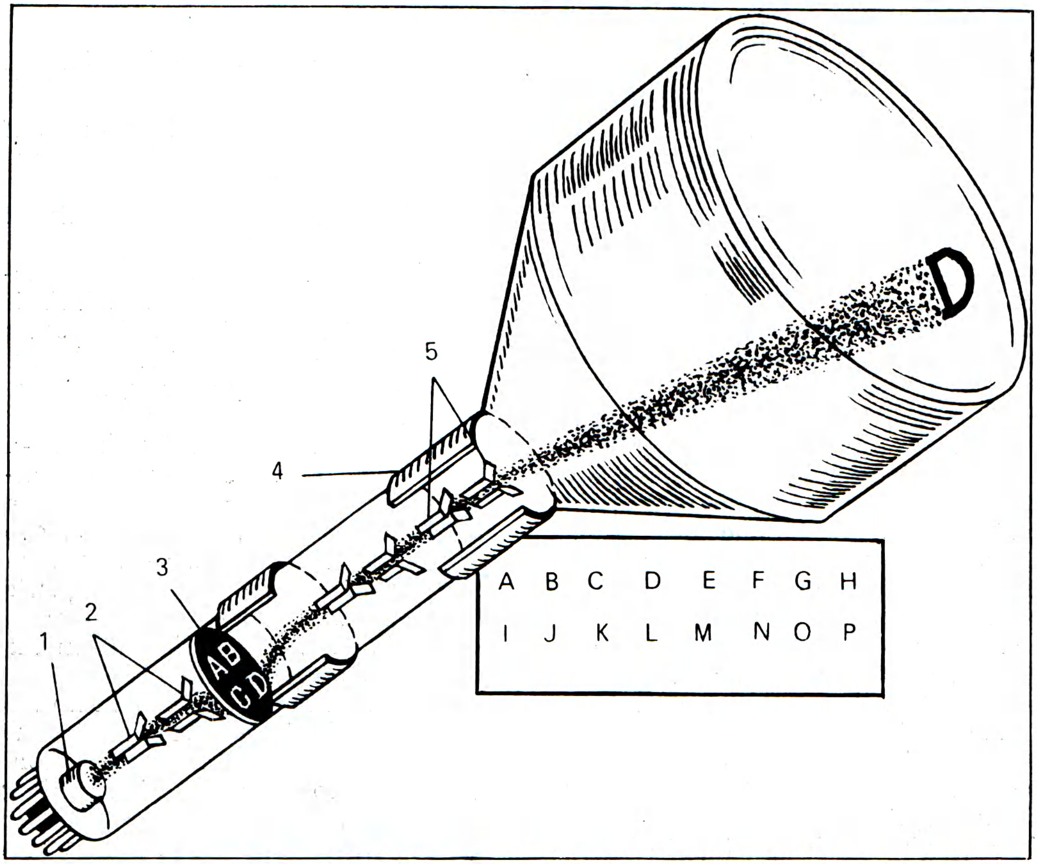
Take the familiar electron-beam tube of the television receiver. This is a tube that draws pictures. The other name for it is the kinescope. It builds up an image by varying the electron beam.

If a highly focused electron beam—a beam incident in one point—is directed onto a screen covered with a luminous compound and made to move across the surface of the screen with the aid of an electric or magnetic field, this will make an oscillograph. It has found wide application in the technique of measurements.

And now we'll try to build into the tube several plates, standing in the way of the electron beam, and connect them to a system of signalling or control.

Next we'll make the beam run in several directions: from the cathode to different plates, whereby the electrical circuit between them will be alternately connected and disconnected. This will make a quite different electronic device—the electron-beam commutator.

Now let's place another obstacle in the way of the electron beam: a plate with letters inscribed on it, the letters being impervious to electrons. This time we again have a new device—an electron-beam writing tube. This is the tube that bears the name of charactron, the luminous pen.



Charactron—the luminous "fountain pen".
1—cathode and focusing cylinder
2—choosing plates
3—code matrix
4—addressing deflection plates
5—card-forming plates

Since our interest is focused on the charactron, let's get down to detail.

In the charactron a metal plate (called the matrix) with a set of letters, numbers or any other signs (called the stencils) is placed in the way of the electron beam. To be able to record the signs-stencils on its screen the tube must also contain some other important parts—systems for the formation, collimation and deflection of the electron beam. In the charactron those systems are: the electron projector ("the electron source"), the system for the selection of signs on the matrix, and the address system.

The projector reflects on the cathode the image of all the signs contained in the matrix. However, not all the signs are needed at the same time. So the selection system goes into operation. It selects the appropriate stencil and takes it through the diaphragm.

However, having passed through the diaphragm the sign without the aid of the address system would "hang in the air", would not be able to find its place on the screen. The address system, so to speak, "takes the sign by the hand" and leads it to the place reserved for it on the screen.

After that the image on the screen disappears, and a new inscription appears. It is, however, possible to make the image stay on the screen for some time; in this case it is possible to read it or photograph it with the aid of a high-speed camera. Here all depends on the designation of the charactron. The time within which the signs disappear—the scientists call it the time of residual illumination—may be short—some 10-20 microseconds (μs) or long—5-10 s.

The signs on the charactron are usually quite small—2-5 mm. But when the need arises they can be enlarged. To this end some devices are equipped with a special electron lense, which with the aid of the electric field can enlarge the signs.

The screen of the electron recording tube is generally large, its diagonal being from 15 to 75 cm long. The density of signs on the surface of the screen is fairly high—the screen accommodates up to 16 thousand letters or numbers. The writing speed of the "luminous pen" reaches 4 thousand signs per second.

The charactrons are widely used in electronic computers, mainly for data output. It's very convenient to obtain the results of the "computer's labours" quickly and in a visible form. Such a charactron does the work of an output printing device. Its data selection speed of 25 thousand signs per second (for information in the form of letters or numbers) is a convincing proof of its quality.

"What's the good of it?" you would ask.

In less than a wink all those 25 thousand signs will disappear to make place for the next 25 thousand. And so every second. What's to be done with them? That's easy—you just have to resort to a high-speed cinecamera. It will photograph the image displayed on a film and thus "preserve" it. These "information preserves"—letters and numbers—can be stored during the time needed to process all the data received.

The use of advanced electronic input and output in place of electromechanical devices for the communications between man and machine brought about a thousand-fold increase in computer input speeds. Now it has become possible to erase immediately, as one would wipe off a speck of dust, an unneeded record or an error, to introduce easily and quickly the necessary data corrections. The "luminous pen" may even be used to control the computer: to this end the word or code of an instruction or an appropriate image should be written on the screen.

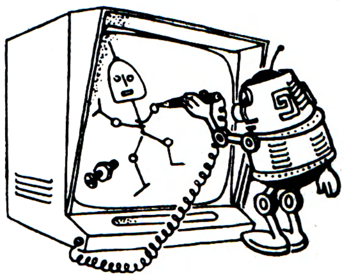
The new devices possess all the advantages: they are fast, noiseless, reliable, universal, provide for an instant, direct and complete access to information stored in the computer.

The operations may be conducted on a real time scale: the computer need not wait for man, and man need not wait for the computer.

The charactron is also used in some control systems. In these cases it is usually connected to a kinescope.

In such a charactron-kinescope system the kinescope screen produces the image of the object, and the charactron screen the "substantialized" signs in the form of cards. These serve as a kind of notes. For example, while the kinescope screen shows some object, the charactron screen shows its card with the symbolic number, type and the nomenclature of the group to which it belongs.

The charactron was developed in 1941. In electronic computers it was employed later—in 1953—after many improvements were made. It won acceptance because of its positive qualities, valuable "traits of character", among which the specialists unanimously acclaim the excellent image quality, the visibility of information, the high speed of data selection. It is these qualities that make charactron one of the principal means of "information representation".



W

Only Dots in Every Line ....

WORD

A set of symbols designed to represent parts of a message transmitted through communications channels.

There's a game called "Hot-Cold". In this game all the words, all the commands boil down just to two symbols. When you go away from the object of your search, it's "cold", when you come nearer, it's "hot".

Guided by these symbolic signs people taking part in the game sometimes solve rather intricate search problems.

Couldn't a text be coded with two symbols?

Here's a line of symbols—only dots and dashes. What do they stand for?

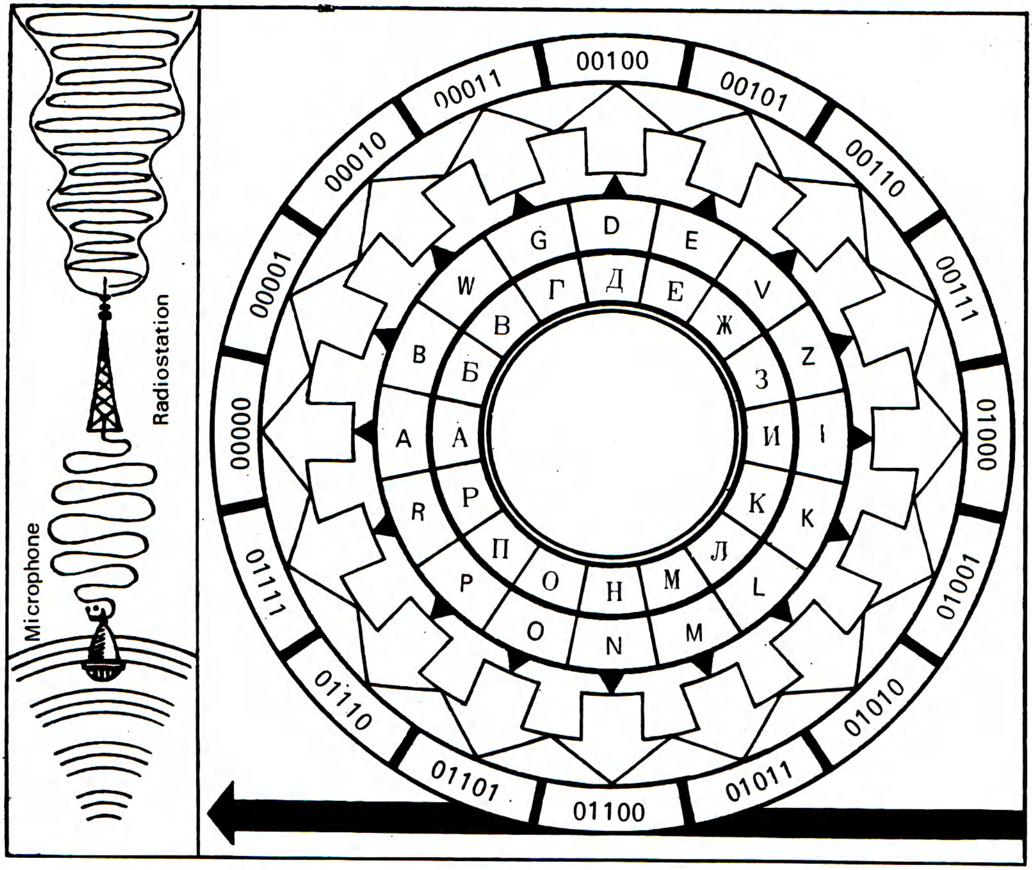
. .—.. . —.—. — .—. ——— —.

If you know the Morse code, you'll read the word "electron". It follows that various combinations of two signs enabled the whole of the ABC to be coded. Actually, in the Morse code there are three signs, the interval (absence of a sign) being the third, but the same is true of a two-sign code.

If you studied the Morse code carefully you would have noticed that some letters are represented by one or two signs: A—dot and dash, I—two dots, N—dash and dot, others by three or even four: O—three dashes, S—three dots, B—dash and three dots, J— dot and three dashes.

Let's try to find out how many signs should there be in a code group so that all letters could be designated by the same number of zeros and unities. To begin with let's take only two signs, 0 and 1. We obtain:

A=00 C=10
B=01 D=11



See how one and the same letter can be coded with different symbols.

This is the limit, and it can't be helped: $2^2=4$.

Now, let's try with three signs:

A=000	E=100
B=001	F=101
C=010	G=110
D=011	H=111

This is again the limit: $2^3=8$.

If we add one more sign, we'll get $2^4=16$. Sixteen combinations isn't enough for our ABC.

Five signs give us enough combinations: $2^5=32$.

Here's an example of such a code:

A=00000	I=01000
B=00001	J=01001
C=00010	K=01010
D=00011	L=01011
E=00100	M=01100
F=00101	N=01101
G=00110	O=01110
H=00111	P=01111

Q=10000	V=10101
R=10001	W=10110
S=10010	X=10111
T=10011	Y=11000
U=10100	Z=11001

Let's count now the number of signs in a code group which would enable all digits from 0 to 9 to be represented by an equal number of zeros and unities. Here, too, two or even three signs is not enough, but four is: they give us 16 combinations, while we need only 10.

Here's how the coded digits look:

0=0000	5=0101
1=0001	6=0110
2=0010	7=0111
3=0011	8=1000
4=0100	9=1001

Don't imagine these codes for digits and letters are unique—there may be billions of them.

Let's use our code to code the word "cybernetics" and the number "13".

Here's the word "cybernetics" concealed in the combination of zeros and unities: 00010 11000 00001 00100 10001 01101 00100 10011 01000 00010 10010. The number "13" will be written like this: 0001 0011.

There are special, very important devices for introducing intelligence into the computer, so that it would be able to process it.

These serve as a sort of gates, the only ones which provide access to the computer.

But those are not simple gates. They are magic gates that transform the number into a code, make it convenient for the computer to operate with.

The decoding device, also termed decipherer, is an absolute "antipode" of the coding device. The decipherer is a "magician the other way round"; its task is to make a "normal number" out of the code.

Coding and decoding are considered to be among the most important logical operations of the "electronic brain". And rightly so, since with their aid the computer is able to transform numbers into the code, to operate with them, and to transform them again into an appropriate code during the output of processed information. Without these devices the computer is powerless. It is interesting to note that in everyday life we continuously come across coding. Not only when we introduce symbols for the normal text or translate the signs of the ABC of one language into those of another, but also when a transmission from a source to a recipient takes place. Thus, in the course of broadcasting sound oscillations enter the microphone. They are transformed into electric oscillations and, eventually, into electromagnetic waves. In this case the coding is done by exchanging one physical quantity for another.

The physical nature of the "letters" of such an ABC, too, may be different. Ink marks on paper, holes in a paper tape, perforations punched in the cards can all serve as "letters". Different positions of rotating elements, electric pulses and light signals can also serve as "letters". Recoding is the operational principle of the teletype—the apparatus that without any human action transforms normal text into combinations of electric signals with an appropriate signal assigned to each letter, to be followed by a reverse transformation of the electric signals into normal letters.

When making a telephone call by turning the telephone dial you, probably, don't suspect that you are engaged in recoding the decimal code into a series of electric pulses, which can be made visual again with 0 (no pulse) and 1 (pulse).

See how it looks.

220—65—99

2 2 0 6

000000011 000000000

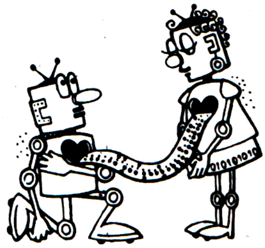
000000011 000111111

5 9 9

000011111 111111111

111111111

Despite the same symbols used (0 and 1) this is not the binary code. It's a decimal code with the number of rotations denoting the decimal order and a unitary code to denote the digits in each order.



X

The Good Fairy

X, Y, Z—CALCULATION MATHEMATICS

A branch of mathematics studying methods of obtaining numerical solutions of mathematical problems and of employing calculation implements.

It's hardly reasonable to entertain doubts as to the greatness of mathematics, for everything in this world may be represented in terms of numbers, every change taking place in it may be expressed by a mathematical dependence. The poet was right in saying: "The intelligent number transmits every shade of meaning."

Now, what is mathematics that is omnipotent, all-embracing, knows practically no limits?

In the words of Friedrich Engels: "Mathematics is a science dealing with the space-patterns and the quantitative relationships of the real world."

The famous mathematician David Hilbert expressed his opinion with a feeling of some superiority: "Mathematics is what competent people suppose it to be." Another prominent mathematician, the American Willard Gibbs, a modest and a reticent man, once uttered "mathematics is a language".

Some people assert that present-day mathematics, like art, absorbs the phenomena of real life, unites similar events, processes and facts and generalizes them.

But the statement best reflecting the spirit of modern times belongs to the prominent contemporary mathematician, Academician A. Kolmogorov: "Mathematics is the means people use to control nature and themselves."

The great mathematician Carl Friedrich Gauss described mathematics as the queen of all sciences. But it's rather a good fairy. It provides not miraculous means of solving all the problems but precise methods. It is a fact that mathematics originated from the five fingers. However, nowadays it may be compared to a great city the suburbs of which are in a process of continuous expansion, and the centre is being rebuilt occasionally, each time to fit a clearer plan. All blocks with tangled bystreets are being cleared, and wide avenues laid in their place.

Frankly, modern mathematics is so extensive and variegated that even a genius cannot master all its branches. The mathematicians themselves are frequently unable to comprehend each other.

A remark once made by a leading mathematician present at one of the world mathematical congresses was not without foundation: "We may not hope to understand everything, or even the greater part, of what we are about to hear."

And yet, we live in an era of numbers and analysis, and this implies rapid advances not only in the vast theoretical field, but also in the practical field of mathematics.

This latter field serves nowadays essentially as a sort of tool for science and technology.

Academician A. Krylov, an erudite mathematician, once said: "This is a tool, quite like the caliper, the chisel, the hammer, the file for the locksmith or the axe and the saw for the carpenter."

Of course, mathematics is a much more intricate tool, since to solve an equation one has to obtain a numerical solution. And this at present is not so easy.

Up to a quarter million precise numerical data may be obtained as a result of wind-tunnel tests of a model.

Billions of parameters are received daily by the weather forecast bureau. And how great is the volume of numerical data in census, opinion polls, commerce statistics. Even purely theoretical studies of the generation of new heavy nuclear particles require the evaluation and processing of some 102 thousand photographs of nuclear reactions.

Quite recently, some 20 years ago, one couldn't hope to be able to calculate different variants of spaceship motion, nuclear reactor operation, gas flow in ultra-high-speed streams, interatomic forces or nuclear accelerators within a reasonable spell of time.

Nowadays such calculations do not present unsurmountable problems for scientists. The ancient science of mathematics profited from new methods and new means.

To take one example. The mathematician Schenks spent his life in the effort to calculate the number π to an accuracy of 707 decimal signs. This result earned for itself the fame of a calculation record of the 19th century. The gravestone of the mathematician rightly bears no inscription, only the sign π. Nowadays a computer doesn't take long to calculate this number to the accuracy of 2035 decimal signs!

The birth of computer technology prompted the development of calculation mathematics, and mathematical abstractions began to pervade everyday life.

Today is the time to speak not only of the mathematization of science, but of the mathematization of life as well. No small part is played here by calculation mathematics. Had it not taken the trouble to modernize calculation methods, no less than half the population of the world would have to be continuously employed in performing calculations.

Eminent mathematicians knew that without a well-developed technique of calculations the enormous structure of theoretical mathematics may become a gigantic isolated tower. Abstract theories locked in this tower would be destined to die a slow death. Life-giving connections between theoretical mathematics and practice exercised through the media of the mathematics and the technology of calculations help man in his practical activities and promote advances in mathematical science.

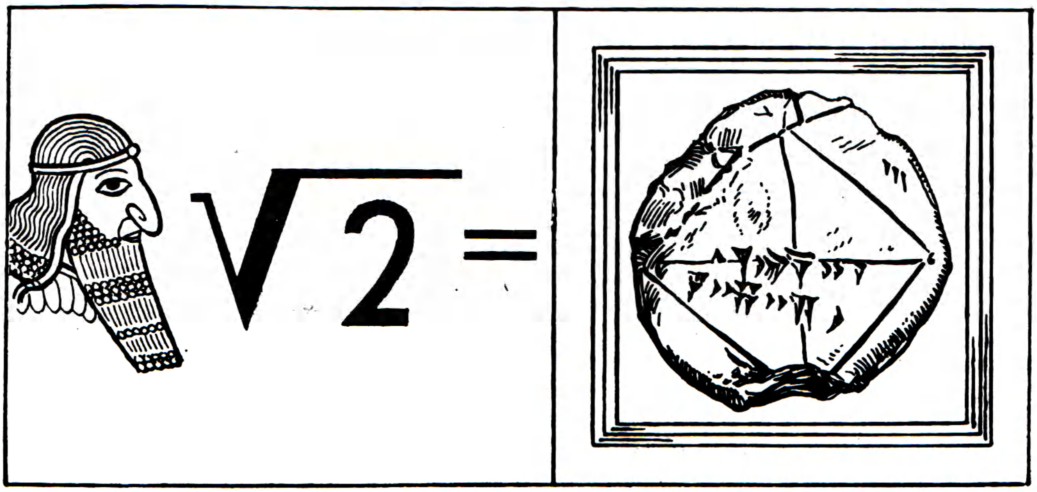
The constant motto of the creators of calculation mathematics is to take a short road from complex mathematical equations to concrete numbers, to speed up the step-by-step movement of numbers and to free man (the conductor of numbers) from tiring work.

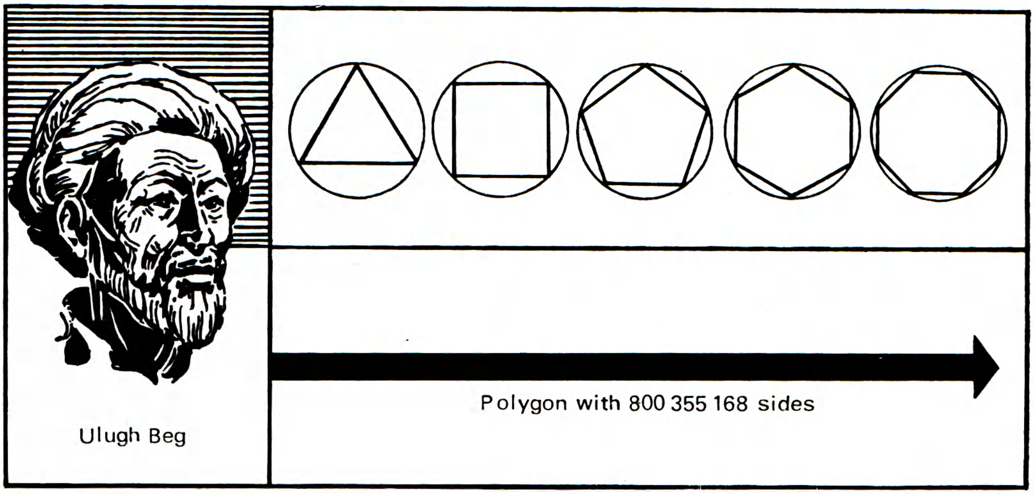
The history of the mathematics of calculations is quite edifying. Unhappily, the lack of space prevents us from telling the full story, and we are compelled to confine ourselves to a few sketches.

The Greek astronomers used mathematical methods to study the laws of planetary motion. They have done much to further calculation mathematics.

The studies of the famous mathematician and astronomer from the city of Alexandria Claudius Ptolemy sum up the works of Greek mathematicians. He lived

A Babylonian cuneiform inscription depicts a square with a diagonal. Its side is equal to 30, and this is written in the left upper part. The approximate value of $\sqrt{2}$ is written alongside the diagonal.





The eminent mathematician and astronomer Ulugh Beg calculated the ratio of the circumference to the radius, i.e. the number 2π, to sixteen signs after decimal point. Gradually increasing the number of the sides of the regular polygon to approximate the circumference he obtained a polygon of 800355168 sides!

in the first half of the 2nd century A.D. and left behind 13 volumes entitled *The Great Collection, or the Great Construction.* This was a kind of contemporary encyclopaedia of astronomical knowledge. It has reached us under the Greek-Arab title of *Almagest.*

Almagest contains the results of enormous calculation work performed by Ptolemy. They were presented in the form of sine tables and were intended to help astronomers in their work.

The tables could be used to find the sines of arcs up to 90° in increments of a quarter of a degree. The Pythagoras theorem enabled any element (a side or an angle) of a rectangular triangle to be calculated from two known elements.

The Ptolemy table is the first trigonometric table to reach us.

The prolonged period of Roman supremacy in Europe was not marked by any conspicuous achievement in mathematics, but for the Greek scientist Diophantus (3rd century A.D.) who introduced into algebra some original algebraic equations. The invention of the logarithm proved of paramount importance to calculation techniques. It affected the entire methodology of mathematical problem solution. People familiar with the use of logarithms from their school days can hardly imagine the marvel and excitement caused by their appearance.

The great scientist P. Laplace wrote: "The invention of the logarithm, by curtailing the calculations of several months to a matter of several days, seems to double the life of an astronomer."

He spoke of astronomers because he was an astronomer himself and because it was they who in those times had to perform the most complex and tedious calculations.

The word "logarithm" is Greek. It is made up of two words: "logos"—"ratio" and "arithmos"—"number". Thus, "logarithm" means "a number which measures a ratio".

What is the basis of the wonderful properties of these numbers designed to facilitate calculations, of the tables you use in your mathematics lessons?

Some simple examples will help you to get a clear notion.

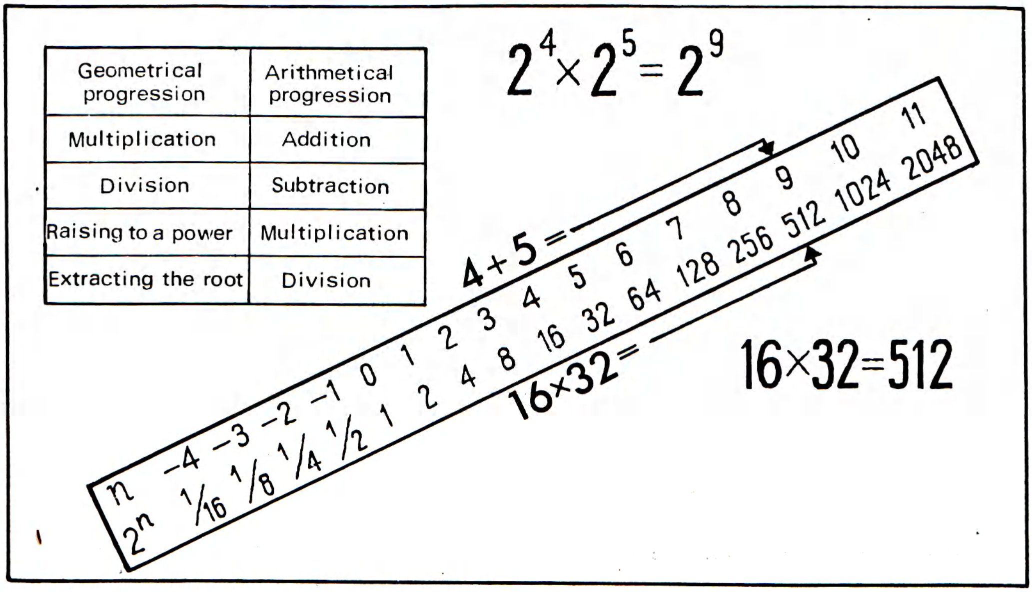
Let's take some number, say 2, and compile a table of integer powers of this number.

The upper line in the table is an arithmetical progression with the difference equal to unity, the lower is a geometrical progression with the denominator equal to 2. This table may already be used to simplify calculations.

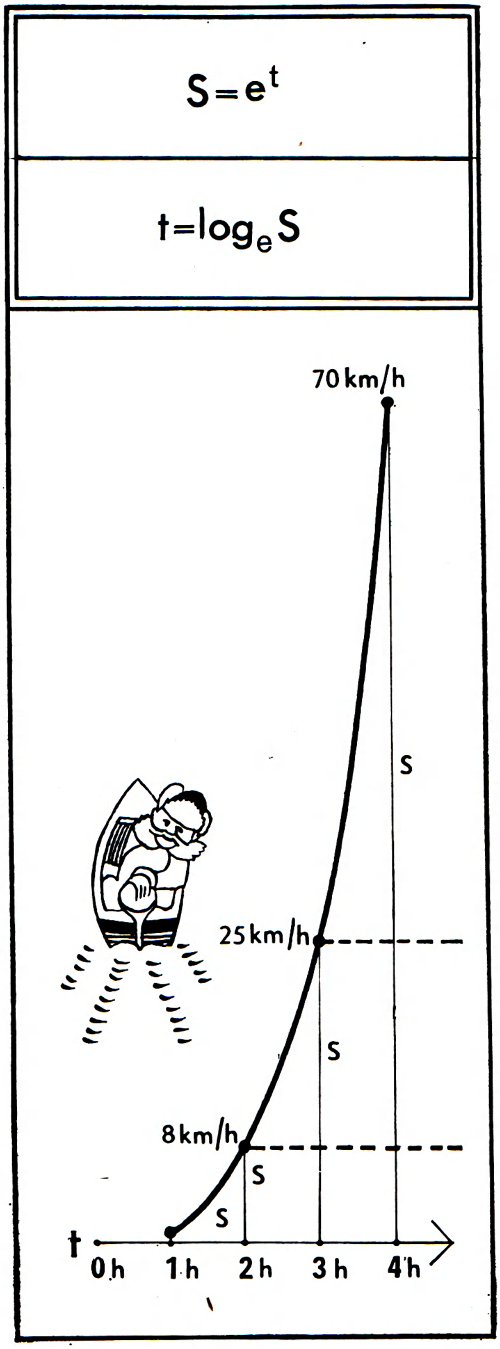
Let's try to multiply 16×32 with the aid of this table. The numbers in the upper line of the table directly above these numbers are 4 and 5. Add them up and obtain 9. In the lower line directly below the nine stands the number 512. This is the result sought. Indeed, $16 \times 32 = 512$.

In almost the same way one may find the quotient, for instance, of 8 divided by $^1/_{16}$. But now one has to take the difference of numbers in the table directly above the former numbers. It is equal to 7 since the difference of $3-(-4)$ after the

It is shown above that the more simple operations with numbers performed in the arithmetical progression correspond to those performed in the geometrical progression.



Geometrical progression	Arithmetical progression
Multiplication	Addition
Division	Subtraction
Raising to a power	Multiplication
Extracting the root	Division



The relationship between the distance covered (S) and time (t) is logarithmic. The Napier curve shows this.

brackets are opened adds up to 7. The lower line below this difference shows the required quotient: 128.

And such a complicated operation as the extraction of a cube root from a three-digit number is performed with the greatest of ease.

Judge for yourselves. A glance at the table, and we find the power of 2 corresponding to 512. It is 9. Now divide it by the power of 3 (the cube root) and obtain the answer below the quotient of 3: it's 8. This is the value of the cube root.

Our table is quite primitive, but it does give an impression of the general properties of the terms of the arithmetical and the geometrical progressions which may be used to simplify calculations. How should this be done?

To explain it in words would take many tiresome phrases. Here's a figure for everyone to see that addition and subtraction in the arithmetical progression correspond to the multiplication and division in the geometrical progression, while raising to a power and root extraction are replaced by multiplication and division.

Arrange all the eight operations we have been talking about in the order of their complexity, and your table will turn into wonderful steps: one step simplifies the operation, another makes it quite easy!

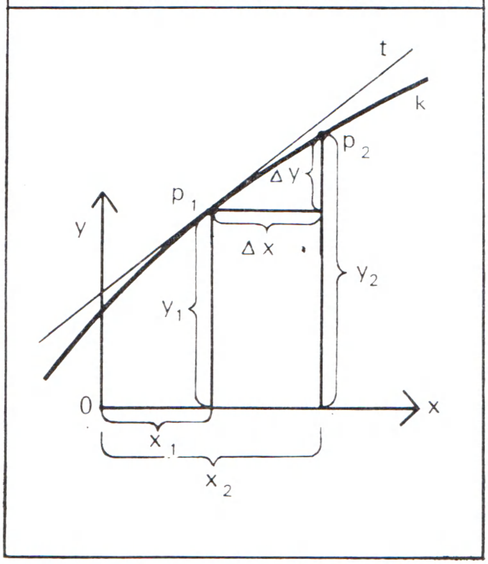
Naturally, the table compiled by us is good only for calculations with integers, and even these may not be chosen at will.

Real working logarithm tables for accurate calculations were first compiled by John Napier. It took this prominent Scotch mathematician twenty years to complete the job. Napier explains the reasons for his work as follows:

"I have tried to do everything in my power to rid myself of the difficulty and ennui of calculations the tediousness of which usually scares a lot of people away from studying mathematics."

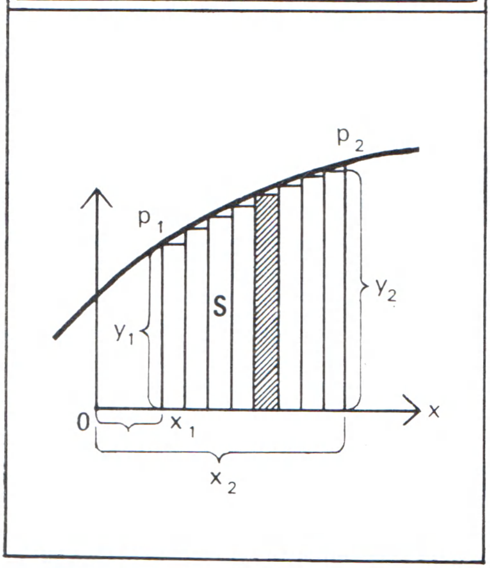
The work of Napier is of outstanding importance because he was the first to divulge the essence of the logarithm, a mathematical quantity hitherto unknown.

$$Y' = \frac{dy}{dx}$$



The study of dynamic processes often involves the solution of extremely complex differential equations.

$$S = \int_{x_1}^{x_2} y\,dx$$



Mathematics was able to sense the limit when rectangular steps turn into a smooth curve. It found the limit of an infinite sum (S) when the number of the additives is increased to infinity while each of them tends to zero. This limit is termed integral.

The value of this discovery for the mathematics of calculations was as great as that of the discovery of the trigonometric functions.

Three hundred and fifty years passed since Napier made his ingenious invention. During this time over 500 types of logarithm tables were devised. They took a firm place in the arsenal of calculation implements and to this day occupy a position of honour as man's aid in calculations.

Millions of specialists use logarithms in their everyday work, from the highly accurate twenty-plus sign tables to the "wooden" logarithms, slide rules, indispensable instruments for technical calculations.

People always lived in a world of incessant motion and continue to do so now.

Everything around us is in motion: the mutual position of the planets, of the solar system, air pressure and temperature, forces active in a machine, currents flowing in an electric circuit, the state of a living cell all change in the course of time.

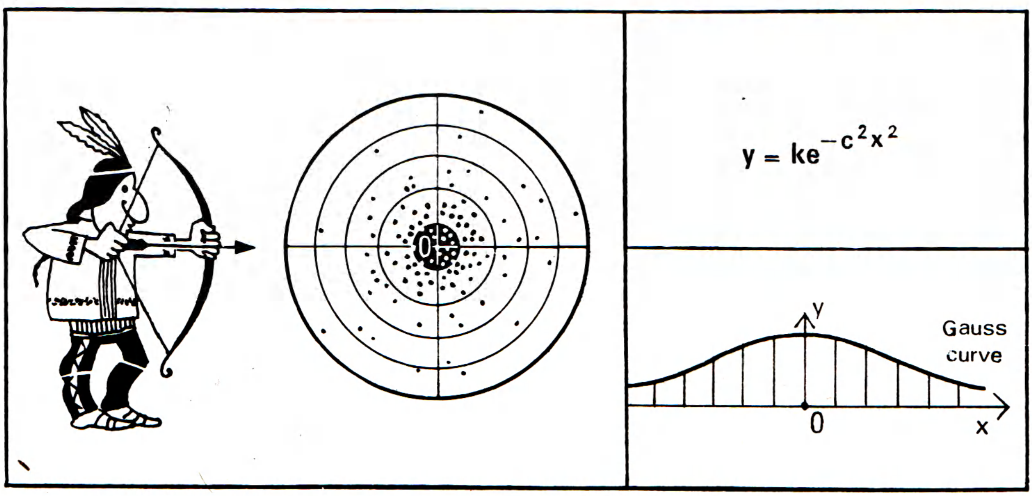
The speeds of other processes are enormous, and their duration quite short: some hundredths, thousandths or millionths of a second. Swift is the drop in air pressure in a region of an approaching cyclone. Colossal is the acceleration of elementary particles in a synchrotron: it takes them seconds to cover cosmic distances.

When studying these so-called dynamic processes scientists are primarily interested in changes taking place in time.

To analyse and calculate these processes mathematical methods are needed which would be able, like an ultra-high-speed camera, to sense changes taking place within the minutest time intervals.

The part of such a "camera" in calculations came to be played by the methods

Mathematicians made a startling discovery: the regularities governing random quantities are themselves not fortuitous. This makes it possible to assess the frequencies of various deviations from the point of aim.



of the differential and integral calculus, the science of varying quantities. It was created by the mathematical genii Leibnitz, Newton, Euler and their disciples.

But it is one thing to study phenomena as regular as the change from day to night, or the alternation of the year's seasons, and quite another to investigate processes liable to be affected by various fortuitous circumstances.

A coin thrown into the air is bound to fall to the ground. Even the time it takes it to do so may be calculated.

But no calculation will be able to predict which side down it will fall: heads or tails. It may fall any way, this being dependent on numerous fortuitous circumstances.

Such eminent mathematicians as Pascal and Fermat evinced interest in games the outcome of which was based on random events. A new branch of human knowledge came into being, the theory of probability. It was proved that probability is a quantity which may be measured.

But it was only in the 19th century that thanks to the endeavours of such mathematicians as Gauss, Chebyshev, Markov, Lyapunov, the theory of probability developed into a separate branch of science, a branch of mathematics the practical importance of which became stupendous.

Many eminent scientists spent a lot of time on tedious calculations trying to discover new roads in mathematics and to check their calculations.

Mathematicians-calculators do not build machines or houses, there are no scales, test-tubes, galvanometers, or microscopes in their studies. They do not conduct experiments. But mathematicians arm the machine designer and the architect, the physicist and the chemist, the biologist and the economist with the skill to solve problems, with the most up-to-date mathematical methods.

Together, we witnessed the time calculation mathematics left its cradle.

Having been born to satisfy practical requirements it itself is now influencing theoretical developments, demanding of the theory new, more efficient methods differing in principle from the previous ones.

Today calculation mathematics evolves rules for the numerical calculation of various mathematical problems, assesses the complexity, the cost in labour and the accuracy of the algorithms and of the methods of compiling computer programmes for them. This is a vast task, for some algorithms contain up to a billion arithmetical operations.

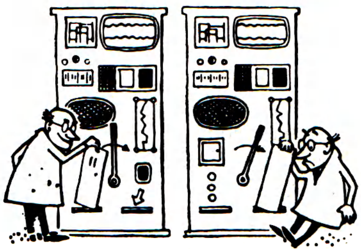
The mathematics of calculations helps not only its wards: mechanics, physics and astronomy, but also such, apparently, distant disciplines as geology, medicine, linguistics and economics.

Here, too, mathematics learned how to reduce the problem to a "number".

Calculation mathematics grew far and wide. It needs a great many specialists.

The most authoritative mathematicians are of the opinion that now is the time to introduce the elements of calculation mathematics and computer technology into secondary-school programmes.

"They are waiting for you, young men," says Academician Vinogradov, addressing himself to young people. "It will be up to you to make use of mathematics to lay courses to distant planets and, possibly, to the stars, to build machines that will liberate man's creative forces from rough physical and mental work. This is a job of the next decades, and you should be ready for it."



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