

This means 100 per cent self checking. The users of the Bell Laboratories' machines have reported only two occurrences of machine faults that resulted in machine errors. These were both reported by the NACA laboratory. No details have been received about these two cases, and as yet, no analysis is being made of them. Rather than try to disprove the claims for these two errors, it may be better to let them stay on the performance record. Perhaps more credence is accorded to our claims for self checking with two errors on the record rather than none. Because of this fine performance, the scientist uses the results obtained from these Bell Laboratories' computers with complete assurance because he confidently believes that his computer has not deceived him.

To acknowledge the names of all of those who have participated in this computer development would make a

long list. It is sufficient to say that at various times, 20 engineers in the telephone switching development department have taken part in the development and construction programs. In the planning stages, mathematicians and scientists in the research department joined in the numerous discussions on fundamentals and objectives.

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# The Transistor as a Digital Computer Component

J. H. FELKER

DIGITAL computers have been defined as machines that use a language explicitly and one may think of them as carrying on interior dialogues. This concept helps to illustrate one difference between the modern computer and other electronic machinery. The principal function of most electronic apparatus is to take low level signals and raise them to a power level sufficient to drive some device such as a loud speaker, servo motor, relay, or perhaps a cathode-ray tube. In a digital computer, however, there may be a thousand active elements that merely converse with one another. There may be a million alterations of state before an output device has to be energized. These internal operations need not be carried out at any particular power level. It is only necessary for one device to talk loud enough for the next device to recognize what was said. Devices are needed

which have stable states that can be changed by very low input signal power. As the computer art advances, one hopes it will move towards the use of devices that listen intently rather than speak loudly. It is in this direction that the transistor can make its earliest contribution to the digital computer field.

## Computer Functions

As is well known, computer operations can be divided into the two classes, memory and logic. Memory can be defined as a representation in space of a function of time. The logic operations can be defined as the recognition of spatial distributions of voltages and currents. These logic operations can be performed with passive nonlinearities, that is, a 3-terminal and circuit and other such logic circuits can be built with crystal diodes without

the use of active elements.<sup>1</sup> It is necessary to use active elements only as amplifiers to make up for loss in these logic circuits and in delay lines. When the work described herein was started, it seemed that transistors could be got into digital computers at the earliest date if the transistors were asked to provide only gain and all the logic functions were performed in diode circuits while the memory functions were performed by use of delay line storage cells. This, of course, is the philosophy that was followed earlier by the SEAC group<sup>2</sup> with the exception that they used a vacuum-tube amplifier rather than a transistor amplifier. Since the transistor itself has voltage and current relationships quite similar to a germanium diode, it is expected that the germanium diode in a transistor computer will operate in a more natural environment than in a vacuum-tube computer and will respond to such favorable conditions by exhibiting longer life and more reliable operation than it has sometimes done in the past.

## Reliability

Many earnest seekers have attempted to find out what kind of reliability can be

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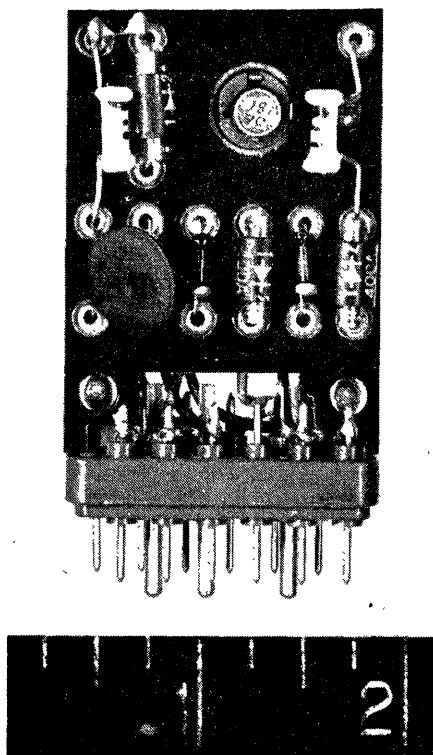


Figure 1. Packaged pulse amplifier

expected in transistors. The answers that they obtained seem to stem as much from the inquirer's pessimism or optimism as from the facts of the case. This is because there have not been many facts established and the reliability tests that have been performed simply have not been on large enough samples nor have they been carried out over a long enough period of time to prove decisively what the reliability of transistors will be. This is not the result of negligence upon anyone's part but stems from the fact that the transistor is only 3 years old. Reliability estimates are complicated by the fact that the transistors that were put on life test as recently as a year ago are known to be very inferior to the transistors that can be made today. One figure that is indicative of the kind of life we may expect is that life figures of 70,000 hours have been predicted on the basis of 25,000-hour tests for devices that were made several years ago. It should be understood that the transistors for which this prediction was made are not the modern transistors we would use in a high-speed digital computer nor were the failure criterion used in the test necessarily the ones that would apply for use in a digital computer. It seems reasonable to say that in its relatively undeveloped state, the transistor appears to have a life that is equal to or better than the best vacuum tubes that have been made for digital computer use. Because transistors operate at reduced

power levels the ambient temperature is expected to be lower in transistor computers. Resistors and condensers will operate at lower voltages and currents as well as temperatures and longer life is expected. The low voltage at which transistors operate is expected to improve the life of associated semiconductor diodes by a considerable factor.

Besides the reliability, and the power level, the speed of operation is also of interest to the computer designer. When comparing transistors to vacuum tubes one is used to thinking of the transistor as a relatively slow device. This is because vacuum tubes can be made to oscillate at 1,000 megacycles or above while transistors cannot. However, the highest frequency of steady-state oscillation is not a satisfactory criterion for the success of a device in a computer. A good vacuum tube may not have serious transit time limits upon its use at frequencies below 1,000 megacycles but the parasitic impedances of the same vacuum tube will limit its use in wide band circuits to bandwidths of about 20 megacycles. High-speed transistors are, at the present time, limited by transit time considerations to frequencies below about 50 megacycles but the parasitic limits are at frequencies above the transit time limitation. For that reason, the slow hole and electron of transistor electronics may be a better carrier for the production or regeneration of high speed pulses than is the much faster electron of vacuum tube electronics. This is a factor which is expected to grow in importance as transistors are improved. At the present time, transistors are entirely practical for the regeneration of pulses at a megacycle rate and rates of perhaps five times as much could be attempted with reasonable hope of success. This puts the transistor in a competitive position with vacuum tubes insofar as speed is concerned.

### Completed Components

One of the first transistor computer efforts has been the development of the high-speed regenerative amplifier shown in Figure 1. This amplifier operates from a maximum supply voltage of  $-8$  volts. The total power drain of the amplifier is approximately 50 milliwatts. When triggered by an input pulse of 2 volts and a current of 0.75 milliamperes this amplifier will develop a 5-volt 10-milliamperes output pulse. The input pulse need last for only a 0.1 microsecond and the output pulse will be a 0.5 microsecond pulse whose duration and time position is set by a master clock signal rather than the input pulse. The ampli-

fier is, therefore, an almost ideal amplifier for use in serial computers. The package illustrated was designed to use the plug-in type transistor. Recent attempts to miniaturize the amplifier by using the bead version of the transistor have resulted in the package shown in Figure 2. Using the first package, a binary word generator, a serial adder, delay line storage cells, and a complete 16-digit serial multiplier have been built. The multiplier uses 42 transistors and operates on a total power supply of less than 5 watts. It occupies almost half of a standard relay rack. It is believed that the entire multiplier could be put in about one-third of an ordinary shoe box. To do this, it would be necessary to package the logic circuits as well as the transistor amplifier. It should be pointed out that the most encouraging thing about miniaturizing transistor systems is not so much the small size of the transistor but is the extremely small amount of power that has to be dissipated in the system.

### Regenerative Amplifier

Some circuit considerations may be of interest at this point. Transistor circuit work is handicapped because some of the working concepts that have enabled engineers to turn out vacuum-tube circuits so successfully in the past do not provide the same assistance in transistor design work. In the first place, the input impedance of a vacuum tube is almost infinite, or at least positive. The input impedance of a transistor is more apt to resemble a short circuit than an open circuit and cannot always be relied upon to be positive. In fact, in computer work it proved so difficult to develop high-speed circuits in which the transistor input impedance was positive that almost all

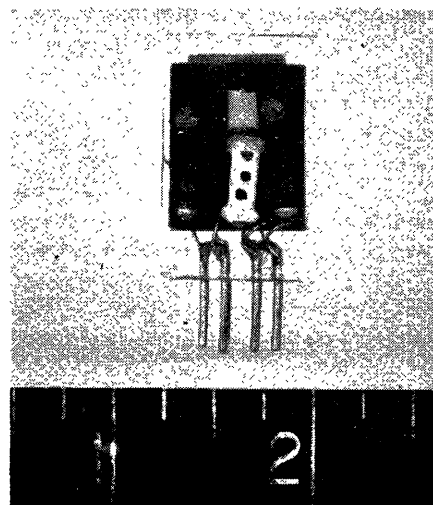


Figure 2. Miniaturized pulse amplifier

workers in the field have decided to live with the negative input impedance and exploit it rather than try to suppress it. Then too, the difficulty of working into a short circuit has proved to be a considerable psychological handicap. However, most workers in the field now consider that a short circuit is just as respectable an input impedance as an open circuit is. In Figure 3, the input characteristic of a diode is illustrated. When the bias is negative the input impedance is very high and when the bias is positive the input impedance is very low. The input characteristic of some transistors follows the same general form. The transistors made for high-speed applications, however, have the type of characteristic shown in Figure 3. If the voltage at the emitter is first negative and then raised towards ground, the emitter current will be very small and of the same order as the reverse current of a diode. As the voltage is raised, a point will be reached at which the input impedance becomes negative. This point is called the peak point. The point on the characteristic at which the impedance ceases to be negative is called the valley point. This characteristic has been exploited in the circuit shown in Figure 4. The circuit is arranged so that without a transistor present, current will flow through  $R1$  and diodes  $X1$  and  $X2$  to hold the junction of diodes  $X1$  and  $X2$  at a voltage just below the peak point of the transistor. When a transistor is inserted the emitter current taken will be very low. Now if the input lead is raised above the peak point, the emitter will be raised in voltage to its negative resistance region. If the transistor has sufficient band width it will not be stable on the negative resistance portion of its characteristic and will snap out on a load line provided by the stray capacity of the circuit to a point  $D$  illustrated in the figure. The capacity will then discharge from  $D$  to  $B$  at which point diode  $X2$  will conduct and the transistor will be locked up in its high current state. Once the emitter starts to go negative diode  $X1$  cuts off and the driving source is isolated from the emitter. What has been described is a flip-flop rather than an amplifier. However, by supplying a regular succession of reset pulses to the base of the transistor, the circuit can be made to behave as a pulse regenerator, that is, every time an input signal locks the transistor in its high current state the next positive pulse that comes to the base will reset the transistor to its low current state.

The circuit has been used with a reset pulse consisting of a 1-megacycle sine-wave signal from a master clock. The

diode  $X3$  permits only the positive halves of the sine-wave to appear at the base. If the transistor has not been locked up in its high current state by an input signal, the base pulse will have no effect on the transistor. However, if the transistor is locked up at  $B$  the positive base pulse in effect pushes the emitter voltage down towards  $C$ . When the negative resistance region is reached at  $C$ , the emitter snaps over to the high impedance portion of its characteristic and the stray capacities charge back to point  $A$  where the circuit rests as it awaits another trigger. If the signal arrives just before the clock lets the base voltage reach ground, the transistor will trigger when the clock signal goes through ground and the onset and the end of the square wave output will be determined by the clock rather than the input, provided only that there is an input. Since the input voltage must raise the emitter only from point  $A$  to above the peak point, little voltage is required to trigger the transistor. An output voltage of 4 to 6 volts is obtained at the collector. The input current need be only slightly greater than the current that flows through  $X1$  into  $R2$  when the circuit is in the quiescent state. In the circuit shown the required input current is about 0.75 milliamperes while the resulting collector current is of the order of 10 milliamperes. As transistors are made with peak points that are more uniform, the point  $A$  can be brought closer to ground and the triggering voltage can be reduced. The present practice is to bias  $X2$  at  $-1$  volt and supply a trigger of about 1.50 volts. This means that the only requirement on the transistor peak point is that it lie between  $-1$  and  $+0.5$  volts. It is believed that a bias on  $X2$  can be chosen that will make the circuit extremely reliable. Experience indicates that obtaining reliability from transistors is by and large a matter of designing circuits that allow sufficient margin for such variables as the peak point.

### Uses of Amplifier

The nature of the input circuit makes the addition of diode logic circuits very simple as shown in Figure 5. To obtain a 3-terminal *or*-circuit it is only necessary to connect the three terminals to the input through diodes pointing towards  $X1$ . The amplifier will then produce an output pulse whenever there is a signal on any of the three input leads. To obtain a 3-terminal *and*-circuit, it is necessary to add only two additional diodes connected to the emitter just as  $X1$  is. Each of the diodes is returned to  $-8$  volts through a

resistor corresponding to  $R2$ . Then the emitter can be raised above the peak point only when positive inputs are applied to all of the input leads and all three diodes are cut off. Inhibition can be obtained by means of an inverting transformer and another diode connected to the emitter and returned through the transformer secondary to a positive voltage. In the absence of any input the emitter is held below the peak point by diode  $X1$ . If diode  $X1$  were cut off the circuit would fire. However, if a positive pulse were fed to the primary of the inverting transformer, the added diode would clamp the emitter below the peak point and the transistor could not fire regardless of what happened to  $X1$ . These elementary logic functions are a complete set and all logic operations can be mechanized by a suitable combination of these elementary ones.

For memory purposes, a delay line is suggested with the transistor amplifier described above used to amplify and retime the delayed signals before they are recirculated. For the kind of memory that is ordinarily provided by a flip-flop, the regenerative amplifier is suggested with its output fed back to its input through a simple delay network. This device has the property that when it stores a one it puts out a continuous train of digit pulses and when it stores a 0 puts out nothing. The reason that the transistor flip-flop itself is not recommended for storage is that when a transistor is left locked up in a high-current state it takes a great deal of power to unlock it and it is easier to obtain that power from a steady-state clock signal than an information containing signal that would have to be supplied by the computer. What amounts to permanent storage is obtained and yet the transistor is still turned off every microsecond by the master clock.

### Proposed Building Blocks

In the first experimental work, only the amplifier was packaged and the external logic circuits and the delay lines were mounted external to the packages. This is why the multiplier took half of a relay rack to mount. To achieve miniaturization consistent with the size of the transistor itself, all the components must be packaged efficiently. Unless a wide variety of packages are developed one must be contented with a relatively small number of available functions and achieve all results with that restricted set. This minimizes the different types of packages required in the computer but probably results in using a greater number of tran-

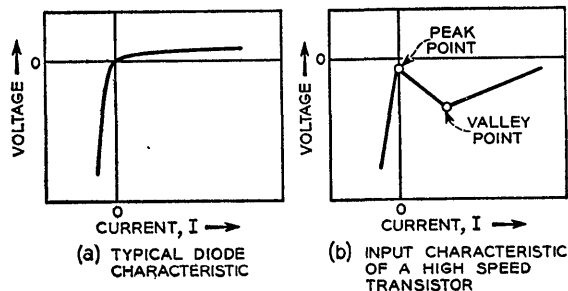


Figure 3 (left). Input characteristics

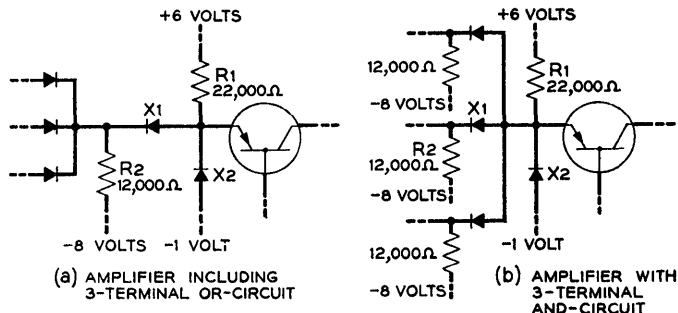


Figure 5 (right). Basic logic circuits added to amplifier

sistors than would be required if a wide variety of functions each designed for a minimum number of transistors were included in the available set.

The set of functions shown in Figure 6 is proposed as a reasonable set for the arithmetic organ of high speed computer. Each package is complete and can drive several packages in parallel. The first package is a 2-terminal *or*-circuit with pulse amplifier. The second is a 2-terminal *and*-circuit with pulse amplifier. The third package proposed is an inhibitor circuit which will regenerate the signal on the lower lead unless there is a signal on the top lead in which case there will be no output at all. In serial arithmetic units some memory is required and the fourth package is proposed as a replacement for the ordinary flip-flop. If a pulse is put on the one lead the bit cell develops a train of timed digit pulses until it is shut off by a pulse on the 0 lead. The fifth package is used to build up memory components for more than one bit. It consists of the transistor amplifier with a simple delay network to delay the output pulse by 1-digit time. If small delay lines were available this fifth package would not be necessary. But until very

much smaller delay lines than are now available are developed, such a package will be very attractive in applications where space saving is important.

One of the reasons that so much emphasis is put upon the small size is that the transistors now available are temperature sensitive. It would complicate transistor design considerably if high-speed transistors had to be made at this time that would operate at very high temperatures. Fortunately, the transistor because of its low power operation does not itself generate much temperature rise, therefore, the transistor may not have to operate at temperatures above ordinary room temperatures. However, applications are foreseeable in which the effective room temperature may be considerably above that, for example, of a university laboratory. For these applications the fact that 400 or 500 transistors with associated circuits can be put in a volume of the order of a cubic foot and that the entire power dissipation of such a computer may be of the order of ten watts

gives us the hope that an entire computer can be placed in a box small enough to be held at a reasonable temperature.

Insofar as predictions for the future are concerned an optimist might subscribe to these: the power per stage will be reduced to the order of 100 microwatts; repetition rates for pulses will increase to 10 megacycles and perhaps 50; miniaturization will be so complete that no application of a digital computer need be held up because space is not available; reliability will be so improved that systems with 100,000 transistors will be practical and the venturesome will contemplate systems containing 1,000,000 transistors.

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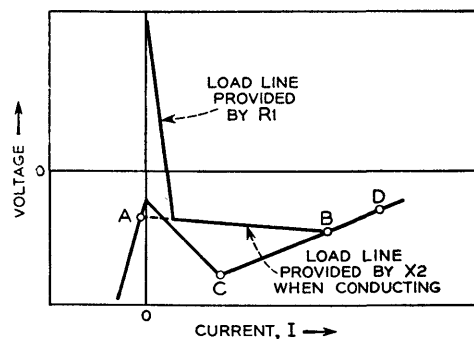


Figure 4 (left). Schematic of pulse amplifier

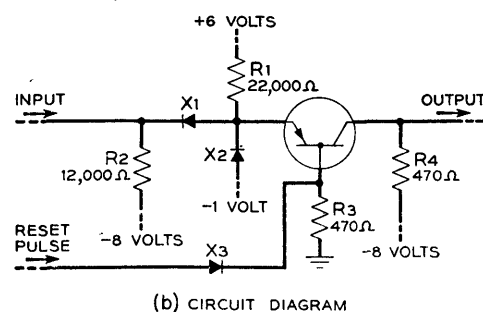
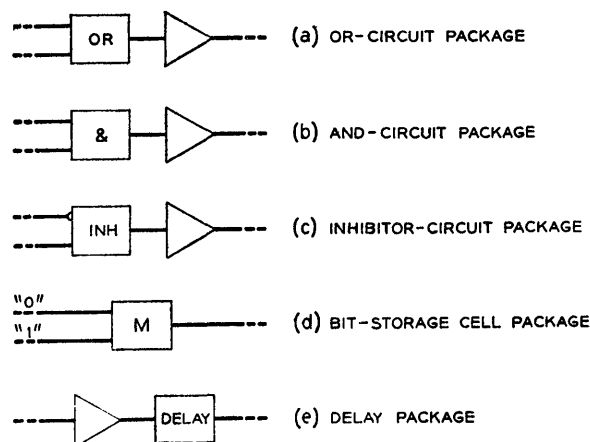


Figure 6 (right). A set of functions for a digital computer



## Discussion

**I. L. Auerbach** (Burroughs Adding Machine Company): Could you tell us the temperature at which you are encapsulating the transistors and crystals and the effect it has on their life?

**J. Felker:** I do not know what that temperature is. I know it is possible to put these in the capsule and still have a satisfactory yield. In other words, we have working units that have been put in plastic.

**J. C. McPherson** (IBM): On the circuits you have already built, what is roughly the ratio of diodes to transistors?

**J. Felker:** The basic amplifier requires three diodes to help the transistor operate as an amplifier. Then if you put the logic functions on also, you can get by with as few as three additional diodes per transistor. If you want to use more logic circuits, the number of diodes will go up. But I would estimate something like eight to ten diodes per transistor in a balanced machine design.

**F. C. Mullaney** (ERA): Your diagram showed certain values on the components. Must these values be changed as different transistors are inserted in the circuit?

**J. Felker:** No. In our multiplier, for example, which had 43 or 44 transistors in it,

all the amplifier circuits were identical to the extent that we could get them so, and all the transistors were interchangeable to the extent that anyone tried to interchange them.

**E. D. Lawler** (Naval Air Development Center): From what I have read, there are a number of different types of transistors. Could you specify exactly the one you used in the circuit?

**J. Felker:** The transistor that was used in these circuits carries the number, M-1734; the short title is "the high-speed transistor." I might mention that it is a point contact transistor, not the junction-type transistor.

# Digital Computers: Present and Future Trends

JAY W. FORRESTER

**T**HE Program Committee asked me to summarize the present status of digital computers; also to point up the better features of the machines described at this Conference, and to forecast trends to be expected in the future.

We might start by determining where the digital computer field now stands along the road of progress. The first round of electronic digital computers has been completed, with a variety of machines showing varying degrees of success. The competitive spirit and rivalry between groups engaged in computer development has been strong in the past. We have met at this Conference for a frank discussion of the good and the weak points of the various machines. Some papers have stressed the good points and the successes. Others have stressed the future objectives. Still others have given us a picture of the shortcomings and weaknesses of the existing machines and frank, although conflicting, evaluations of what these results indicate for the future.

## Present Status

A comparison of the present status of the digital computer field with any of our older branches of engineering shows that we are not far advanced. We are

firmly on the threshold of a new field, but the digital computer work has reached no real maturity. Up to the present time people have made impressive contributions to the field of digital computation. Digital computation, however, has not yet made nearly the contribution to society that our enthusiasm might lead us to believe.

Maintaining the proper perspective here is important. It is entirely possible that the work of the world which has been accomplished by the modern automatic digital computer could have been more than accomplished if the man hours thus far put into the development of digital computers had instead been applied to the solution of the ultimate problems. We must look upon the results thus far as an investment in the future. We have first models of a new type of machine. There is no reason to believe that they are relatively any more advanced than were the first models of automobiles, the first aircraft, or the first radio sets.

Some rather remarkable attitudes have existed in the digital computer field. First models, without any tested predecessors, have been scheduled for production. Contracting officers have even bought first experimental machines on the assumption that they would be final production models rather than being

useful primarily for evaluation. In few other fields would this be done. A first model of a new airplane is built for testing and evaluation, not for delivery to the fighting Air Forces or to an airline. -

The machines reported at this Conference might properly be looked upon as exploratory models for evaluating physical techniques and design procedures, as vehicles for the assembly and training of organizations capable of designing computers, and, to the extent that the machines operate successfully, as devices for training people in the use of digital computers.

Big steps have been taken, but they represent only a beginning on the road ahead. We have first models of machines, but we don't even have adequate or recognized evaluation criteria for their assessment or discussion.

We are almost without experience in using these machines outside a development laboratory atmosphere. Most of the machines are still under the care of their designers or operated in a sympathetic research laboratory environment.

Until now we have been occupied by plans for proposed machines. In this new period ahead when the electronic digital computer is being evaluated, we will obtain results from the first round of computers and interpret these results for guiding future models of machines.

In building the first generation of electronic digital computers, we have learned the magnitude of the engineering involved. In the past 5 years, time estimates in the digital computer field have been a standing joke. Many of the cost

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