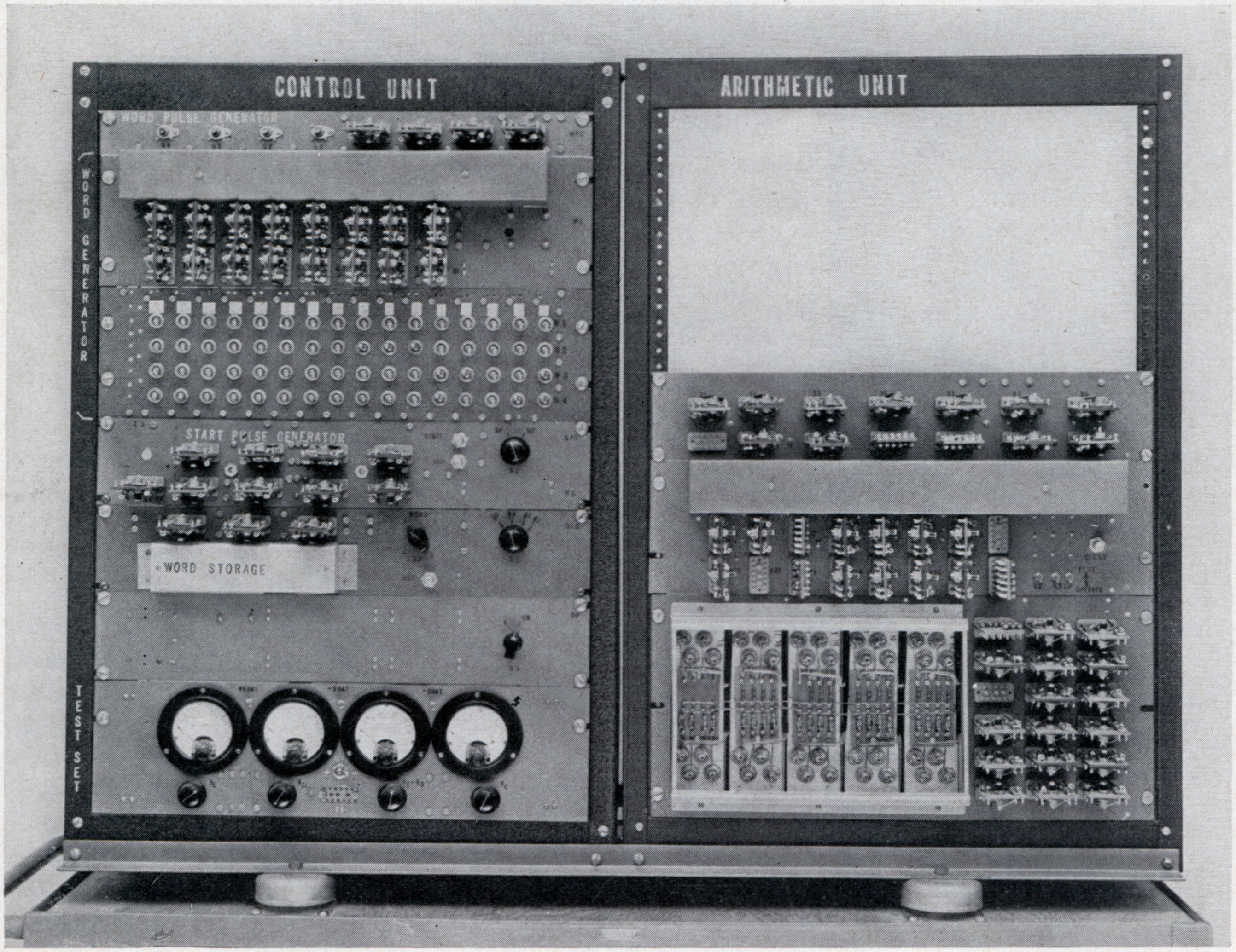
THE ROLE OF THE COMPUTER

The multifarious control loops of a fully automatic factory must be gathered into one big loop. This can best be done by means of a digital computing machine

by Louis N. Ridenour



COMPUTER OF THE FUTURE is suggested by this experimental machine built by J. H. Felker of Bell Telephone Laboratories. Instead of vacuum tubes or relays it uses germanium diodes as its logic elements. It also uses the germanium triode, or transistor, as an amplifier. Because these germanium devices are about the size of a pea, a computer utilizing them is much smaller than an equivalent machine employing vacuum tubes or relays. The germanium diodes and triodes also use very little power; the entire computer draws only 5 watts. The machine is capable of multiplying 4,000 16-digit binary numbers a second. One of its interesting features is that each of its 80 transistors is part of an identical plug-in unit (*see pages 124 and 125*).

IF THE thermostat is a prime elementary example of the principle of automatic control, the computer is its most sophisticated expression. The thermostat and other simple control mechanisms, such as the automatic pilot and engine-governor, are specialized devices limited to a single function. An automatic pilot can control an airplane but would be helpless if faced with the problem of driving a car. Obviously for fully automatic control we must have mechanisms that simulate the generalized abilities of a human being, who can operate the damper on a furnace, drive a car or fly a plane, set a rheostat to control a voltage, work the throttle of an engine, and do many other things besides. The modern computer is the first machine to approach such general abilities.

Computer is really an inadequate name for these machines. They are called computers simply because computation is the only significant job that has so far been given to them. The name has somewhat obscured the fact that they are capable of much greater generality. When these machines are applied to automatic control, they will permit a vast extension of the control art—an extension from the use of rather simple specialized control mechanisms, which merely assist a human operator in doing a complicated task, to over-all controllers which will supervise a whole job. They will be able to do so more rapidly, more reliably, more cheaply and with just as much ingenuity as a human operator.

To describe its potentialities the computer needs a new name. Perhaps as good a name as any is "information machine." This term is intended to distinguish its function from that of a power machine, such as a loom. A loom performs the physical work of weaving a fabric; the information machine controls the pattern being woven. Its purpose is not the performance of work but the ordering and supervision of the way in which the work is done.

There are in current use two different kinds of information machine: the analogue computer and the digital computer. Several excellent popular articles have discussed the characteristics of these two types of computer; here we shall briefly recall their leading properties and then consider their respective possibilities as control mechanisms.

THE ANALOGUE machine is just what its name implies: a physical analogy to the type of problem its designer wishes it to solve. It is modeled on the simple, specialized type of controller, such as a steam-engine governor. Information is supplied to the machine in terms of the value of some physical quantity—an electrical voltage or current, the degree of angular rotation of a shaft or the amount of compression

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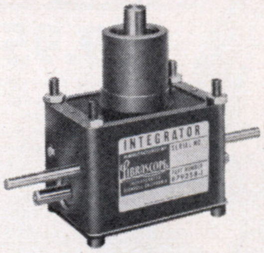

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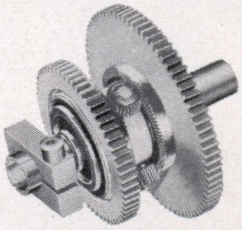

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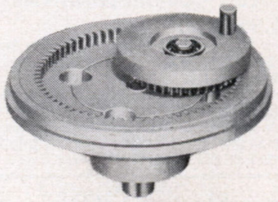

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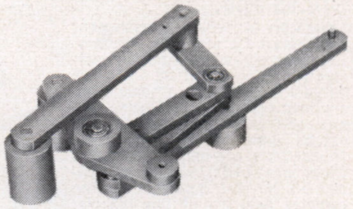

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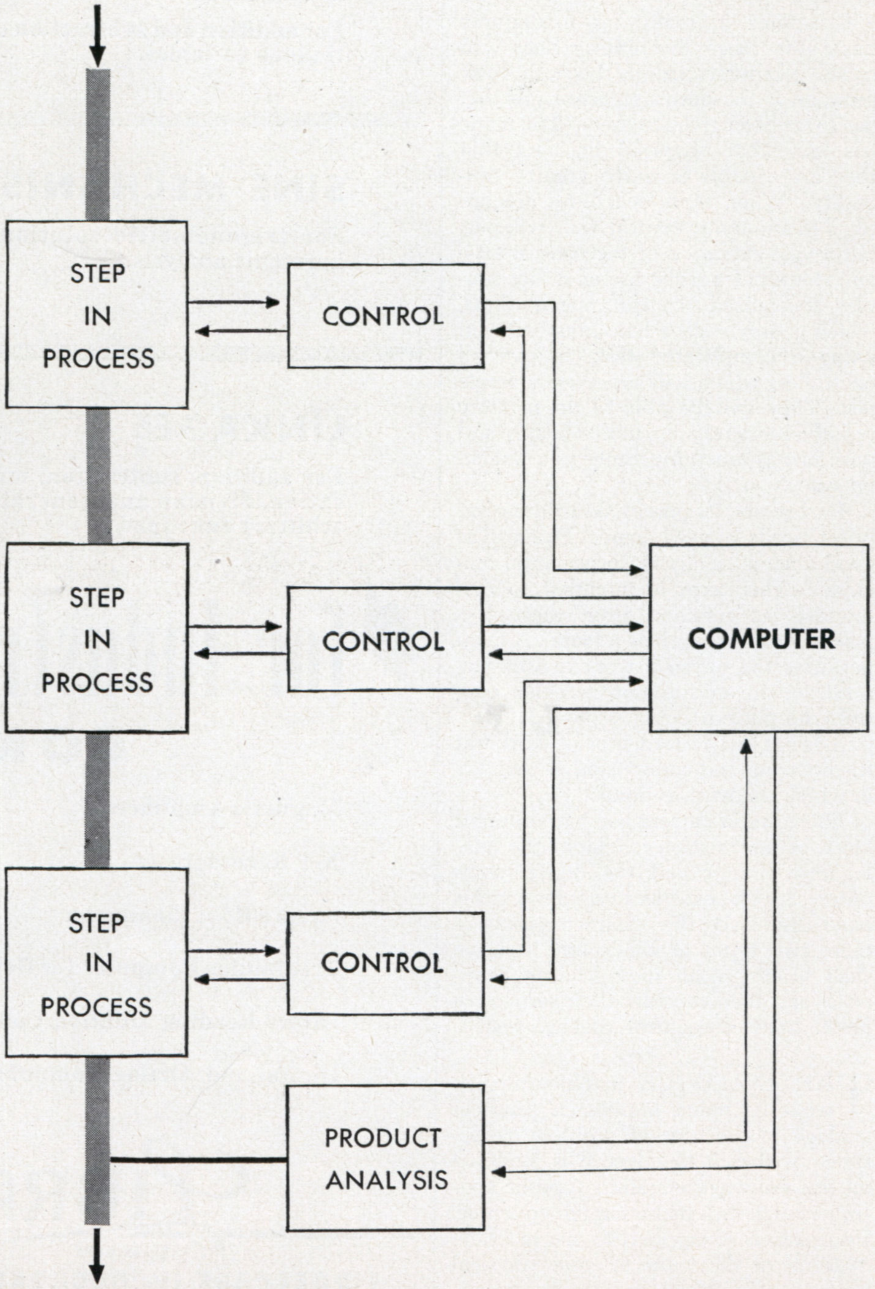
of a spring. The machine transforms this physical quantity into another physical quantity in accordance with the rules of its construction. And since these rules have been chosen to simulate the rules governing the problem, the resulting physical quantity is the answer desired. If the analogue machine is being used as a control device, the final physical quantity is applied to exercise the desired control.

Consider, as an example, the flyball-governor pictured on the cover, whose purpose is to hold a steam engine to a constant speed. We notice, first, that information on the engine speed reaches the governor in the form of the speed of rotation of a shaft, while the output of the governor is expressed as the motion of a throttle which is closed or opened as the whirling balls rise or fall. Second, we notice that the relation between these two physical quantities is determined by the actual construction of the governor. The design of the controller has been dictated by its function.

In contrast to the analogue machine, a digital machine works by counting. Data on the problem must be supplied in the form of numbers; the machine processes this information in accordance with the rules of arithmetic or other formal logic, and expresses the final result in numerical form. There are two major consequences of this manner of working. First, input and output equipment must be designed to make an appropriate connection between the log-



ROLE OF THE COMPUTER is shown in block diagram. Computer receives information from product analysis and feeds it into the various control loops.

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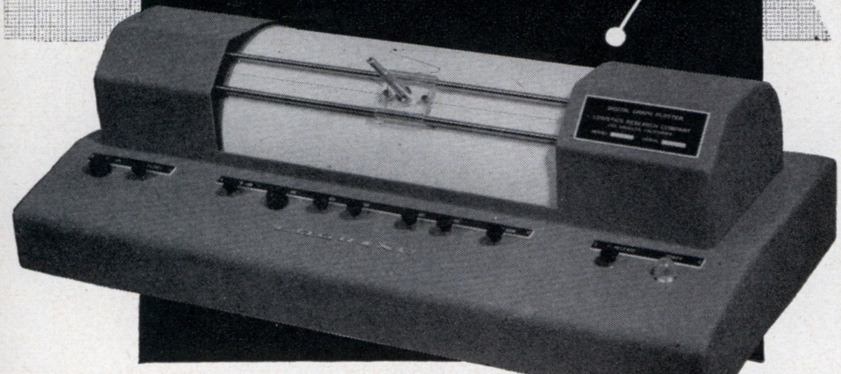

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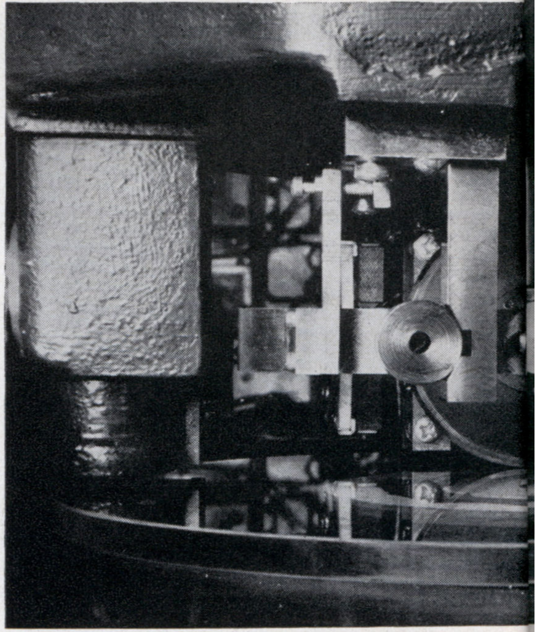
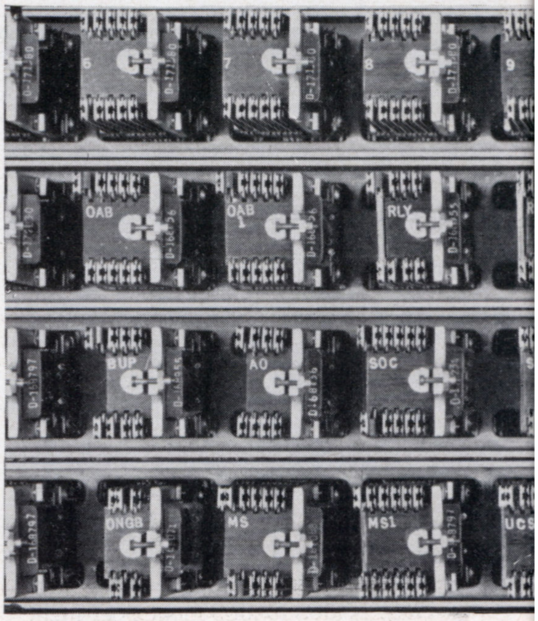


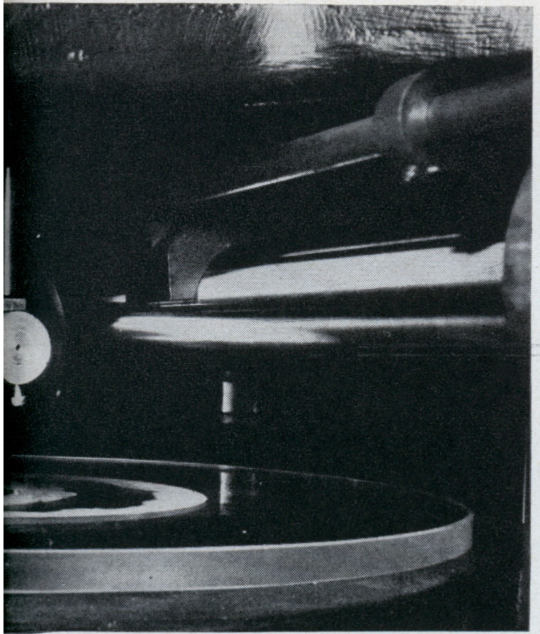
ANALOGUE DEVICE integrates variables with two disks. One variable

ical world of the digital machine and the physical world of the problem being solved or the process being controlled. Second, the problem to be solved must be formulated explicitly for the digital machine. In the case of the analogue machine, the problem is implicit in the construction of the machine itself; construction of a digital machine is determined not by any particular problem or class of problems but by the logical rules which the machine must follow in the solution of *any* problem presented.

Thus far the need for specialized input and output equipment, more than any other factor, has restricted the role of digital information machines to computing. In a computation, both the in-

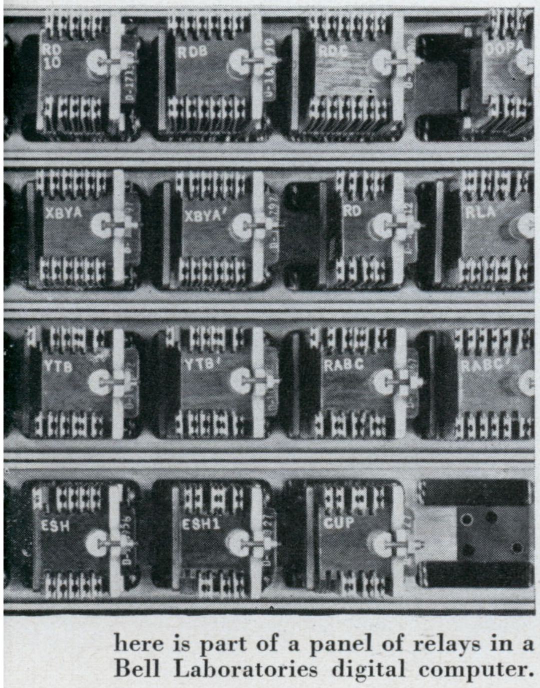


DIGITAL DEVICE such as the relay does not measure but counts. Shown



is given by position of small disk; the other, by angle of large disk.

put and the output quantities are numbers, so the most rudimentary equipment will suffice to introduce the problem and register the result. There is no need (as there would be in a control application) to transform various physical quantities into numerical form before submitting them to the machine, or to transform the results of the calculation into a control action, such as moving a throttle. To use a digital information machine as a computer it is necessary only to provide (1) an input device such as a teletypewriter, which with the help of a human operator can translate printed numbers into signals intelligible to the machine, and (2) an output device such as a page-printer or electric



here is part of a panel of relays in a Bell Laboratories digital computer.

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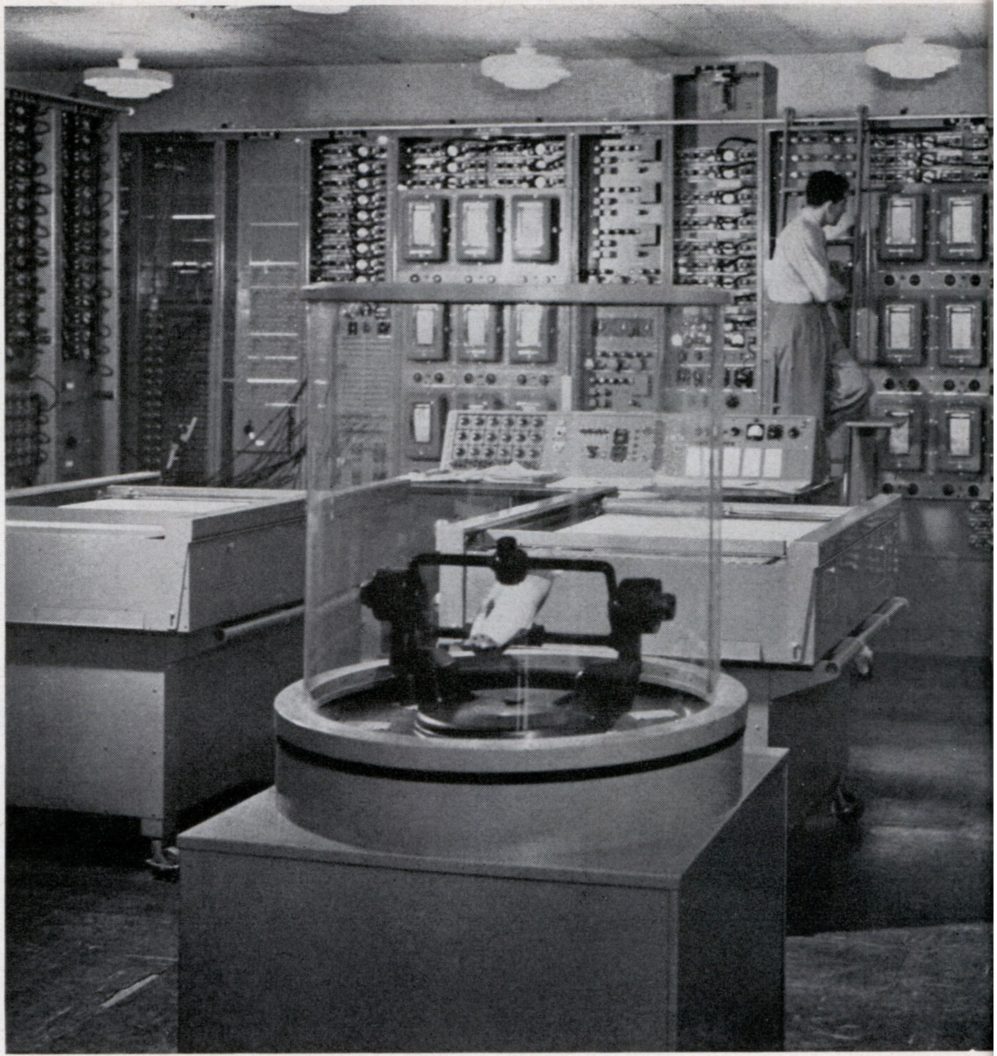


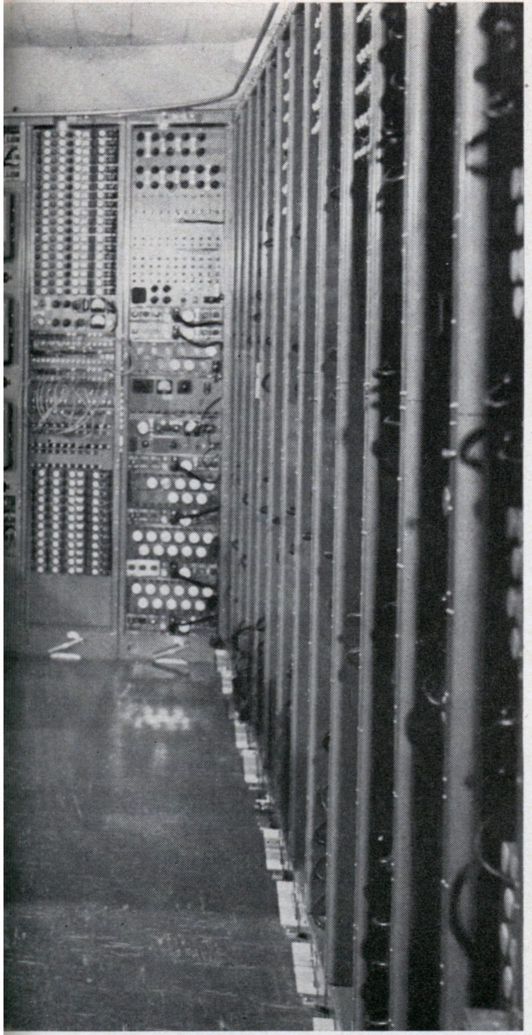
LARGE ANALOGUE COMPUTER is exemplified by the machine of Project Typhoon, built by the Radio Corporation of America to simulate the

typewriter, which can translate the signals generated by the machine into the printed numbers intelligible to men. Even this simple requirement, however, has not always been well met by the designers of information machines.

When a digital information machine is to be used as an instrument of control—and we can confidently expect that this will eventually be its major role—the design of input and output equipment becames a more formidable task. While it is true that the structure of the machine itself depends on principles of logic rather than on the nature of its application, this is by no means true of the input and output elements. The input devices, or receptors, can use standard elements for receiving the program of instructions, but they must also receive data specifying the state of the particular process being controlled, and for this the detailed design will vary widely from one application to another. Similarly the effectors, which exercise the machine's control, must be designed in terms of the nature of the process or device being controlled.

In comparing digital and analogue machines as instruments for automatic control, we observe, first, that for simple control applications the analogue machine is almost always less elaborate than a digital machine would be. Even the most elementary digital machine requires an arithmetical (or logical) unit, a storage unit, a control unit, receptors and effectors. For simple problems, this array of equipment is wastefully elaborate. In contrast, an analogue machine need be no more complicated than the problem demands. A slide rule, for example, is a perfectly respectable information machine of the analogue type. The analogue machine's ability to do simple work by simple means explains its current predominance in the field of automatic control. The whole control art is so new and so little developed that most of the problems thus far tackled have been of a rather elementary nature.

As the control task becomes more complex, however, the analogue machine loses its advantage, and we begin to see a second fundamental difference



performance of guided missiles, aircraft, ships, submarines and so on.

between the two types of machine. The analogue machine is a physical analogy to the problem, and therefore the more complicated the problem, the more complicated the machine must be. If it is mechanical, longer and ever-longer trains of gears, ball-and-disk integrators and other devices must be connected together; if it is electrical, more and more amplifiers must be cascaded. In the mechanical case, the inevitable looseness in the gears and linkages, though tolerable in simple setups, will eventually add up to the point where the total "play" in the machine is bigger than the significant output quantities, and the device becomes useless. In the electrical case, the random electrical disturbances called "noise," which always occur in electrical circuits, will similarly build up until they overwhelm the desired signals. Since "noise" is far less obtrusive than "play," electrical analogue machines can be more complicated than their mechanical equivalents, but there is a limit. The great machine called Typhoon, built by the Radio Corporation of America for the simulation of flight performance

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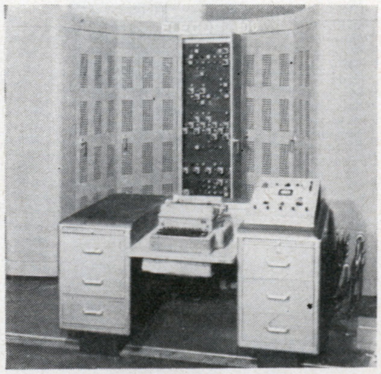

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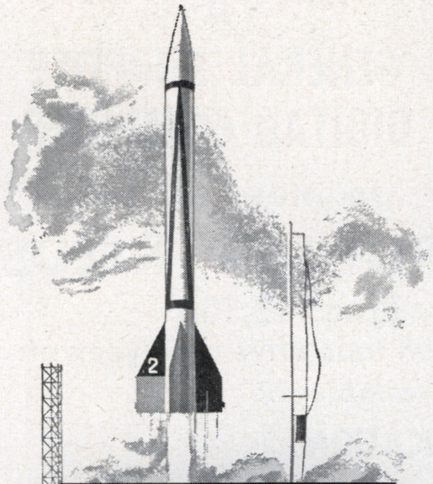

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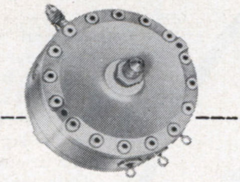

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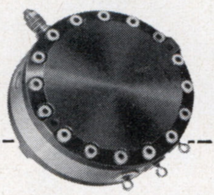

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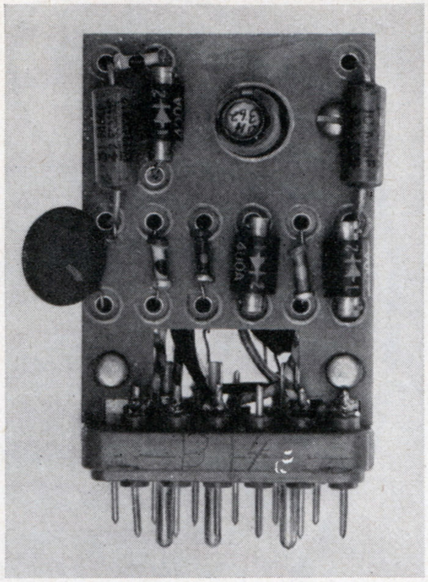

AMPLIFIER for the Bell Laboratories computer on page 116 is a standard unit an inch and a half wide.

in guided missiles, closely approaches that limit. It is perhaps the most complicated analogue device ever built, and very possibly the most complicated that it will ever be rewarding to build.

The digital machine, on the other hand, is entirely free of the hazards of "play" and "noise." There is no intrinsic limit to the complexity of the problem or process that a digital machine can handle or control. The switching system of our national telephone network, which enables any one of 50 million phones to be connected to any other, is a digital machine of almost unimaginable complexity.

THE THIRD important difference between analogue and digital machines is in their accuracy potential. The precision of the analogue machine is restricted by the accuracy with which physical quantities can be handled and measured. In practice, the best such a machine can achieve is an accuracy of about one part in 10,000; many give results accurate to only one or two parts in 100. For some applications this range of precision is adequate; for others it is not. On the other hand, a digital machine, which deals only with numbers, can be as precise as we wish to make it. To increase accuracy we need only increase the number of significant figures carried by the machine to represent each quantity being handled. Of course in a control operation the machine's over-all precision is limited by possible errors in translating physical quantities into numbers and *vice versa,* but this does not alter the fact that where high precision is required, a digital machine is usually preferable to the analogue type.

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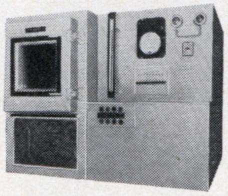

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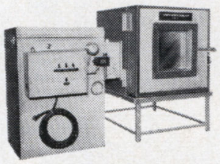

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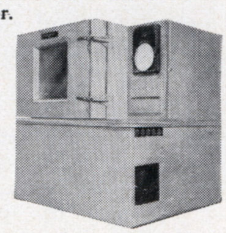

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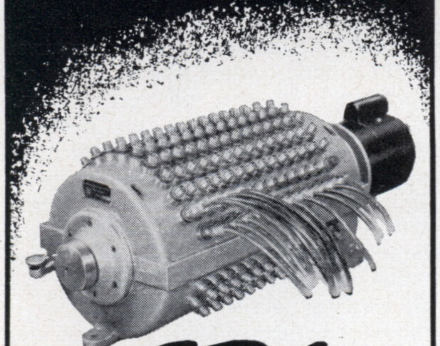

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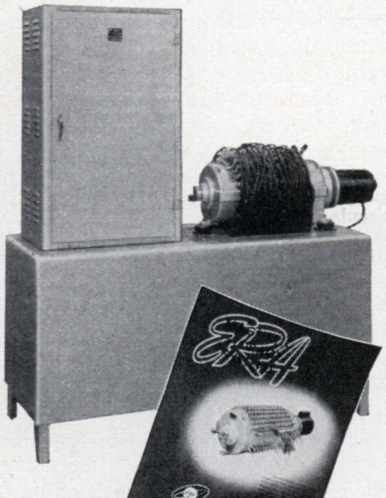

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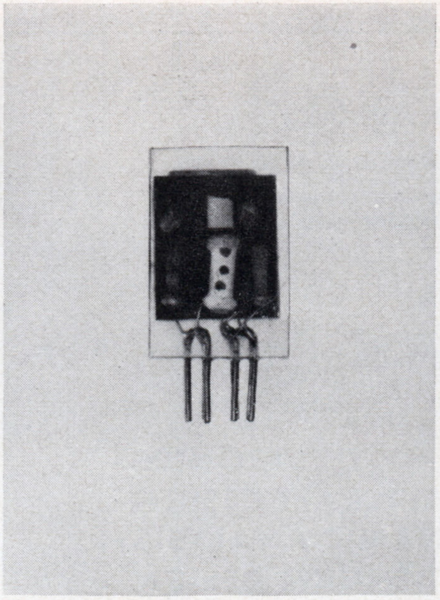
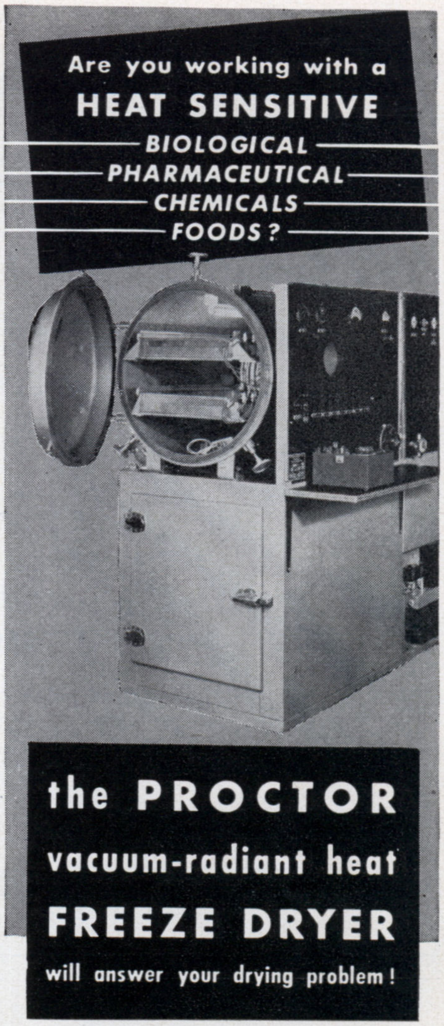


REFINEMENT of amplifier on opposite page is only 3/4 inch wide, suggesting even smaller computers.

two machines differ. An analogue machine works in what is called "real time." That is, it continuously offers a solution of the problem it is solving, and this solution is appropriate at every instant to all the input information which has so far entered the machine. If the machine is doing a mathematical problem, for example, it need not formulate explicitly the equations to be solved and then go through the steps of solving them, as a digital machine would have to do. The equations are inherent in the very structure of the machine, and it solves them by doing just what it was built to do. It can thus respond promptly to changing input data, and offer an up-to-date solution at every moment. This property of working in "real time" is very important in most problems of automatic control. An autopilot flying a plane must respond at once to an attitude change resulting from a gust of wind; the most precise information on how to adjust the flight controls will be worthless if it comes 30 seconds too late.

Since a digital machine works by formulating and solving an explicit logical model of the problem, it can work in "real time" only if the time it requires to obtain a solution, given new input data, is short compared with the period in which significant changes can take place in the system being controlled. Present-day digital machines can achieve this speed for many important problems—flight control of aircraft, for example—but they are not yet fast enough to handle all the "real-time" problems that we should like to turn over to them. It has been estimated that the fastest existing digital machines are some 20 times too slow to deal with the problem of simulating the complete flight performance of a high-speed guided missile—the



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problem that Typhoon was built to handle. As development proceeds, the operating rates of digital machines can be expected to increase rapidly.

WE SEE, then, that both analogue and digital machines can be used for automatic control, and each has advantages in its own sphere. For simple applications in which no great precision is required, an analogue controller will usually be preferable. For complex problems, or problems in which high precision is required, a digital controller will be superior. Where "real-time" computations must be made, analogue machines are almost always used now, though digital machines are beginning to achieve speeds that fit them for this type of application.

All this refers to the present state of the art of automatic control. What can we guess about the developments to come?

The simple specialized analogue controllers already in use will surely be extended to wider application. But the most significant and exciting prospects reside in the digital machine. We can expect that it will soon open up a new dimension of control. The meaning of this prediction can be admirably illustrated in terms of the highly instrumented catalytic cracking plant which Eugene Ayres has described in a preceding article.

Mr. Ayres tells us of a plant in which there are some 150 different analogue controllers, each governing some aspect of the continuous process that the plant performs. Several hundred indicators on a central control panel offer the most detailed information on system performance. Many of these indicating instruments also provide continuous recordings. Manual controls which can override any automatic controller are present for use in emergency. The instruments and controls have been arranged on a flow diagram which simulates the organization of the plant and helps the human operator to find his way through the complexities of instrumentation. And the most important process-controls are adjusted manually according to the results of a periodic product analysis.

Clearly the human operator is still the master of this "automatic" plant. However elaborate the instrumentation, the readings of the instruments are still presented to men; however competent the automatic controllers, provision for human veto of their action is built into every one of them. Men are expected to meet emergencies, and to take control under "conditions of unstable equilibrium such as starting up or shutting down." The cracking plant is automatic only when the unexpected is not happening; in times of stress it falls back on human control, and its whole design is dictated by this necessity.

To this scheme there will soon be

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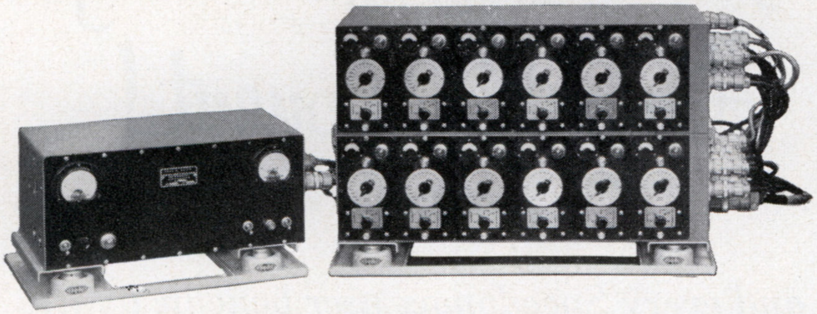

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added end-point control—continuous adjustment of the main process-controls on the basis of a continuous product analysis within the system itself. This modification will improve performance, but it will leave the situation essentially as it was before: more routine responsibility will be given to machinery, but the human supervisor will still be vital to proper operation.

THE DIGITAL information machine, employed as an instrument of supervisory automatic control, can change this picture radically. Since such a machine can be instructed to perform any set of logical operations, however complicated, it can be programmed at the outset to react in emergencies precisely as would a well-instructed human operator—and it can react at least a thousand times faster. Further, the machine can be given a set of criteria for appraising the relative success of its various acts, and can be enabled to alter its own program of instructions in the light of experience on the job. Hence it will be capable of "learning" and of finding a better way to perform its operations than the one prescribed in the original instructions. And this universally adaptable machine can encompass the tremendous job of orchestrating the joint behavior of the hundreds of individual analogue controllers built into a modern cracking plant. The same machine can regulate the performance of the factory and keep the necessary accounting records.

The replacement of human operators in a refinery by a control machine would probably result in substantial economies, both in first cost and in operating cost per unit of product. Most of the saving in first cost would come from the elimination of the costly display and recording instruments that human operators require. In a machine-controlled plant, display would be unnecessary. The measurements vital to the process would be communicated directly to the control machine and processed there. The machine would issue the necessary commands to the specialized controllers which served it, and would print out in fully digested form the summary records of plant performance.

The saving in operating cost would come, not from eliminating the salaries of the few displaced operators, but simply from the fact that the machine could do a more efficient job. A human operator, even one of the greatest virtuosity, is a bottleneck in modern plant performance. Mr. Ayres has told us how the modern cracking plant simply cannot be operated, even by throngs of men, if its individual automatic controllers are left out. The cracking plant of tomorrow, controlled by a suitable information machine, will similarly be beyond the powers of human operators, even skillful ones equipped with all the control instrumentation—of

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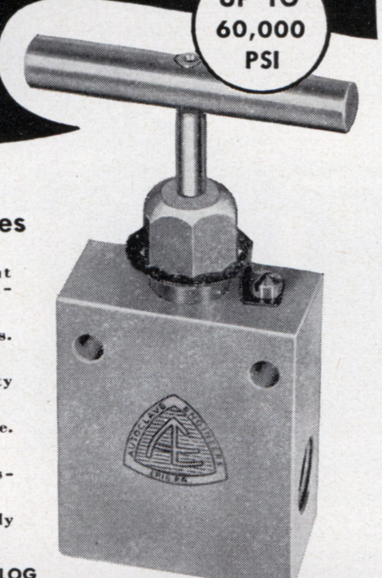

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the present variety—that can be devised.

The difficulty of designing a control room which will not baffle the operators is already substantial in present plants. This means that designers cannot increase the complexity of the plant, or its speed of operation, even though such changes might enhance efficiency. Removal of the limitations of human supervisors will open the way to vast design improvements. The information machine can remove them.

SOME CHEMISTS think that a big new development in industrial chemistry lies just ahead, a development based on exploiting certain new types of reactions. These are fast reactions which take place within microseconds, reactions of gases flowing at velocities above the speed of sound, and reactions that will make it possible to capture valuable but fleeting intermediate products in a chemical system by preventing the system from reaching equilibrium. The enthusiasts say that the jet engine is the model of the chemical plant of the future. A supersonic chemical plant of the kind envisioned cannot be operated by men in white overalls reading carefully arranged gauges in an elaborate control room; the speed of nerve impulses from eye to brain to muscle is just too slow for that. Reactions occurring in microseconds must be controlled by machines that can respond in microseconds. Men will design these machines, build them and give them instructions, but men will never be able to compete with their performance.

If this last assertion seems outrageous, it is not more outrageous than it once was to assert that a man could design and build a derrick which would lift a load no man could ever budge. We are familiar with power machinery, and we take for granted its superiority to human muscles. We are not yet familiar with information machinery, and we are therefore not prepared to concede its superiority to the human nervous system. Nevertheless, a digital information machine can surpass human capabilities in any task that is governed by logical rules, no matter how complicated such rules may be.

Man's machines are beginning to operate at levels of speed, temperature, atomic radiation and complexity that make automatic control imperative. As an instrument of over-all automatic control the digital information machine has a great but as yet untouched potential. In the next few years this potential will begin to be realized, and the results are certain to be dramatic.

Louis N. Ridenour, physicist, was formerly Chief Scientist of the Air Force. He is now vice president of the International Telemeter Corporation.