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THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

departments

the cover

The painting, "Integrated Circuitry," is the free-wheeling interpretive work of a man well known in the electronics industry, Dr. Daniel Noble, Vice Chairman of the Board of Motorola, Inc. In the interview that begins on page 96, Dr. Noble discourses on the progress and problems of the integrated-circuitry art, and portrays for us his recent involvement in another art, that of painting.

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Spectral lines

The New Publications Board. Some changes were made in the IEEE Bylaws by the Board of Directors at its August meeting in San Francisco, Calif., which will affect the publications of the Institute. The objective is an improved publications program.

For some time it has been recognized that the functions of the Editorial Board, of which the IEEE Editor (the undersigned) is the chairman, have expanded into several areas other than those of a strictly editorial nature. As well as being concerned with the editorial policies and practices of SPECTRUM, the PROCEEDINGS, the STUDENT JOURNAL, and less directly with the TRANSACTIONS, the Editorial Board has also been wrestling with problems such as the implications of automated procedures for handling information, the program for translating journals from Russian and Japanese into English, improving abstracting and indexing procedures, the appropriate role of advertising in IEEE publications, and the overlap between publications.

In recognition of this wider sphere of activity, the Board of Directors replaced the present Editorial Board with a Publications Board. To make it representative of all IEEE publications it included two editors of Group TRANSACTIONS as members. In addition to the two Group editors, the new Board will include the editors of SPECTRUM, the PROCEEDINGS, and the STUDENT JOURNAL, three to six additional members, a chairman, and a vice chairman. If the membership of the Institute approves the Constitutional change required, the chairman will have the title of Vice President for Publications Activities.

In a further change, the PROCEEDINGS and SPECTRUM will now be organized with a volunteer Editor, an Editorial Board, and a Managing Editor from the headquarters staff. This organizational arrangement should strengthen these publications by putting them under more direct management than previously, and should make them more responsive to members' needs.

The Bylaws revision also gives the new Publications Board explicit responsibility for coordinating all the technical publications of the Institute. The role of each of the IEEE publications will need to be clearly enough defined so that there will not be large areas of overlap or large gaps in the Institute publications.

Another addition to the Bylaws was the formalization, as a standing committee, of the Panel of Group Editors. This Panel, whose membership consists of the editors of each of the Group publications, is a mechanism for implementing overall policies. In operation since last March, it has already proved effective in tackling problems common to all of the publications.

These changes are designed to enable the Institute to improve its publications. But what are the problems? A partial list follows:

1. To improve the technical integrity of our publications by improving review procedures and other techniques for eliminating unsound material.
2. To reduce the delay between submission and publication of material.
3. To reduce the overlap among our present publications so that authors know to which periodical their papers should be submitted and readers know which periodicals they should read to keep current in their fields.
4. To modify the scope and content of present publications or start new publications in response to new needs.
5. To modify or eliminate those publications that have proved that they are not effective channels for the dissemination of technical information by their inability to attract enough good papers to maintain regular publication schedules.
6. To draw a clear distinction between papers that are written for oral presentation and those whose contents are such that they should be part of the permanent record.
7. To develop publications that do as effective a job of presenting present technological applications as they do for new research and development results.
8. To develop a clearer view of factors affecting publication economics.

Even this incomplete list gives some indication of the challenge facing the new Publications Board.

F. Karl Willenbrock

Semiconductor switching at high pulse rates

Semiconductor devices are now being used in high-speed switching circuits that require not only transition times as short as one nanosecond but also repetition rates above 100 Mc/s

Dankwart Koehler *Bell Telephone Laboratories, Inc.*

The availability of increasingly fast semiconductor devices is continuously opening up new fields of application. Those fields, in turn, stimulate the device designer to increase the speed of these devices even further. The circuit engineer who is working at this speed frontier is faced with the problem of always utilizing the presently available elements to the limit of their capabilities.

The following study represents an up-to-date survey of the state of the art in the field of high-speed digital circuit techniques. Such a survey cannot claim to be exhaustive and is necessarily biased by the personal experiences of the writer.

The technology and the discussion apply to various fields of application such as computers, digital data processing, pulse code modulation, or nuclear detection. We shall restrict ourselves to pulses that are characterized not only by rise and fall times of the order of one nanosecond, but also by high repetition rates of 100 to 500 Mc/s.

Available semiconductor devices

Transistors. We can no longer expect an increase in transistor cutoff frequency by something like a decade per year, as was the case in the early days of the transistor. Instead, we seem to approach almost asymptotically some upper limit. Such a limit exists, at least for a given transistor technology, and can probably be overcome only by means of basically new concepts. The field of majority carrier transistors might, for example, be a candidate in this respect.

Based on previous work by Pritchard,[1] J. M. Early[2] in 1958 computed the following relation for the gain bandwidth limit in germanium transistors:

$$\sqrt{\text{Power gain}} \times \text{Bandwidth} \simeq \text{Max. frequency of oscillation} \simeq \frac{7.5 \times 10^6}{s}\ \text{c/s}$$

where s is the width of the emitter stripe in centimeters. In mesa transistors, stripe widths of about 0.3 mil are technologically feasible. This width corresponds to a calculated maximum frequency of oscillation of about 10 Gc/s. Practical f_T values of germanium mesa transistors are as high as 3 to 3.5 Gc/s, which corresponds to a maximum oscillation frequency of perhaps 5 to 6 Gc/s.[3] The upper frequency limits are determined not so much by the problem of making the stripe width sufficiently small as by the difficulty of attaching contacts to these small stripes. Other problems include the undesirable formation of excessively high local current densities associated with devices of such small dimensions.

With the present extension of planar technology to germanium devices the contacting difficulty is being overcome, and stripe widths as small as 0.1 mil are now feasible. Thus we can expect the f_T values of germanium transistors to increase to about 6 Gc/s within the next few years.

The speed of silicon transistors lags behind that of germanium transistors by about a factor of three, mainly because of the smaller carrier mobility in the base and in the collector depletion layer of silicon transistors. Commercially available silicon transistors have entered the frequency range between 1 and 2 Gc/s.

With respect to speed, both the germanium and the silicon transistor are at a disadvantage when compared with tunnel diodes or charge-storage step-recovery diodes. But other properties such as large power gain, isolation, or impedance transformation compensate for this deficiency and keep the transistor in the center of interest even at pulse rates as high as 300 megabits per second. For use in this frequency range, however, it is necessary to optimize the operation of the transistor with respect to its speed capabilities.

Majority carrier transistors. There has been an increasing amount of interest in recent years in various types of transistors that might collectively and vaguely be identified as "majority carrier transistors." As an attempt at classifying such transistors, we might distinguish the following groups[4,5]:

1. Field-effect transistors
2. Space-charge-limited transistors
3. Metal-base transistors
4. Tunnel-emitter transistors

Of these groups only the field-effect transistors have reached a sufficient degree of reliability to be considered for mass production. According to Early's paper,[2] the speed which can be achieved with the FET lies about an order of magnitude below that of germanium mesa transistors. The speed is ultimately limited by the charging time constant of the gate capacitance and by the drift time of the carriers that have to traverse through the length of the channel (and not, as in junction transistors, perpendicular to the plane of a small base layer). On the other hand, carrier storage effects are normally negligible in majority carrier devices. With "induced channel metal oxide field effect transistors"[6,7,8] switching times of the order of 10 nanoseconds have been achieved.[7]

The speed properties for the metal-base transistor were predicted to be inferior to those of the field-effect transistor.[4] More recent announcements in the press, however, indicate theoretically possible frequency limits of 10 Gc/s.[9] So far, the indicated devices are not available on the market. The future development in the field of majority carrier devices deserves some attention.

Avalanche transistors. The avalanche effect in transistors permits generation of short pulses in the nanosecond range.[10,11] Nevertheless, we shall omit the avalanche transistor from our further considerations for two reasons. The dominant reason is its excessive recovery time, which normally precludes its use at high repetition rates.* The second reason arises from the fact that very few manufacturers are willing to guarantee a sufficiently close tolerance on the collector breakdown voltage, since such control in production is uneconomical. As a consequence, each circuit in which avalanche transistors are used must normally be adjusted to the particular transistor unit.

Computer diodes. Above 200 Mc/s, computer diodes can be used to perform logic operations; but, due to the lack of gain, they must be supported by active elements. A diode for use in high-speed circuits must meet three requirements. The capacitance must be of the order of 2 pF or less. The recovery time must generally be less than 1 ns; that is, after being operated in the forward direction, the diode must open up very quickly when reverse biased. Furthermore, the voltage drop across the parasitic inductance must be small compared with the drop across the diode resistance; typical values for the inductance lie between 0.5 and 4 nH.

The advent of the metal semiconductor diode (also called "Schottky diode" or "hot-carrier diode") is closing an existing gap in available high-speed devices. The recovery times of these diodes are too small to be measured with presently available sampling oscilloscopes. Even if they were measurable, they would be masked by the effect of the capacitance, which is about 1 pF.

Some silicon point-contact diodes with capacitances around 0.5 pF yield about the same reverse recovery times as the Schottky diodes under the same drive conditions. Reliability and breakdown considerations might give the Schottky diode an advantage over the silicon point-contact diode.

Tunnel diodes. During the time when transistors with f_T values greater than 1000 Mc/s were hardly available on the market, the art of tunnel-diode circuitry progressed greatly. Even today, many circuit functions cannot be performed at repetition rates above 200 Mc/s without the help of tunnel diodes.

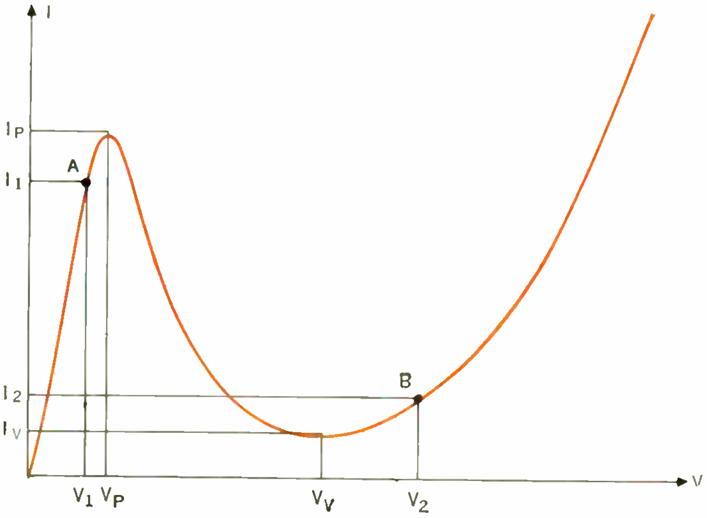
In a simplified representation, as shown in Fig. 1, the switching time for the transition from point A to point B is basically given by the time required to charge the diode and load capacitances from the voltage V_1 to V_2, whereas the available current is given by the difference $I_2 - I_1$ plus any available trigger current. As a first-order estimate the switching time is described[12,13] as

$$T = C\,\frac{V_2 - V_P}{I_P - I_V}$$

More precise switching-time calculations must consider the actual shape of the tunnel-diode characteristic and the path over which the transition between A and B is made; the latter is determined by the parasitics of the diode and by the external circuit.

Switching times of 0.5 to 1 ns are readily achievable;

Fig. 1. Tunnel-diode switching.



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* J. M. Eubanks and R. C. Bedingfield at the Greensboro Bell Telephone Laboratories recently achieved pulse rates above 200 Mc/s with an experimental avalanche circuit in the common-collector mode.

moreover, switching times as low as 50 picoseconds would be feasible were it not for the degrading effects of parasitics, especially the package capacitance and inductance. Integration of the tunnel diode with the adjacent circuit components is therefore quite desirable.

The disadvantages of the all-tunnel-diode circuit are generally known: lack of isolation, low immunity to noise, tight tolerances for other elements, low voltage swings, and certain reliability and aging problems (especially with gallium arsenide diodes). An example of how the tunnel diode can be usefully combined with charge-storage step-recovery diodes will be shown subsequently.

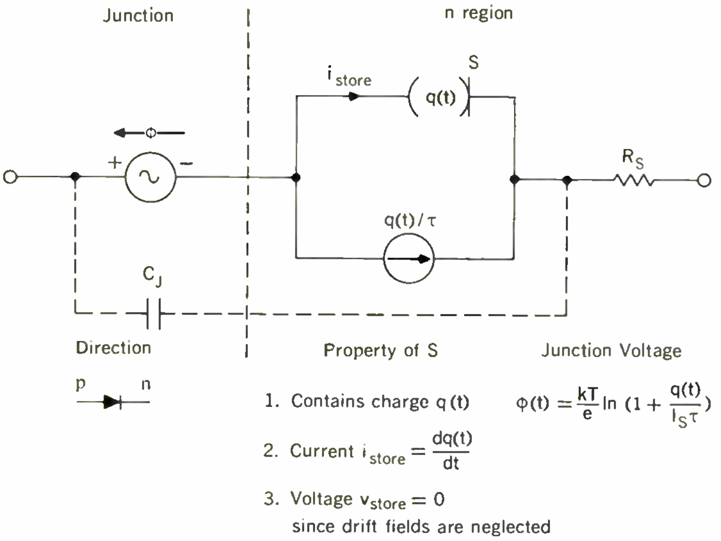
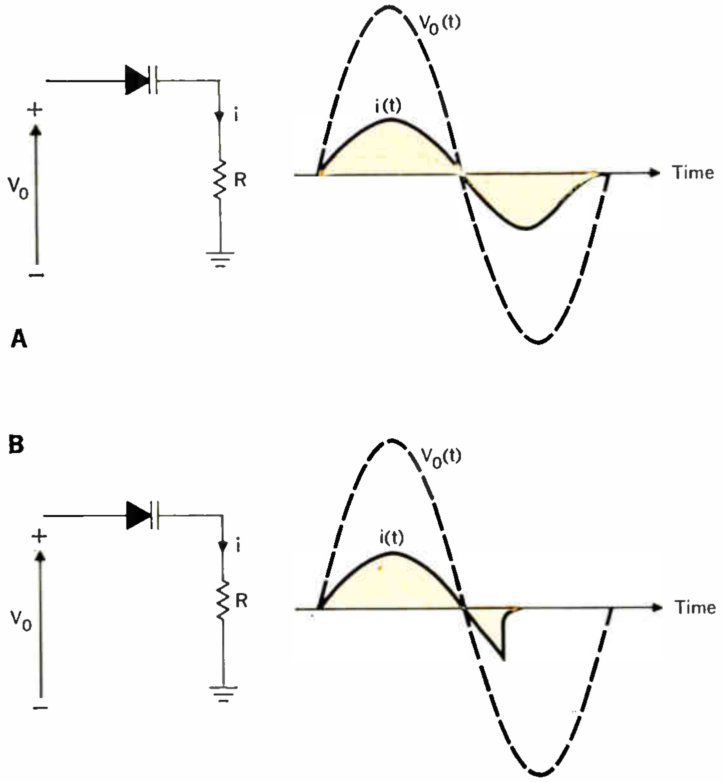


Fig. 2. Diode charge-control equivalent circuit.

Fig. 3. (A) Charge-storage and (B) step-recovery properties of diodes, with sine wave applied.



Charge-storage step-recovery diodes. Charge-storage diodes that exhibit the so-called step-recovery effect have proved to be quite useful in the field of high-speed pulse circuitry.[14-18] Note that the charge-storage property and the step-recovery or "snap-back" feature are two different physical properties; charge storage does not imply step recovery, and the step-recovery effect can exist with little storage (in which case it is, however, less efficient). This statement needs to be qualified: Since the stored charge is exposed to a relaxation process, this "efficiency" increases with frequency, as will become evident from the following considerations.

Figure 2 shows a simple charge-control model[19] of a diode. Except for numerical values it is, in a first-order approximation, valid for computer diodes as well as for step-recovery diodes. The voltage source simulates the junction. This voltage is a logarithmic function of the carrier density at the boundary between the junction and the n region or, in a first-order approximation, a logarithmic function of the total stored minority carrier charge. (For most applications it suffices to use a piecewise linear approximation of this function.) S is a store[20] which is described uniquely by the relation

$$i = \frac{dq}{dt}$$

and since drift fields are neglected in the model, the voltage is described as

$$v = 0$$

(It can be visualized as an infinitely large capacitor.) The current source q/τ represents the charge loss caused by recombination.

In a "charge-storage" diode, the recombination time τ is so large that the current through the current source q/τ is small compared with the current dq/dt that discharges the store. Note that this requirement is a function of the operating conditions. The shorter the charging and discharging times the closer a given diode "approaches" such an ideal charge-storage diode. Figure 3(A) shows the current through a charge-storage diode* for the case of an applied sine wave. If a diode's behavior is very close to that of the idealized model shown in Fig. 2 and if the junction capacitance C_J is small, then the current waveshape approaches that shown in Fig. 3(B). As soon as all of the stored charge is recovered, the current suddenly becomes zero. Low values of C and R are necessary but not sufficient conditions for this step recovery. Another condition is that no "dirt effects," such as surface recombination, prevail. The step-recovery effect in diodes can be produced in two ways: first, by a fairly abrupt junction with retarding field in the region where storage occurs, and second, with certain p-i-n diodes having abrupt junctions.

Step-recovery diodes that show this behavior have found applications in three fields:

1. Generation of harmonic components (up to 11 Gc/s)[21-24]
2. Pulse generation and current amplification[25]

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* Because of the lack of a standard circuit symbol for charge-storage diodes, the special symbol shown in Fig. 3 is used throughout this article.

3. Logic[26-28]

Concluding remarks on high-speed devices. The tunnel diode has gained the most widespread popularity in nanosecond circuitry. As more transistors with f_T values above 1 Gc/s become available, the interest in transistors increases. In combination with tunnel diodes or transistors, the charge-storage step-recovery diode has proved to be a useful tool. Whether the majority carrier transistor moves up to the forefront of high-speed devices remains to be seen.

Synchronous circuits

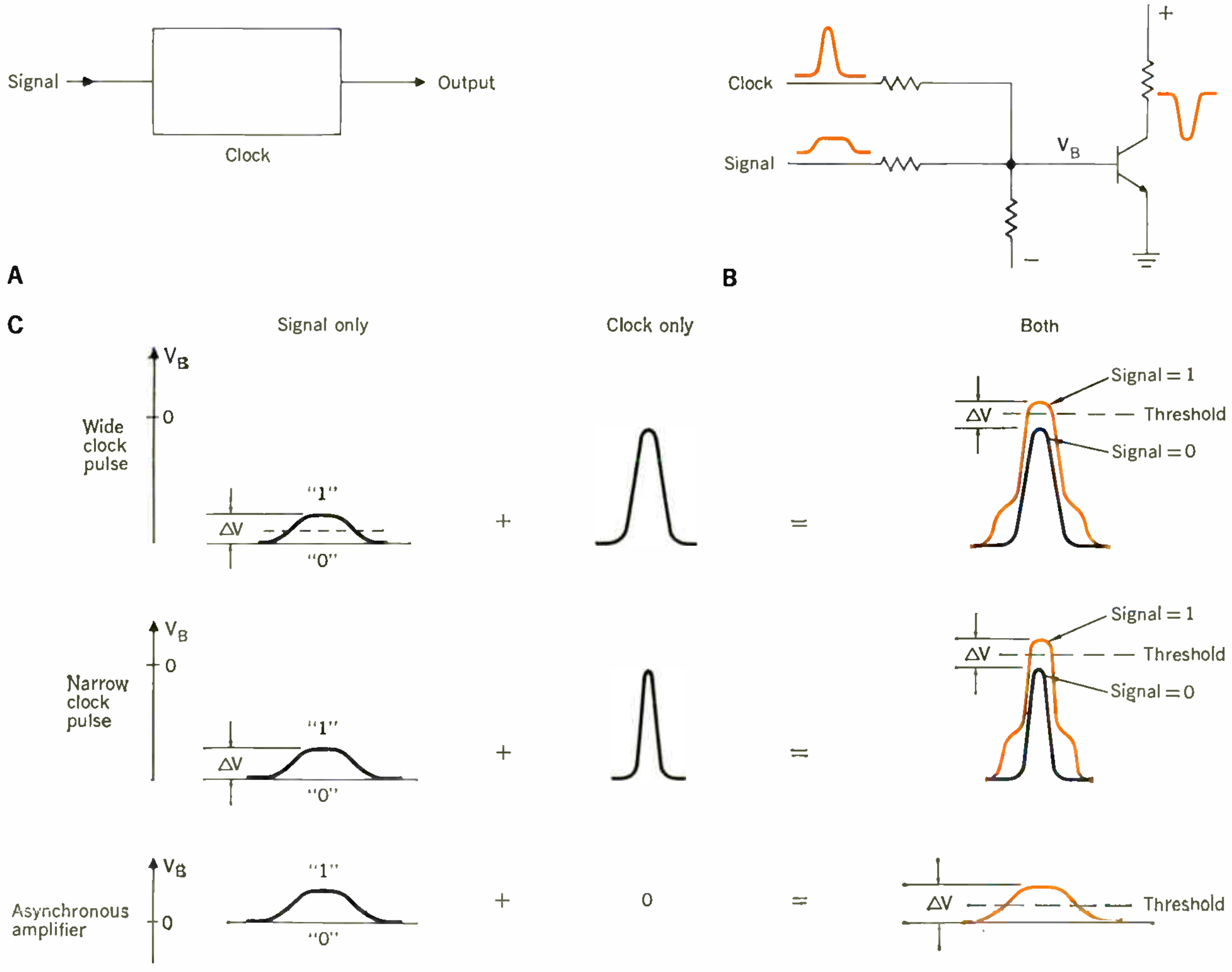
Before we begin to discuss the optimal use of the foregoing devices, it appears appropriate to insert some remarks about synchronous circuits. The basic concept stems from the realm of switching logic; there a group of logic circuits is usually called "synchronous" if the instant at which a logic switching operation is performed is determined not by the transient of some preceding circuit but by the occurrence of a clock pulse. Organization of the occurrence of the clock pulse at any specific circuit must, of course, allow adequately for any transients in the preceding stages.

In this study of pulse circuits we shall not try to answer the question of whether synchronous logic is more suitable than asynchronous logic for building a high-speed computer. The answer depends, for example, very much on the statistical variations of switching times; the optimum solution might well be some hybrid form of the two principles, in which certain groups of asynchronous circuits operate synchronously with other similar groups. Our primary concern is with the individual pulse circuit, be it a logic circuit or not. Here the question that arises is whether or not certain performance parameters, such as switching times, logic delays, or threshold resolutions, can be improved by the use of a centrally controlled auxilary clock pulse.

An attempt is made in Fig. 4 to illustrate the effects of a strong clock pulse, as used in synchronous circuits, on the switching properties of a nonlinear pulse amplifier. The chosen circuit is only a very simple example of a synchronous circuit, yet the arguments brought forth below are believed to hold for many or even most synchronous circuits.

A signal and a clock pulse are fed additively to a circuit element, which in Fig. 4 is the base of a transistor. As is usually the case in synchronous circuits, the clock pulse is assumed to be large in amplitude. Figure 4(C) shows the superposition of the signal and the clock at the strongly reverse-biased base in terms of the base voltage,

Fig. 4. Illustration of the speed advantage of clocked circuits. A—Block diagram. B—Realization example (regenerative pulse amplifier). C—Base-voltage addition.



and compares this synchronous case with the asynchronous situation. In the latter, no clock is used and the base must be more positively biased, or, in other words, the clock must be replaced by an equally large dc level.

The discrimination ΔV between a logical "1" and a "0," as defined in Fig. 4, is practically the same in the synchronous and in the asynchronous case. The presence of the clock pulse yields a larger delay time in the clocked circuit. With the use of a clock pulse whose width is narrower than the signal pulse, the leading edge of the output pulse is determined mainly by the clock pulse; the faster the clock pulse rises the shorter is the output rise time, but this occurs at the expense of delay. The advantage of the clocked circuit lies mainly in the turnoff process. The turnoff time is greatly improved by the use of the clock pulse, since the base is driven rapidly toward a very large reverse bias point, and, therefore, draws a much stronger reverse current than in the asynchronous case. It is evident from this example that this turnoff effect is especially useful if it is employed to enhance the discharge of minority carrier storage—that is, to turn off a saturated transistor.

Transistor operation at high speed

It is possible to establish certain basic rules for the operation of transistors in nonintegrated lumped circuitry. The circuit designer usually has to cope with parasitic circuit capacitances of at least 0.5 to 1 pF and parasitic inductances around 3 to 5 nH. This results in an optimal impedance level of

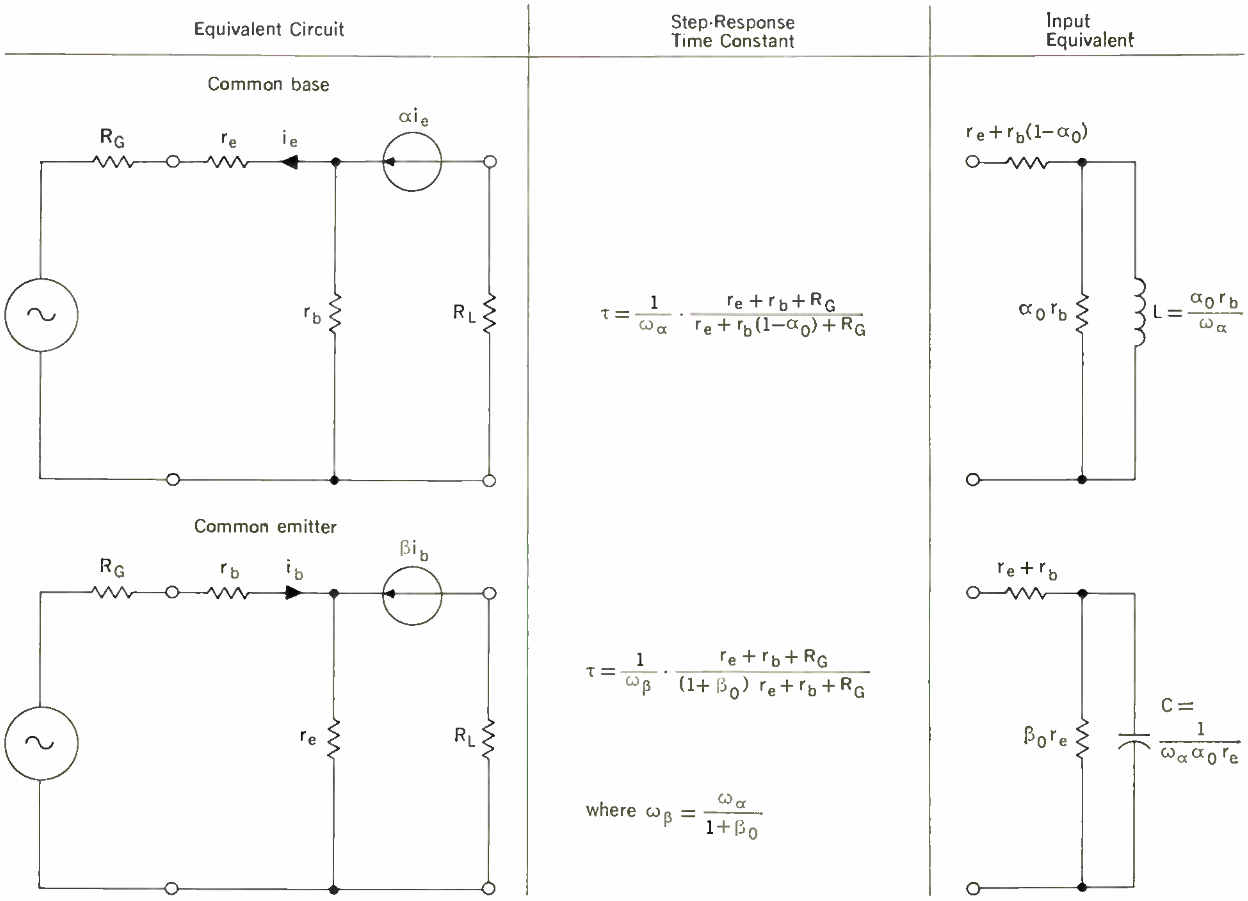
$$R = \sqrt{L/C} = 50 \text{ to } 100 \text{ ohms}$$

If the power dissipation is to be maintained at a tolerable level, pulse amplitudes above 1 or at most 2 volts are undesirable; however, for reliable switching of diodes, one might want to set a lower limit of 1 volt. This leads to current amplitudes of 10 to 40 mA, which corresponds to the upper limit of presently available high-speed transistors.

A good rule of thumb for common-emitter connections is to make $C_{ob}R_L$ about half as large or, at most, equal to $1/\omega_T$, where C_{ob} is the collector-to-base capacitance and R_L is the load resistor. If this condition is not met, one either "wastes" C_{ob} or ω_T. (The manufacturer too can trade off these two values within certain limits.) Transistors in the 1- to 3-Gc/s range usually have C_{ob} values between 0.4 and 2 pF. The optimal load resistance is then around 80 ohms.

The three basic connections. As a starting point for a discussion of the basic transistor connections, the results of a crude analysis of the common-base and the common-emitter connection in the linear region are tabulated in Fig. 5. (All capacitances are omitted for simplicity.) The figure gives the time constants obtained in the output wave as a consequence of step inputs in the voltage sources. The common-base connection yields a τ =

Fig. 5. Transistor operation in the linear region for common-base and common-emitter connections.



$1/\omega_\alpha$ time constant if, and only if, R_G is very large compared with r_b.

The time-constant expression for the common-emitter case indicates that τ would approach the value

$$\frac{1}{\omega_\beta(1+\beta_0)} = \frac{1}{\omega_\alpha}$$

if both r_b and R_G could be made small compared with r_e. This condition can be approached only through the addition of an external R_E such as is the case in series feedback amplifiers or in common-collector connections; otherwise the common-emitter time constant is close to $1/\omega_\beta$.

The difference between the various basic connections can be illustrated by means of the pulse shapes observed at the three electrodes. These waveshapes, given in Fig. 6, assume that the common-base stage is operated from an emitter-current step and the common-emitter stage from a base-current step. The common-collector stage would not differ from the common-emitter stage if it were driven with a current pulse. Therefore, a voltage input pulse has been chosen for the representation of the common-collector waveforms in Fig. 6.

Because of the finite diffusion time, the base current has to equal the emitter current at the very first instant. For the common-base connection, this results in a base current spike as shown in Fig. 6(A). The resulting fast response of the common-base stage is obtained only if the source impedance is sufficiently high to force a large current into the emitter whose equivalent circuit is inductive, as shown in Fig. 5. In this case, then, the base charge is controlled by the emitter.

The input impedance for the common-emitter connection looks capacitive. Therefore, in response to a base-current step, the base charge, which is controlled by the base current, builds up gradually. In fact, it builds up β times as slowly as it would if an emitter-current step could be applied. However, the amplitude of this base-current step is β times smaller than the corresponding emitter-current step amplitude required to reach the same output swing.

The output response $i_c(t)$ obtained in the common-collector connection after a base-voltage step has been applied consists of a step followed by an exponential transient, as shown in Fig. 6(C). With increasing load resistor the output step amplitude increases, whereas the relaxation time constant decreases, thus representing a trade-off between speed and gain.

Transistor pulse circuits using the common-base connection. The major disadvantage of the common-base connection as a main digital-circuit building block lies in the lack of current amplification. Apart from this deficiency, the common-base operation represents a useful and reliable circuit design tool.

It has been shown[29] that transformers as coupling elements can be used to provide the necessary current gain. Careful optimization of the transformer ratio with respect to rise time, overshoot, and ringout is mandatory.

A very useful example of a high-speed common-base circuit is the "pulse-routing circuit" in Fig. 7. The positive current pulse from collector Q_1 is routed to Q_2 if the base of Q_2 is sufficiently more negative than Q_3; it is routed to Q_3 if the base of Q_2 is sufficiently more positive. The speed advantage associated with common-base operation is achieved only if the base charges in Q_2 and Q_3 are controlled by the emitter current—that is, if the base potentials have settled before the emitter pulse arrives. Otherwise, the transistor behaves as in the "current-routing circuit" to be discussed later. In the circuit of Fig. 7, Q_1 can also be operated in the common-emitter connection. In all instances, care has to be taken not to saturate any of the transistors.

Speed-up principles for the common-emitter connection. We can learn, from the step-response curves in Fig. 6, that in order to obtain a fast collector response in the active region, the base current must in any connection show a strong peak. In the common-base circuit, this peaking occurs automatically if the source impedance is high

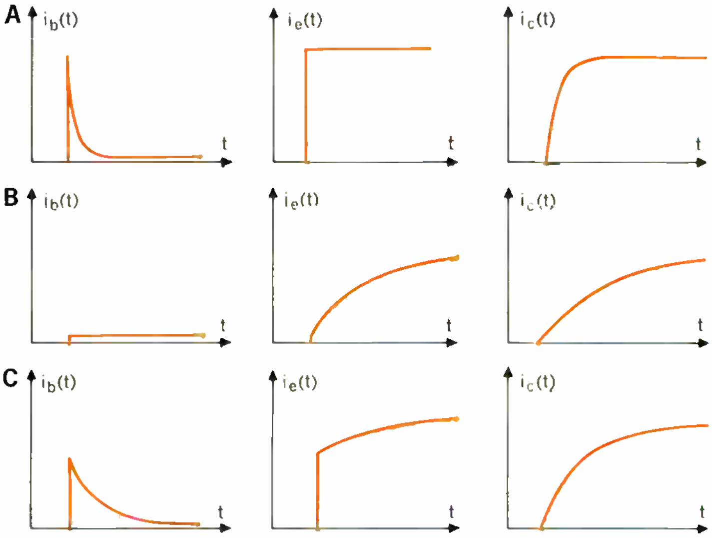
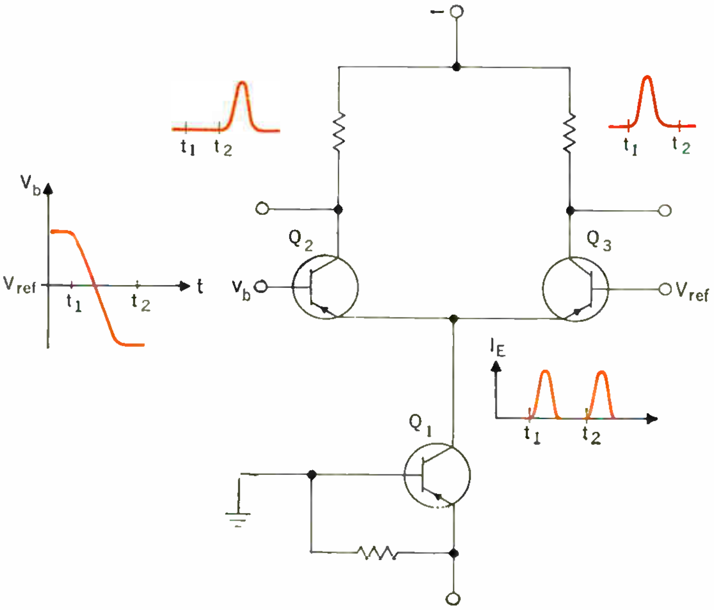


Fig. 6. Time-response curves for the three basic connections. A—Common-base connection, assuming emitter-current step. B—Common-emitter connection, assuming base-current step. C—Common-collector connection, assuming base-voltage step.

Fig. 7. Pulse routing.



enough. In the common-emitter connection, this peak must be produced by special means, unless one prefers to increase the speed through overdriving into saturation. Various methods to accomplish a speed-up of transistors in the common-emitter connection are shown in Fig. 8.

In a single-stage amplifier, linear feedback can be employed in the form of series feedback or of shunt feedback. The emitter series feedback stabilizes the transconductance $I_{\text{out}}/V_{\text{in}}$. In the light of the discussion in Fig. 5, this means that r_e, which is to be replaced by $r_e + R_E$, is no longer negligible. It also follows that this type of feedback is effective only if R_G is not so large as to represent a current source. As indicated in the last column of Fig. 8(A), gain is being traded for bandwidth. When a voltage step is applied from the source, the base current exhibits a step which then decreases during the rise of the collector current, since more and more of the input voltage appears across R_E. Thus the desired base-current spike is obtained.

The collector-to-base shunt feedback stabilizes the transimpedance $V_{\text{out}}/I_{\text{in}}$. It is this parameter that is being traded for more bandwidth. This type of feedback is effective only if R_G is large. With an input current step applied, the base draws additional current from the collector supply through R_F; but this extra current is reduced as the collector voltage decreases, thus again creating the desired base-current spike.

Another method for trading gain for speed is that of "overdriving" the base current.† If the base current sup-

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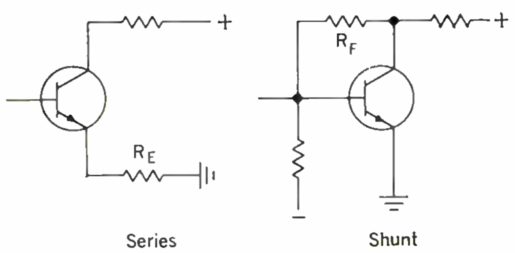
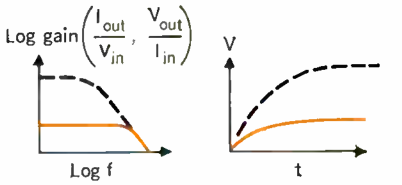
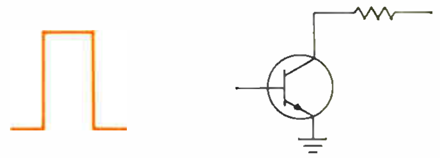
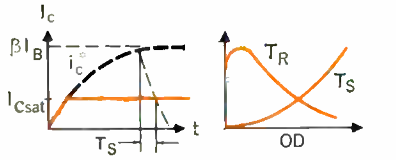
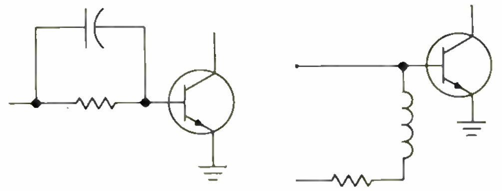
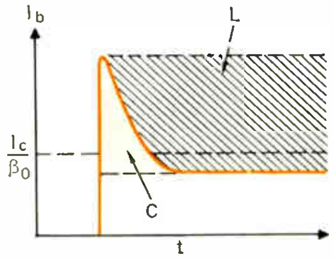
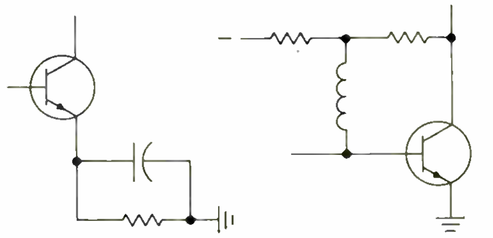
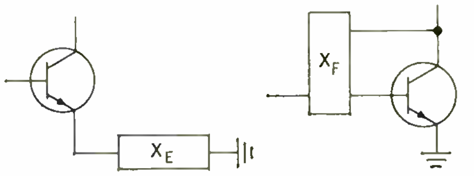
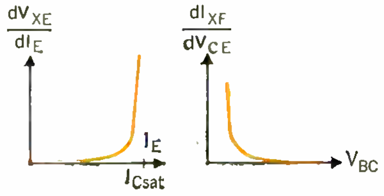
† This discussion is not restricted to very large source impedances. Switching speeds are generally improved as the source impedance is reduced. For low source impedances it is appropriate to replace the current overdrive concept by that of "voltage overdrive."

Fig. 8. Speed-up for common-emitter transistor. For large-signal operation, (B) is most effective if the pulse length is short and (E) is most effective with nonlinear-emitter feedback.

Type	Principle	Circuit	Explanation
Linear feedback **A**	Gain for speed trade-off		
Overdrive **B**			
Spiking = temporary overdrive **C**	Capacitive or inductive base-current spike generation		
Reactive feedback—delayed feedback **D**			
Nonlinear feedback **E**	Feedback: Low in active region, high near saturation		

plied is greater than that required to saturate the transistor, a situation as shown in Fig. 8(B) arises. A fictitious current i_c* continues to flow toward a value $\beta_0 I_B$. At the end of the pulse, this current must first decay during the storage time T_s before the collector current actually falls off. (In the Ebers–Moll transistor model, the excess current also flows toward the collector but is emitted from there again into the base by the inverse transistor; in the charge control model the dotted curve can be thought of as the time function of the excess base charge.) If we compare the trade-off between gain and rise time with the linear feedback case in Fig. 8(A), we see that the overdrive case is more favorable. The price to be paid for this advantage is the storage effect. Whether or not this storage effect can be tolerated depends very much on the type of transistor to be used. Storage time can be reduced in silicon transistors by means of gold doping (at the expense of breakdown voltage and f_T). However, in fast germanium transistors the benefit to be obtained from gold doping is very small.

It can be seen from Fig. 8(B) that the storage time can be kept small if the ON-pulse length is extremely small, and thus no appreciable amount of charge can accumulate in the base. This means that under steady-state conditions the transistor must be kept turned off. This mode of operation is very useful at high frequencies since its effectiveness increases with decreasing pulse lengths.

What appears to be an almost obvious solution to this storage problem is the generation of a reactively controlled overdrive that relaxes under steady-state conditions. Two basic circuits using capacitors and inductances, respectively, are shown in Fig. 8(C). The solution using capacitors is widespread, e.g., in *R-C* transistor logic. The inductive solution is inefficient and is mainly of academic interest; after the decay of the basic current spike the difference current supplied by the source is drained away through the inductor.

Proposals have been made to transformer couple[30] emitter and base for providing the basic current spike. Special precautions are required to keep the circuit from becoming a "blocking oscillator."

Two problems arise in the capacitively spiking circuit. First, the source impedance has to be sufficiently low to provide the base-current spike. Second, the charge coupled through the capacitor must match the transistor. With very small pulses it appears difficult to provide sufficient charge into or out of the base and still guarantee that the capacitor relaxes fast enough to preclude any memory from one pulse to the next.

A situation similar to the one discussed before can be created on the basis of feedback; if we add a capacitor or an inductor to the resistive feedback of Fig. 8(A), the feedback can be made ineffective during the early phases of the transient, as illustrated in Fig. 8(D). Thus, the time function of the output begins to follow the dashed line in Fig. 8(A), but then relaxes toward the solid line. The capacitive solution is well known but, like the capacitive overdrive, poses relaxation problems at higher repetition rates. The inductive solution shows the same inefficiency as mentioned with regard to the inductive overdrive case.

Although the types of feedback discussed so far are among the most useful tools in linear high-speed amplifiers, the very same property of linearity is normally not desirable in digital circuits. Here, the input–output transfer characteristic is sought to be highly nonlinear, so as to provide output levels that are well defined from the viewpoint of logic.

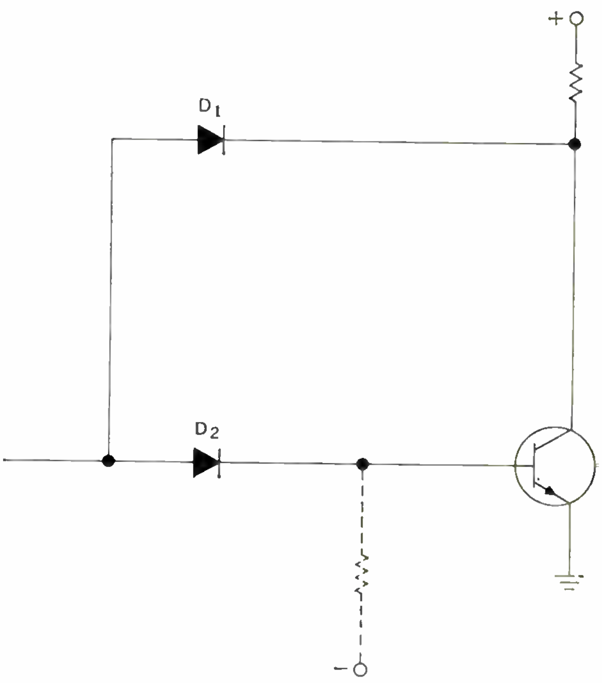
From this discussion it can be seen that the "ideal" digital circuit should have little or no feedback during the rise or the fall periods (i.e., over most of the active region), but considerable feedback shortly before saturation is reached. The stronger the overdrive used the faster would be the switching times, and thus saturation could be avoided.

Various techniques employing nonlinear feedback are possible on this basis. In view of their importance, the following paragraphs will be devoted entirely to their discussion.

Nonlinear base-to-collector feedback. Figure 9 shows an old circuit classic. A clamping diode from collector to base in conjunction with a shifter diode in series with the base prevents saturation. The clamping diode presents exactly the nonlinear feedback characteristic which we found to be desirable—i.e., conductance that is extremely low through most of the active region, but increases suddenly as saturation is approached. The voltage shift must be included in the base path if the feedback is to be made effective before the collector-to-base voltage reaches zero. Since a diode is used for that purpose, it is desirable for the base diode to have a slightly larger forward drop than that of the collector-to-base diode. Diode D_1 must have a low capacitance and negligible storage.

The circuit suffers from one major drawback—whenever the transistor is turned off, diode D_2 cuts off. Thus no reverse current can be drawn and the collector fall time can become excessively large. It is possible to replace diode D_2 by a resistor, but the value of the resistor must be different for transistor units with different β values, unless the circuit is driven from a current source.

Fig. 9. Collector-to-base diode feedback. Diode D_2: Low capacitance, high storage. Diode D_1: Very low capacitance, very low storage.



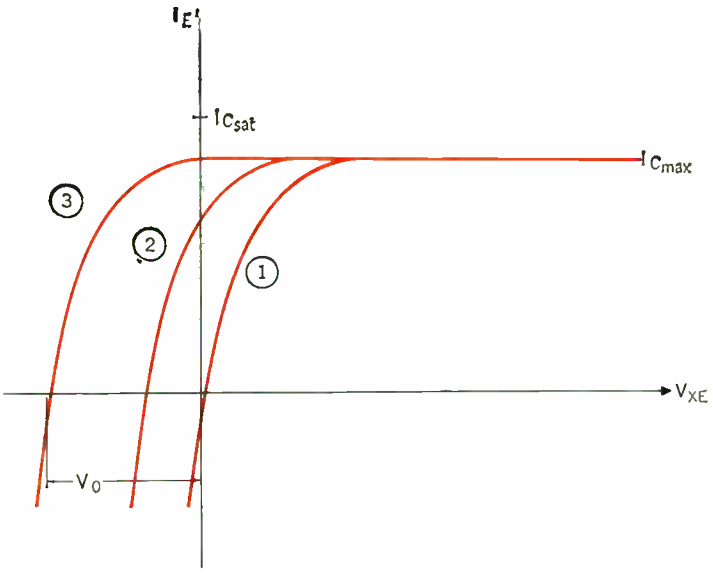
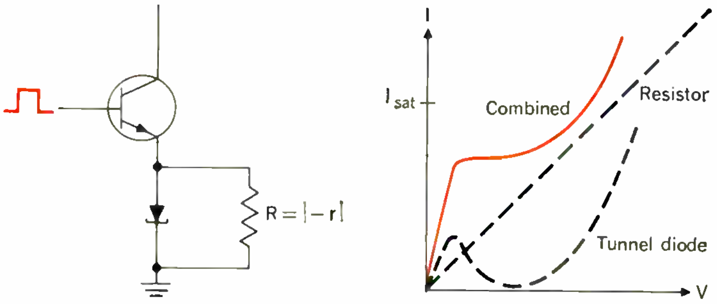


Fig. 10. Desired nonlinear characteristic in series with emitter, indicated for three examples.

Fig. 11. Tunnel-diode emitter feedback.



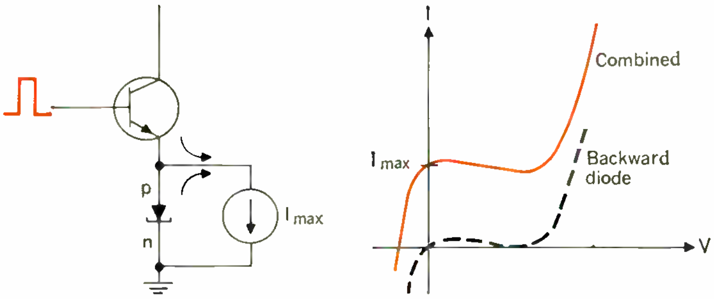
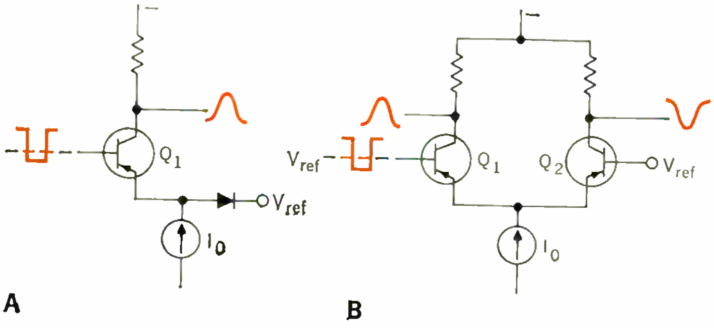


Fig. 12. Backward-diode emitter feedback. Note that a backward diode normally exhibits some Esaki current.

Fig. 13. Current routing.



Two other possibilities are known to speed up the turnoff process. A resistor (dashed in Fig. 9) can be connected to a voltage source. In order to speed up the turnoff process appreciably the resistor must be made very small; it then represents a heavy drain on the signal. In a more elegant solution diode D_2 is replaced by a charge-storage diode. Again, some difficulties in a design for production might arise from the need for matching the diode and the transistor charges. With respect to D_1, the development of Schottky diodes with low forward voltage drops might again stimulate the interest in this clamping circuit for higher-frequency applications.

Nonlinear feedback in series with the emitter. Figure 8(E) shows the desired characteristic for the differential impedance dV_{XE}/dI_E in a nonlinear series feedback circuit. Three examples of the corresponding I vs. V characteristics are shown in Fig. 10. The three curves differ only by a voltage shift. Mathematically, this shift corresponds to the difference in the integration constant that one must choose when integrating the $dV_{XE}/dI_E = f(I_E)$ curve shown in Fig. 8(E).

Curve 1 in Fig. 10 can be realized by a tunnel diode with a parallel resistor equal in magnitude to the negative tunnel diode resistance, as shown in Fig. 11. As the tunnel diode enters its normal forward region with increasing voltage the feedback becomes ineffective. It is, therefore, desirable to use a tunnel diode with a large forward voltage drop, such as a GaAs diode.

Another realization, corresponding to curve 2 in Fig. 10, is shown in Fig. 12. In this case a backward diode is combined with a current source. The current from the source is split up between the breakdown current of the diode and the transistor; close to saturation, however, practically all the current flows into the transistor, whose feedback resistor is determined by the internal resistor of the current source.

It is also possible to replace the backward diode of Fig. 12 by an ordinary computer diode, the polarity of which must be such that the p junction of the backward diode becomes the n junction of the computer diode, as shown in Fig. 13(A). This realization of nonlinear feedback corresponds to curve 3 in Fig. 10, in which the absolute voltage shift V_0 is largest. In contrast to the backward diode circuit, the current-limiting feature is no longer restricted to very low values of voltage.

The computer diode, in turn, can be replaced by the emitter-to-base junction of a second transistor, as shown in Fig. 13(B).

Current-routing circuit. The two circuits of Fig. 13 that evolved from the preceding discussion of the optimum utilization of transistor speed rank among the most successful high-speed circuits. Rather than being described as examples of nonlinear feedback, they are known in the literature[31] as "current-routing" or "current-switching" circuits.

As the base of Q_1 is made more and more negative in comparison with the reference voltage V_{ref}, the fraction of I_0 that is routed to Q_1 becomes larger until the other device cuts off. Likewise, when the input base is driven strongly positive, Q_1 is cut off and all current is routed to the right. The diode in Fig. 13(A) requires a very low impedance reference voltage, whereas the requirements on the reference source impedance in Fig. 13(B) are considerably relaxed. The transistor circuit also offers the convenience of a dual output.

It appears worth noting that if both transistors in Fig. 13(B) are operated entirely in the active region—i.e., without being driven into cutoff—little advantage† exists over a common-emitter stage. It is not incorrect, but it is misleading, to interpret this circuit as a cascade of a common-collector stage with a common-base stage, since all requirements for high-speed operation as discussed in connection with Figs. 5 and 6 are violated as a consequence of the extremely low impedance level at the interface between the two stages. (This situation differs from that in the pulse-routing circuit of Fig. 7, in which the transistor base charge is controlled at the emitters.)

The usefulness of the current-routing circuit as a high-speed principle is based on its *nonlinear* application, whereby one of the two transistors is cut off in the steady-state condition. The transistor can be strongly overdriven, but before it reaches saturation the feedback impedance is changed from that of the diode forward resistance or the common-base input impedance to the current-source impedance; in other words, the emitter current is limited to the current I_0 supplied by the source. The collector supply voltage has to be sufficiently negative and the load resistance sufficiently small to avoid causing saturation when the base is at its most negative potential. Figure 14 shows the steady-state collector voltages as functions of the controlling base voltage. This transfer characteristic shows that only a small base voltage is necessary to control the routing action. A simple calculation yields that the base-voltage swing required to switch between 10 and 90 percent of the collector current is

$$V_{90-10} = 2\left[\frac{kT}{q}\ln\frac{0.9\,I_E}{0.1\,I_E}\right] + 2(I_B r_b + I_E r_e')$$

$$= 115\text{ mV} + 2I_E\left(\frac{r_b}{1+\beta_0} + r_e'\right)$$

where

kT/q = 26 mV at room temperature
I_E = current being routed
r_b = series base resistance
r_e' = series emitter resistance

If the base-voltage swing exceeds this minimum value the switchover times decrease. The delay times, however, increase gradually with larger swings. The noticeable slope at Q_1 is caused by the finite impedance of the emitter resistor.

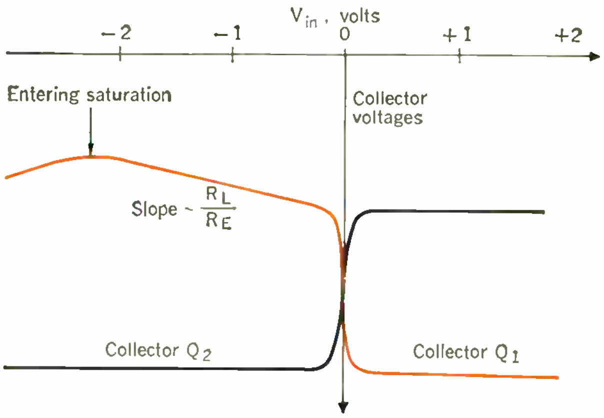
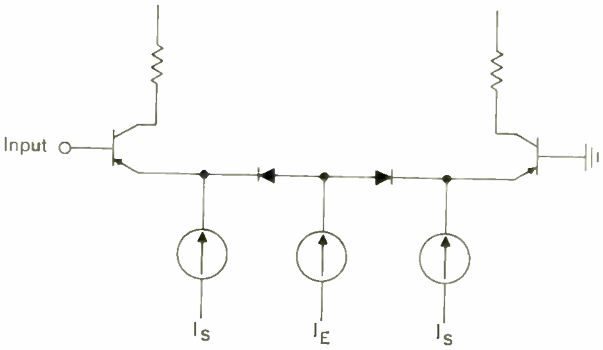


Fig. 14. Current-routing transfer characteristic.

Fig. 15. Technique for avoiding complete cutoff in current routing. I_E = main routing current, I_S = small current that flows in the OFF state.



It is especially important to keep the parasitic emitter inductances small. Excessive inductance not only degrades switching time but also can cause ringing, especially when small base swings are used. Compensation of the emitter inductances by small capacitors of a few picofarads to ground might be useful for reducing the ringing tendency but must be determined in each case and according to the desired pulse shape.

Proposals have been made in the literature[32, 33] to reduce the delay by means of a current source that provides a small ON current for each transistor when it does not carry the main current. This technique is illustrated in Fig. 15. At the higher frequencies, however, it might be difficult to maintain a sufficiently low emitter series inductance with such a circuit and the two advantages must be weighed against each other.

Current-routing circuit applications. The current-routing circuit not only is a useful nonlinear amplifier, as shown in Fig. 13, but also can be readily extended to form a logic circuit. Such a "current-mode logic" (CML) or "emitter-coupled logic" (ECL) circuit is shown in Fig. 16. Several transistors are paralleled in such a way that the circuit yields at one output the OR function on negative inputs and the AND function on positive inputs. The NOR and NAND functions are available at the complementary output.

To make the various stages in a logic chain dc-compatible, the voltage drop from base to collector must be compensated. One technique[31] is to alternate p-n-p with dual n-p-n stages; however, sufficiently fast transistors of both kinds must be available.

An alternative method, in which emitter followers are added to both of the dual outputs of each stage,[34] not only provides dc shift equal to the emitter-to-base ON voltage but also increases fanout. Fanout in emitter-coupled logic is mainly limited by the capacitive load and not by the dc load; thus a low output impedance is desirable. One of the most serious problems encountered in ECL circuits using emitter followers is the instability of the emitter followers[35, 36] that arises under certain drive and load conditions. Usually it is possible to reduce ringing sufficiently by means of an *R-C* circuit in series with the base of the emitter follower[35] or by means of degenerating collector-to-base feedback.

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† The "Miller effect" is reduced in the second transistor and the source impedance behaves as if reduced by a factor of two.

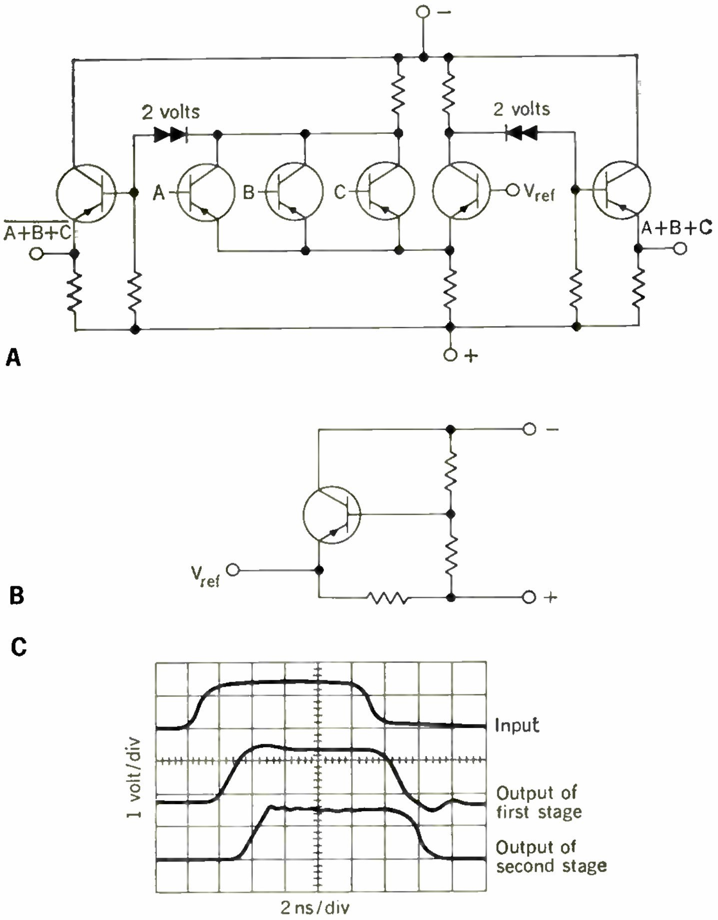
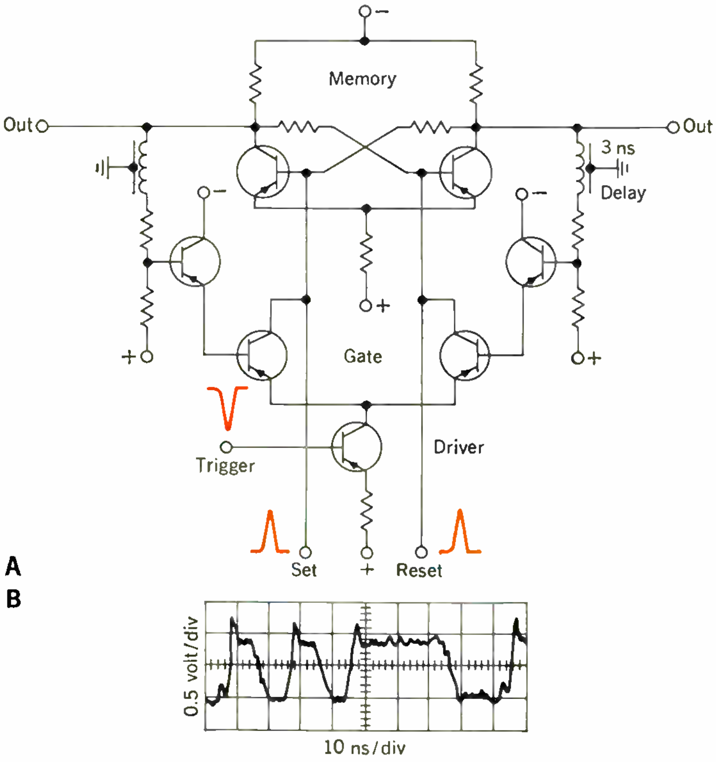


Fig. 16. Emitter-coupled logic. A—Circuit. B—Resistive dividing of supply voltage to generate reference voltage. C—Waveshapes obtained from a chain of two logic circuits.

Fig. 17. Emitter-coupled binary counter. A—Circuit. B—Output waveform.



The small amount of emitter-to-base voltage of the emitter follower results in an equally small collector-to-base voltage for the ON transistor of the current-routing circuit. This is an undesirable feature not only because of the risk of possible saturation with large input signals but also because of the increase of collector junction capacitance with decreasing junction voltage. These difficulties can be overcome successfully with the use of two-volt shifter diodes, as shown in the circuit of Fig. 16. Inserting the shifter diodes usually results in an increase of power dissipation.

In applying integrated circuit techniques to such a circuit, one might want to split the "current-source resistors" for the shifter current and the emitter current in such a way that only a part of each resistance is integrated. Parasitics are thereby reduced and the bulk of the heat dissipation is placed outside the integrated can. The margin against noise on the input of this circuit increases with the voltage swing for which it is designed. The constant current demand feature guarantees a small degree of parasitic coupling through the power supply and ground lines. Sensitivity to any power supply noise can be reduced further by generating a reference voltage for each circuit by resistively dividing the supply voltage in the fashion shown in Fig. 16(B).[37]

Figure 16(C) shows waveshapes obtained from a chain of two such logic circuits, each with a fanout of one. The transistor used in these tests was an experimental germanium mesa transistor with a minimum f_T of 2.5 Gc/s.

Emitter-coupled binary counter. Another example of the use of pulse routing and current routing is the binary counter shown in Fig. 17. Due to the delay in the collector-to-base feedback loop of such a flip-flop the regenerative action does not yield fast switching times.[38] In order to achieve switching times of 1 to 2 ns with 2.5-Gc/s transistors, strong trigger pulses are required. It usually suffices to turn only the ON transistor off; the emitter-coupling resistor in the memory provides symmetry and forces the other transistor on.

In the circuit of Fig. 17 steering is accomplished by a pulse-routing pair. The state of the counter is fed back to the gate by means of emitter followers. The pulse-routing arrangement provides a sufficiently high current source, which could not be obtained with the conventional trigger arrangement that uses computer diodes.

Figure 17(B) shows waveforms obtained from such a circuit. The positive spikes are overshoots created directly by the trigger pulses. Two delay lines, used to prevent racing of the counter in case of long-duration input pulses, are achieved by means of printed strip lines two mils wide. Precise matching of these lines is very difficult, but appears unnecessary. In a circuit realization for lower frequencies, a lumped approximation to such a line in the form of a chain of three series inductors and shunt capacitors was found to be adequate. The counter was designed for operation at 110 megabits per second and could be operated with selected transistors at speeds as high as 200 Mb/s.

Tunnel diodes

Two properties make the tunnel diode one of the most important elements in the region above 100 Mb/s: its high speed and its potential low cost. Even with transistors that have f_T values around 3 Gc/s certain circuit functions, such as binary counting, monostable pulse

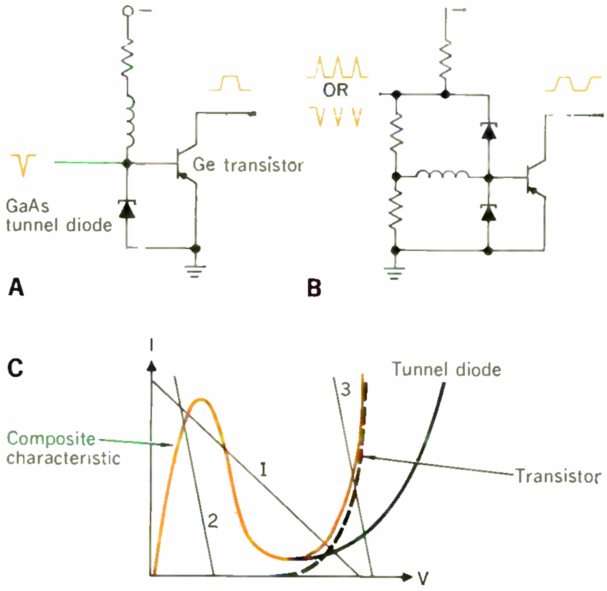


Fig. 18. High-speed tunnel-diode circuits (combined with transistors). A—Monostable circuit. B—Bistable counter. C—DC characteristic for tunnel-diode transistor pair. (1—Bistable load line; 2,3—Monostable load lines.)

forming, pulse regeneration, or critical threshold detection, can hardly be realized at such high bit rates.

Most high-speed circuit engineers are quite familiar with the basic tunnel-diode circuits. For this reason and because of the existence of a wealth of literature on the subject[12, 13, 39] we shall not cover this topic in detail.

Typical tunnel-diode circuits. At frequencies slightly greater than 200 Mb/s, the combination of tunnel diodes with transistors was found to be extremely useful. Although a monostable or bistable circuit can be realized in the conventional way with tunnel diodes, the addition of a transistor to the output provides isolation and additional power gain, as shown in Figs. 18(A) and (B). The most suitable combination is that of a GaAs tunnel diode with a Ge transistor. Other materials may require separate biasing for the transistor emitter, which can result in excessive parasitic inductances. A similar argument holds if one reverses the polarity of the tunnel diode with respect to the transistor. In this case it is useful to provide current biasing rather than voltage biasing for the emitter by means of a small emitter current flowing in the OFF state.

Figure 18(C) shows a dc analysis of the tunnel diode–transistor pair. The input characteristics of the transistor can be combined with the current–voltage characteristic of the tunnel diode. Depending on the impedance level at the base, monostable or bistable quiescent points result. The transistor has to protect the tunnel diode from drawing excessive forward current, which is prohibitive for many GaAs diodes. (Computer diodes might also be used for such protection if no transistor protection is available.) The circuit does not work with low-gain transistor units and saturates with high-gain units. But storage effects can be kept negligible if the pulse is short enough to prevent accumulation of excess base charge, as described in the discussion of Fig. 8(B).

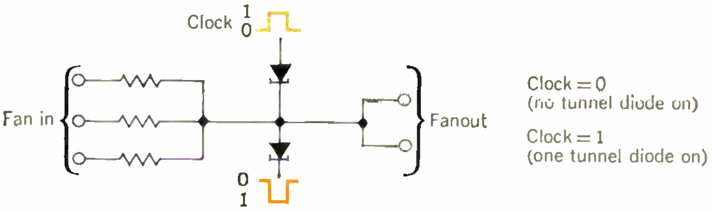


Fig. 19. Goto pair, used as majority gate.

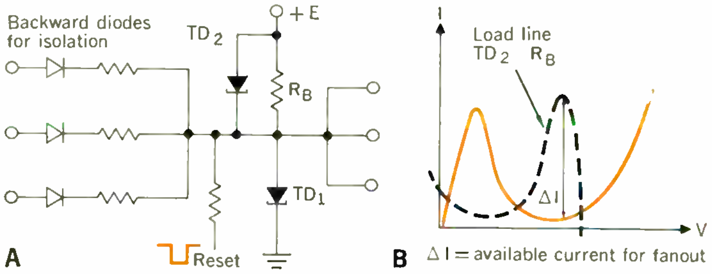


Fig. 20. Analog threshold AND gate (Chow circuit).

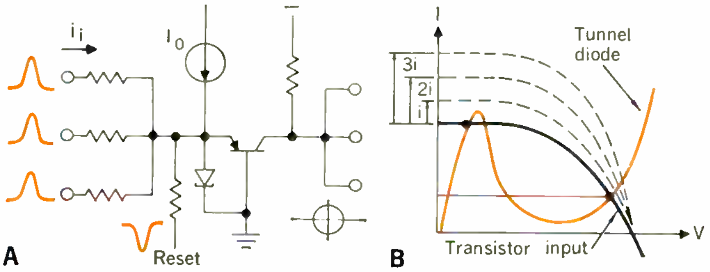


Fig. 21. Tunnel-diode transistor resistor logic.

Another typical high-speed circuit is the Goto pair[40] shown in Fig. 19. It requires a symmetrical pulse or sine-wave clock. The circuit can be used as a majority gate and for regeneration.

Logic tunnel-diode circuits. There are various ways of building simple logic circuits with tunnel diodes, most of which involve synchronous circuits with multiphase clocks to control the direction of the information flow. Figure 20 is the so-called "Chow" circuit,[41] wherein the load line is represented by another tunnel diode. The result is a larger available fanout current as compared with a purely resistive current bias. This circuit performs the OR function on positive input pulses. Any input pulse turns the tunnel diode and the transistor on. A reset pulse restores the OFF state periodically. In Fig. 21, the transistor input characteristic is drawn as a load line to the tunnel-diode characteristic.

One of the fastest and most interesting logic circuits is the "pumped tunnel-diode transistor logic" (PTDTL) circuit[42] shown in Fig. 22. This circuit was developed for 200-Mb/s operation and was operational up to 500 Mb/s. The operation can be explained, with the help of Fig. 23, as follows: A quiescent current I_c is supplied to the tunnel diode by the preceding transistor, and the tunnel diode is biased in the bistable mode. A sinusoidal pump clock, coupled through a capacitor, switches the binary stage periodically from the low-voltage state to the high-voltage

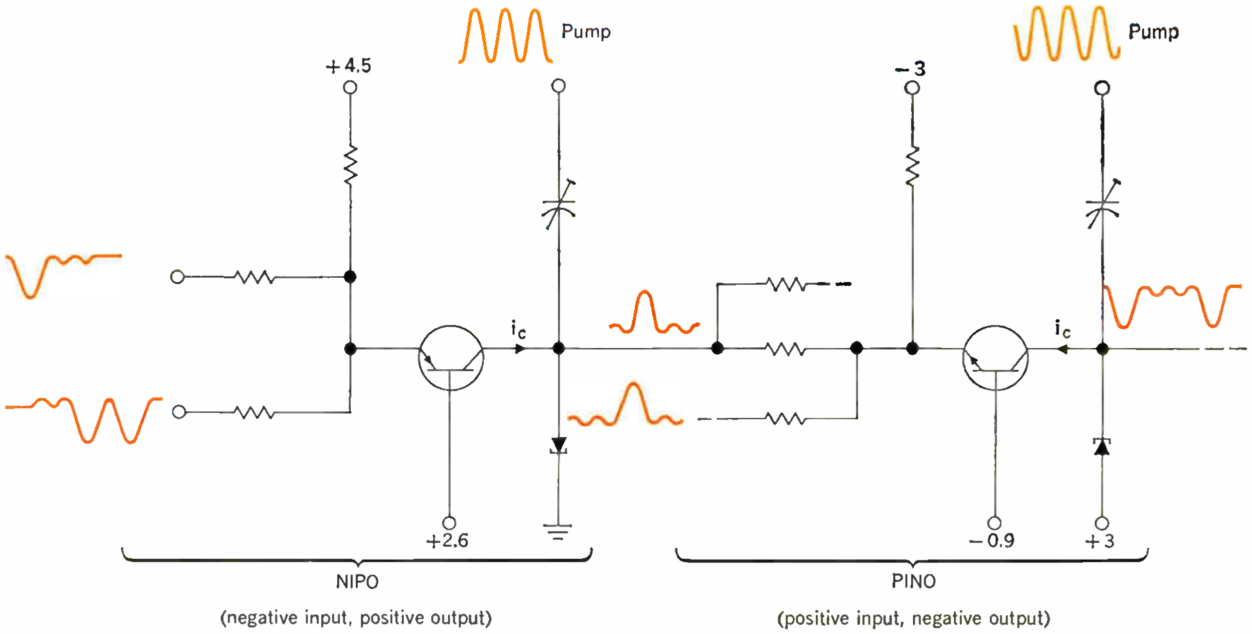
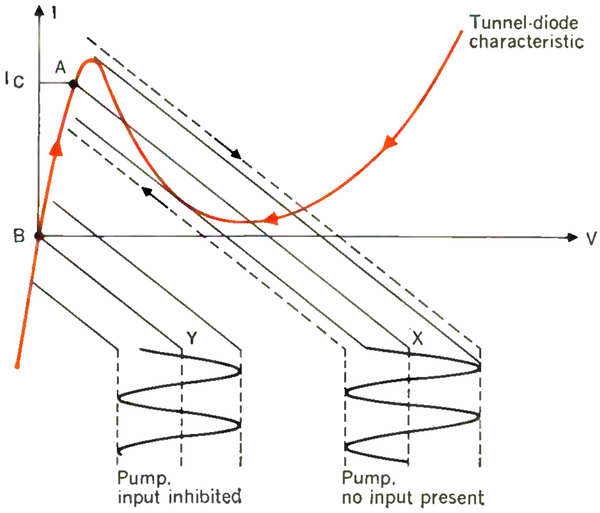


Fig. 22. Pumped tunnel-diode transistor logic.

Fig. 23. Switching in pumped tunnel-diode transistor logic.



state and back, unless the transistor current I_c is inhibited. Such inhibition occurs if any of the inputs is supplied with a negative pulse, in which case the quiescent point moves from A to B and the pump clock becomes ineffective. Alternating stages are made dual to restore the original polarity and the dc level.

Circuits using charge-storage step-recovery diodes

We mentioned earlier three general fields of application for charge-storage step-recovery diodes. The generation of harmonic components represents the chronologically first application of the "snap effect." Goodall and Dietrich[22,23] generated 11-Gc/s bursts from a pulse step fed into a waveguide.

It can be seen from the general description of operations given in Fig. 3 that current amplification is obtained whenever the reverse current exceeds the forward current. Due to the conservation of charge the pulse length is reduced accordingly. When a sinusoidal input is used, the difference between forward and reverse current can be controlled by an additional dc bias, which can also be used to determine the instant of step recovery.

Pulse generation by use of a short-circuited transmission-line stub. One pulse generation scheme involves the use of a step-recovery diode driven from a large sine wave and connected to a coaxial line, as shown in Fig. 24(A). One end of the line represents a short-circuited reflecting stub, and the other end leads to the load through a filter, which eliminates the fundamental frequency component. Figure 24(B) shows the equivalent circuit and Fig. 24(C) illustrates the superposition of the incident and the reflected wave. The main shortcoming of the circuit is its restriction to a fairly small frequency band over which tuning of the input and the filter can be performed.

Pulse generation by use of forward and reverse current routing. The circuit shown in Fig. 25 gives an example of a pulse generator that avoids the need for tuning. During the positive cycle of the sine-wave input, the forward current flows through a computer diode to ground and charges the charge-storage diode; during the negative part of the cycle, the computer diode cuts off and the transistor carries the diode reverse current until the charge stored in the charge-storage diode is exhausted. The current pulse thus generated is amplified in a common-base stage and in a following common-emitter stage. If the computer diode also shows a minor "storage plus snap" effect, the pulse shape is enhanced, since such storage delays the beginning of the rise of the transistor current. However, the charge stored in the computer diode must be small compared with that in the charge-storage diode.

Figure 26 shows waveshapes obtained with a circuit that is almost identical to that in Fig. 25. In Fig. 26(A) a transmission-line-type ferrite transformer[43] is inserted between the common-base and the common-emitter stage for phase reversal, thus permitting the use of two

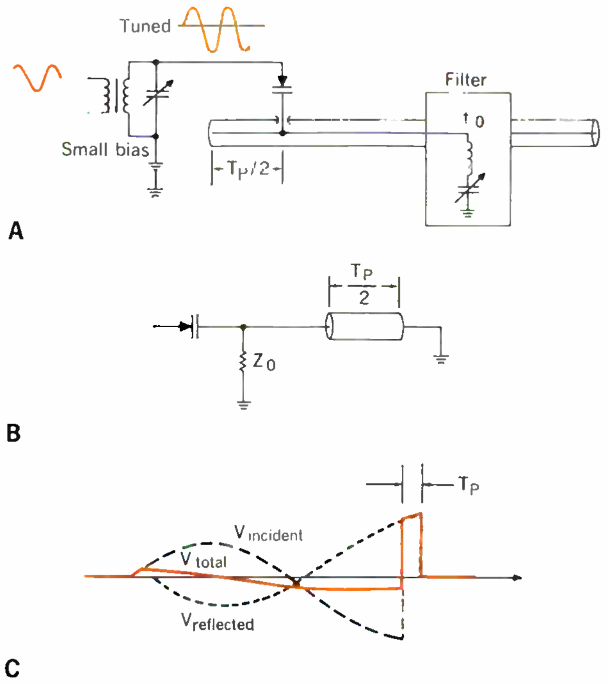


Fig. 24. Pulse generation from sine wave using reflecting coaxial stub. A—Basic circuit. B—Equivalent circuit. C—Superposition of incident and reflected waves.

germanium 2.5-Gc/s p-n-p transistors. The amplitude of the input sine wave is about 2.5 volts peak to peak. The "pulse amplitude to sine wave" input efficiency could probably be improved by providing some bias for the transistor and the charge-storage diode. In Fig. 27 two circuits of the type shown in Fig. 25 are combined to form a variable-pulse-length generator. A bistable tunnel-diode circuit is set and reset by two dual charge-storage step-recovery diode circuits.

High-speed pulse regenerator. The circuit in Fig. 27 can be converted into a pulse regenerator simply by gating the set (or the reset) pulse with the signal to be regenerated. The same circuit can be used to build a pulse word generator.

Enhanced tunnel-diode logic. Figure 28 gives an example of a 250-Mb/s logic circuit[44] which combines charge-storage step-recovery diodes with tunnel diodes. The operation of the circuit can best be understood by considering three time phases: (1) If no positive input pulses are present at any of the inputs A, B, and C, the storage diode is charged by a current which flows from the positive to the negative supply. If any of the inputs is positive, this charging effect is inhibited. (2) Immediately thereafter, a set clock pulse reads out the charge. If charge has been stored a bistable tunnel-diode stage is set into the positive ON state. (3) A reset clock pulse resets the tunnel diode.

From a gain point of view we might consider the charge-storage diode as the current amplifier and the tunnel-diode memory as the time amplifier.

Construction requirements for high-speed circuits

There can be little doubt that the production of high-speed circuits will gradually move toward an integrated-

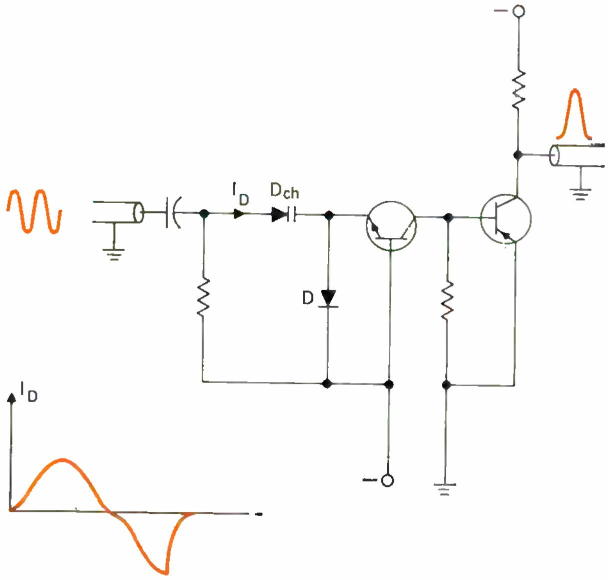
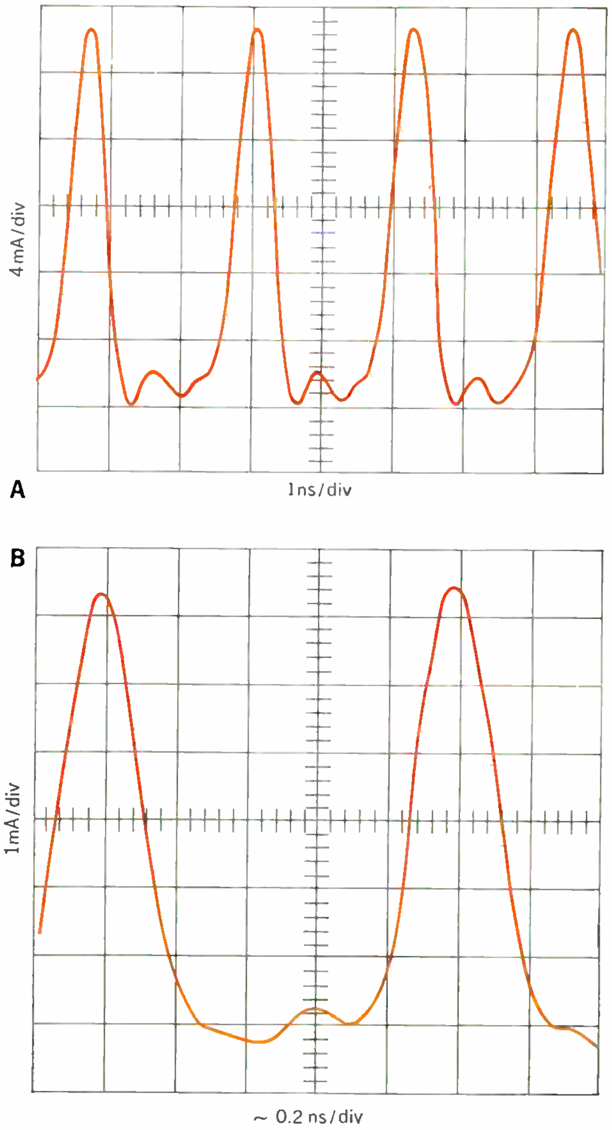


Fig. 25. Charge-storage step-recovery diode pulse generator circuit, in which tuning is unnecessary.

Fig. 26. Step-recovery diode pulse generator output. Input = 2.5-volt peak-to-peak sine wave. A—n-p-n/p-n-p version, 450 Mc/s. B—p-n-n/p-n-p version, 900 Mc/s.



circuit technology. However, the integration of small-tolerance resistors within a can still poses problems today. Integrating only the active components is advantageous—perhaps even mandatory—in certain circuits. For example, in emitter-coupled circuits, such as pulse routing and current routing, the reduction of emitter lead inductances is important; in transistor flip-flops or feedback amplifiers, the overall feedback delay must be kept extremely small. But in most other applications little can be gained through integration from the performance viewpoint unless certain critical passive components are included in the integrated circuitry.

As long as integrated technology has not advanced far enough to eliminate the "soldering iron" completely, we must concern ourselves with the problem of keeping the parasitics to a bare minimum when using lumped-element construction. A few basic rules can be established—rules that seem almost trivial but are often violated. Interconnection lengths and component sizes should be as small as possible. However, it is not desirable, from a high-speed-performance point of view, to package all elements side by side as close together as possible as, for example, in the so-called cordwood approach.

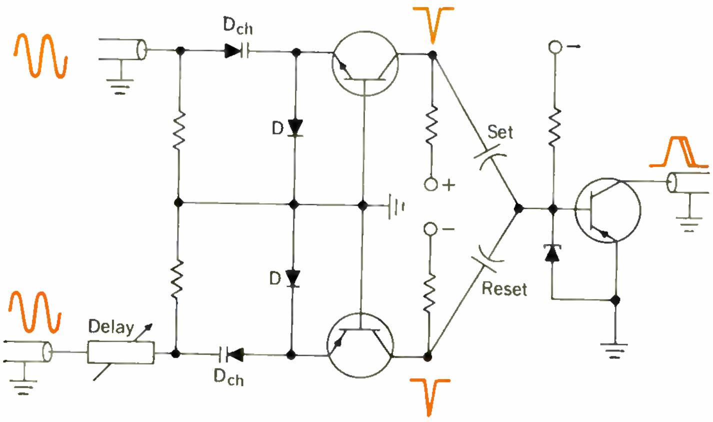
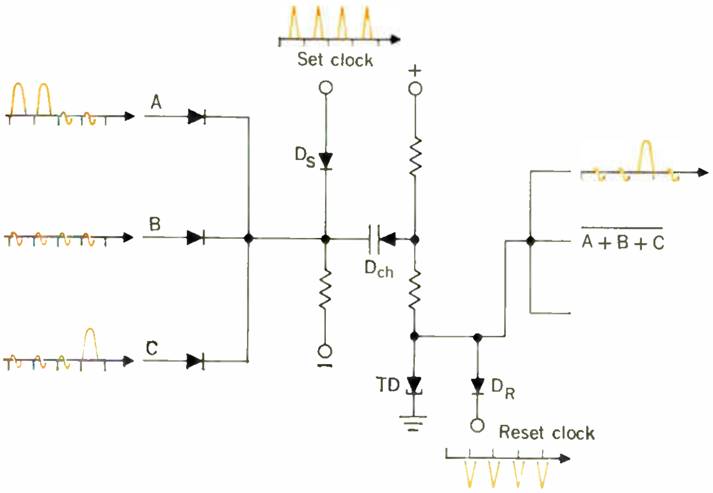


Fig. 27. Charge-storage step-recovery diode pulse generator. By gating the set signal, the circuit can be made into a regenerator or word generator.

Fig. 28. Enhanced tunnel-diode logic.



Instead, some form of impedance matching must be attempted.

Coaxial and strip-line techniques. For a small number of applications, especially in the field of high-frequency measurements, a coaxial construction technique represents an ideal solution. But this technique becomes prohibitive for more complex circuits because it is practically impossible to match the diameter ratios at all points precisely to the respective impedance levels. Even in cases in which this matching appears feasible, the delay time becomes excessively long—an intolerable situation in circuits containing feedback loops.

Similar considerations hold for some forms of strip-line construction, especially those in which each circuit element is mounted in a separate strip-line module ("triplate"). This construction technique, developed for microwave applications, cannot be extended to lumped-element circuits, where at most points in the circuit the impedance level is not well defined.

Optimized construction in nonintegrated circuitry. A basic rule for circuit construction may be stated as follows: At points of high impedance levels the parasitic capacitance must be kept small; at points of low impedance the parasitic inductance must be kept small.

Whenever two points of the same impedance level Z are to be connected and the distance cannot be made negligibly short, a transmission line with characteristic impedance Z should be used. With good impedance matching, which can readily be achieved with a printed strip line, only the delay needs to be considered. However, increase of the characteristic impedance above 400 ohms soon leads to microscopically small and unreliable conductors.

It follows from transmission-line theory that for a given connection length l, the product of L and C is a constant equal to the square of the time delay; that is,

$$LC = \frac{\epsilon_{\text{rel}} l^2}{c^2} = T_{\text{delay}}{}^2$$

where c is the velocity of light and ϵ_{rel} is the relative dielectric constant. If the length l cannot be reduced it is not possible to reduce both L and C; they can only be traded off against each other. Their ratio determines the impedance level, according to the well-known equation for a lossless transmission line

$$Z = \sqrt{\frac{L}{C}}$$

These considerations can be applied not only to conducting connections but also to connections made through a resistor. Figure 29 shows various idealized configurations for mounting a resistor with respect to ground. Figures 29(A) and (B) represent the analog to the exponentially tapered coaxial terminating resistor, but in approximated form. Figures 29(C), (D), (E), and (F) show the optimized positioning of a resistor that connects two points, with no grounding. The desired elimination of degrading parasitics is poorly realized if both impedance levels are high as in Fig. 29(C), since under this condition the lumped coupling capacitor is most harmful. Shielding of the two sides by means of a properly chosen capacitor to ground, as in Fig. 29(C), is possible only in the rare case of well-defined linear impedances Z_1 and Z_2. In general, it is essential to keep the capacitor small by choosing an appropriate type of resistor, which should be long and thin. Accordingly, the connection through a low value of resistance, as shown in Fig. 29(D), is optimized with a low inductive resistor; Figs. 29(E) and (F) are hybrid situations.

For economic reasons these rules cannot always be followed in a practical circuit. Yet, they should serve as a goal; they become especially important if it is impossible to keep interconnections short. A flat strip-line-type layout seems to be a good approach to this goal, provided the resulting delay can be tolerated. In a number of years the speed frontier will have advanced by another order of magnitude; perhaps then some of these rules will have to be applied to the layout of integrated circuits.

Another important point to consider in any layout is the decoupling of the dc supplies. If several resistors of a stage lead to the same supply, it is advantageous to connect them in a starlike fashion to the same dc supply point and to connect a low-inductance capacitor of, say, 500 to 1000 pF (preferably with ribbon leads), from that point to ground, to filter out the highest-frequency components. The medium frequencies can then be filtered at the input of the dc supply to the circuit by means of a capacitance of a few microfarads, whereas the low-frequency components are taken care of at the output of the power supply, as usual. As long as there is sufficient lead inductance between such capacitors, which differ by several orders of magnitude, there seems to be no ringing problem; any direct parallel connection of capacitors whose numerical values differ by more than one order of magnitude must be avoided. In manufacture for production an economic solution must be sought which might also take into account the problem of providing connections between the various circuit boards. Solutions are known where the original boards are mounted perpendicular to a "mother board" which provides the interconnections between the boards as well as the dc supply. Good dc decoupling can be obtained from a distributed capacitor made up of the ground plane and a dc supply plane, both of which are separated by a very thin sheet of Mylar or a layer of epoxy. The feed point must not be too small, as can be seen from the equivalent circuit of such a distributed capacitor, shown in Fig. 30. The capacitance per unit length increases in proportion to the distance from the feeding-point center. The inductance per unit length decreases inversely in proportion to that distance. If the radius of the feeding area is infinitely small, the impedance is infinitely high. With increasing radius, the impedance quickly reaches a sufficiently low value, as may be described by cylinder functions.

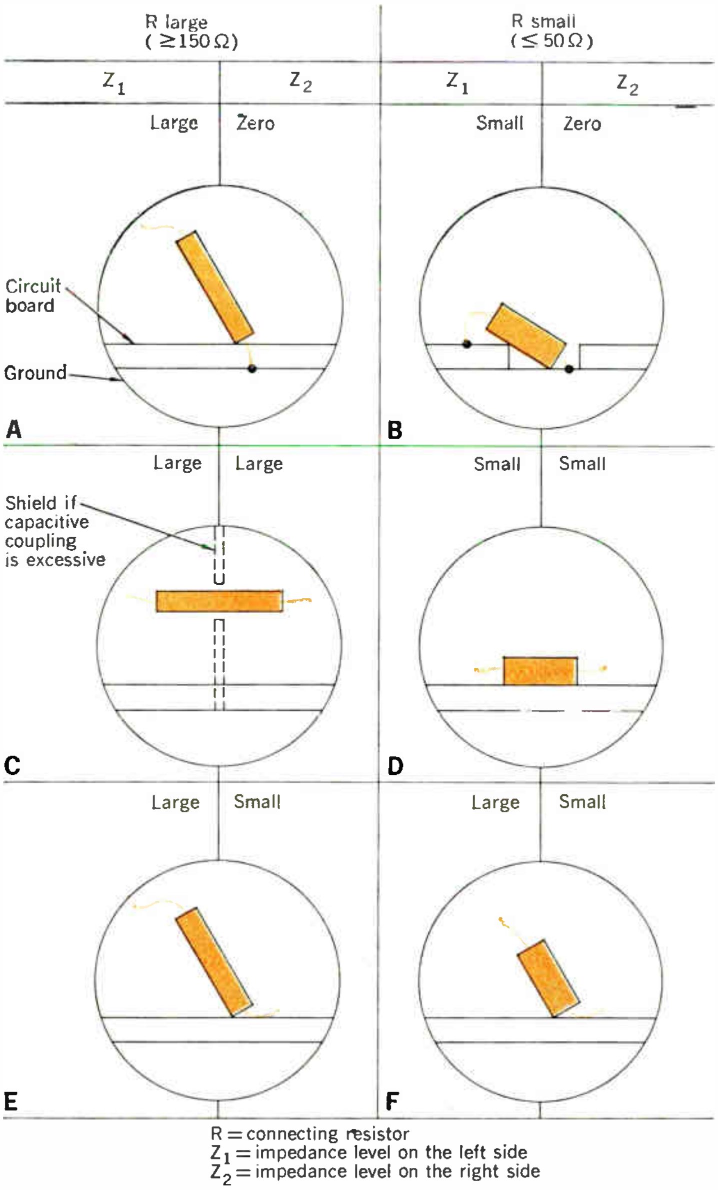


Fig. 29. Idealized positioning of resistor with respect to ground for various impedance levels.

Conclusions

As the f_T values of transistors entered the gigacycle range it became possible to realize all-transistor circuitry at frequencies higher than 100 Mc/s. With germanium transistors having f_T values between 2 and 3 Gc/s, many digital operations can be performed even at frequencies above 200 Mc/s.

Two high-speed circuit principles are mainly responsible for achieving those speeds with transistors in the common-emitter connection. One consists of operating the transistor only in the OFF-ON-OFF mode while using only short ON pulses, so as to avoid the accumulation of an appreciable amount of excess charge in the base. The other solution utilizes nonlinear feedback in various schemes, of which current routing appears to be the most useful.

However, certain feedback circuits, such as monostable flip-flops and counters, cannot be made readily with transistors at speeds above 200 Mc/s. Here the combination of tunnel diodes and transistors can be used successfully.

Generation of extremely short pulses can be accomplished with charge-storage step-recovery diodes. Pulses generated in such a way are feasible at repetition rates as high as 900 Mc/s.

The future trend in circuit design is expected to move toward all-integrated circuitry. Until a time when all circuit work, including breadboarding, will be done in some form of integrated circuit technology, there will be a need for lumped high-speed circuit construction. The necessary minimization of parasitics in these circuits

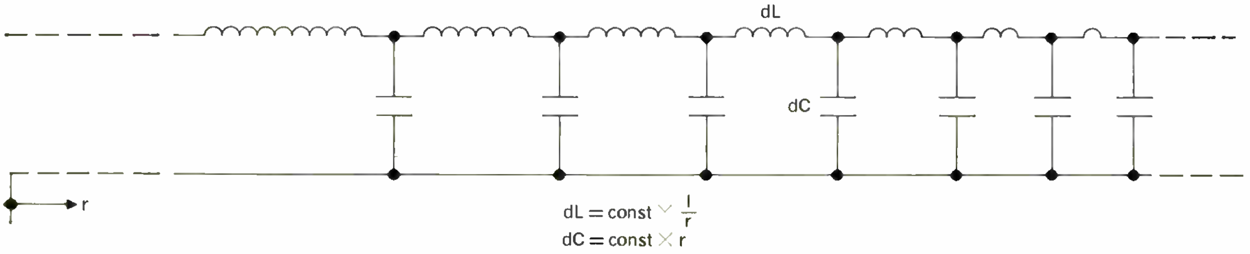


Fig. 30. Equivalent circuit for distributed capacitor, made of two parallel planes separated by a thin sheet of an insulating material.

must be achieved through short connections and through balancing inductive and capacitive parasitics according to the specific impedance level at any circuit point.

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The automatic control of electric power in the United States

Automation of the electric power industry is well under way. Comprehensive coordinated control systems, derived from theory and practice, have been developed to solve complex multivariable control problems of the modern steam plant. Controls are primarily analog in nature but direct digital control is being investigated

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In reviewing the state of the automatic control art in a given field of application, it seems appropriate first to take note of progress in the field itself. Changes in process techniques or objectives define new requirements and opportunities for advances in control concepts and equipment. Accordingly, this survey article will endeavor to "close the gap" between theory and practice by doing three things: (1) review in brief the growth and progress of the power industry itself; (2) make some comments on recent significant trends and innovations in its processes insofar as they relate to major areas of automatic control application; (3) discuss the state of the art in these applications.

The electric power industry

A considerable portion of the economic growth and industrial strength in the United States relates to the growth of its electric power industry, which is by far the largest of the country's industries[1] (Fig. 1). In recent decades the electric power industry in the United States has been growing at a rate of about 7 percent per year, more than doubling its generating capability every ten years[2] (Fig. 2). At the beginning of last year, generating capacity totaled over 228 million kW.

Annual output of generating plants has been steadily growing over the years (Fig. 3), and is now of the order of 1000 billion kWh, or—using more modern terminology—1000 TWh (terawatthours). An interesting figure is that with only 6 percent of the world's population, the United States generates 37 percent of the world's power.

Power processes

Electric power processes are concerned with energy conversion and the delivery of energy to users in useful form, when and where and for as long as wanted, as economically and dependably as possible.

To help clarify these processes and their control problems, and to provide a basis for an orderly review of recent progress and present state of the control art in this field, two general areas in this review shall be considered, namely:

1. Energy conversion plants. The objective is to operate each plant at optimum efficiency at the power generation level assigned to it.
2. Interconnected networks of such plants. Here the objective is to assign and maintain plant generation levels and tie-line power flows that will yield optimum overall system economy consistent with continuity of system operation.

Generating plants

As can be noted from Fig. 3, over 81 percent of the present output of the industry is derived from fuel, and almost all of this is from fossil-fuel-burning steam-electric plants. In discussing progress in plant processes and automatic control applications within plants, this article will accordingly confine itself to such fuel-burning plants. That is not to say that other forms of energy conversion are not important, but time and space limitations will not permit their inclusion in this discussion beyond these brief comments:

Pumped storage. In a typical area, over a typical day, power demand will vary over a range of about two to one or more between the periods of highest and lowest demand. Power demand in the valley period is likely to be below the total capability of the most efficient available units, some of which would therefore have to be idle for parts of the day. There has been increasing interest in recent years in taking advantage of the variation in power demand by utilizing "pumped storage" for "peaking" purposes.[3]

Under some conditions it is advantageous, during off-peak hours, to use low-cost steam plant energy to

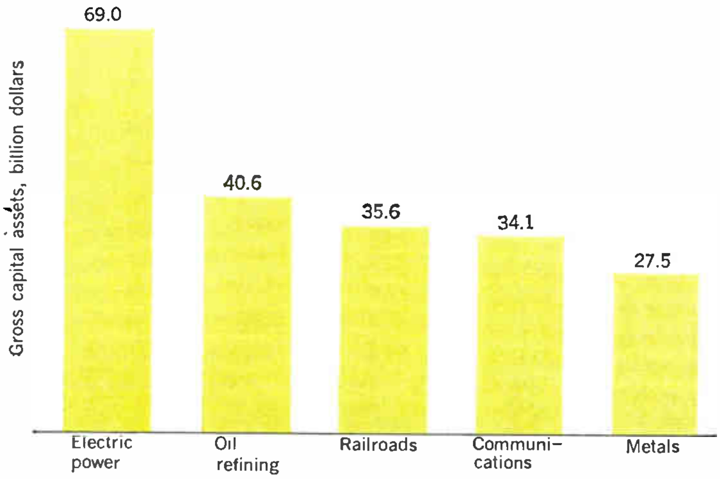


Fig. 1. Gross capital assets (in billions of dollars) of the largest United States industries in 1962.

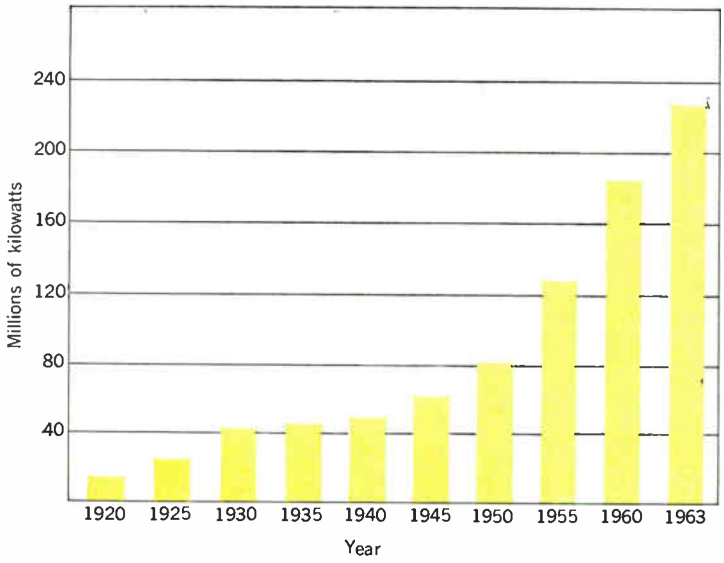
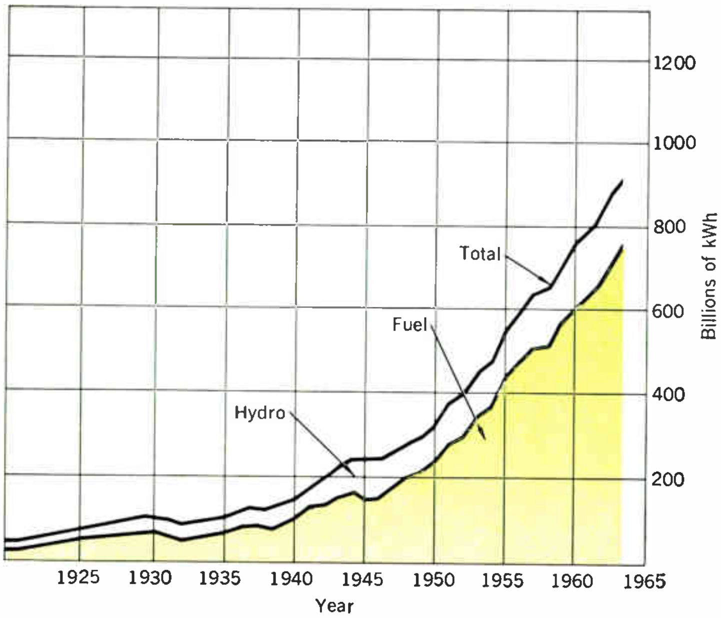


Fig. 2. United States generating capacity.

Fig. 3. United States electric power production.



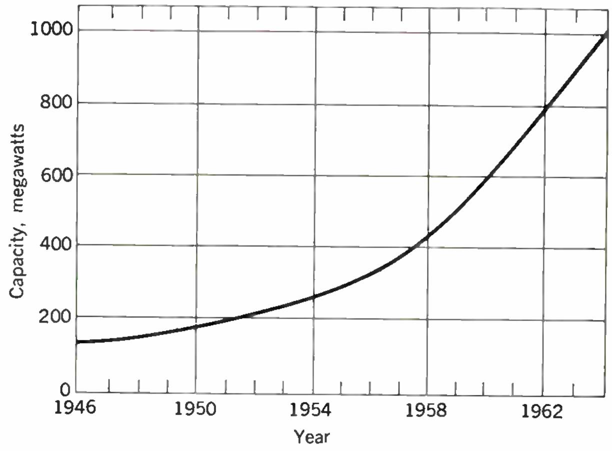


Fig. 4. Largest turbine–generator set, 1946–1964. Progressive growth in size of individual units.

pump water up to high-elevation reservoirs, and then run the pumps as generators during high-demand periods. About 2000 MW of pumped storage capacity is currently in operation or under construction. Several thousand megawatts of additional capacity are under consideration.

Control specialists will recognize that there are interesting optimizing challenges in the operation of such facilities.

Nuclear power. Nuclear plants at present account for only a small fraction of a percent of the nation's power capability. It has been estimated, however, that by 1980 nuclear power installations will aggregate about 70 000 MW, or about 13 percent of the total capability expected to exist at that time. Such plants will engender a particular awareness of economy and safety, and will provide many automatic control opportunities.

Fossil-fuel plants. Let us turn now to fossil-fuel-burning plants. Here a first major point of interest is the progressively increasing sizes of individual units.

The trend of increasing sizes is shown in Fig. 4. A typical size in 1950 was 175 MW (compared with 100 MW in 1940). A number of units in the 500–700-MW range are now in operation or under construction. Units of 900 and 1000 MW will start commercial operation within the next two years. A 1200-MW unit is already under contract.

Increased size has generally meant increased complication, with greater demands from, and greater dependence on, automatic control.

Paralleling the increased sizes, and reflecting continuing progress and improvements in the energy conversion process, has been improved efficiency. This is illustrated for the years 1930–62 in Fig. 5.

Best plant heat rate, which was 15 000 Btu per kilowatthour back in 1925 (not shown in Fig. 5), had improved to approximately 8600 Btu per kilowatthour by 1962. For *all* plants in operation the drop has been from 25 000 Btu per kilowatthour in 1925 to approximately 10 500 Btu per kilowatthour in 1962.

Such steady and significant improvements in plant efficiency have counterbalanced the continuing increases in the price of fuel over the years, permitting a fairly constant cost of fuel per kilowatthour despite the fuel price increases. These factors are illustrated in Fig. 6. Auto-

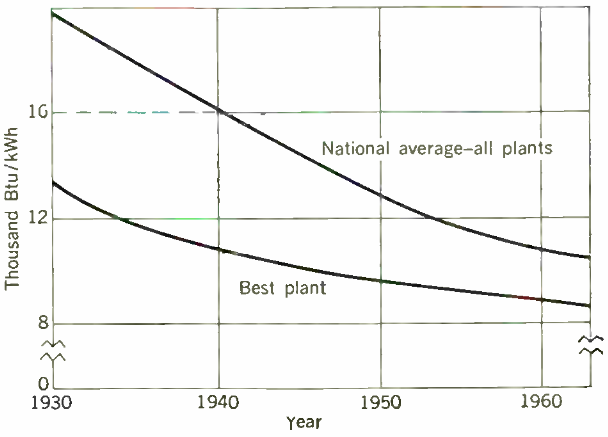


Fig. 5. Improvement in plant heat rates.

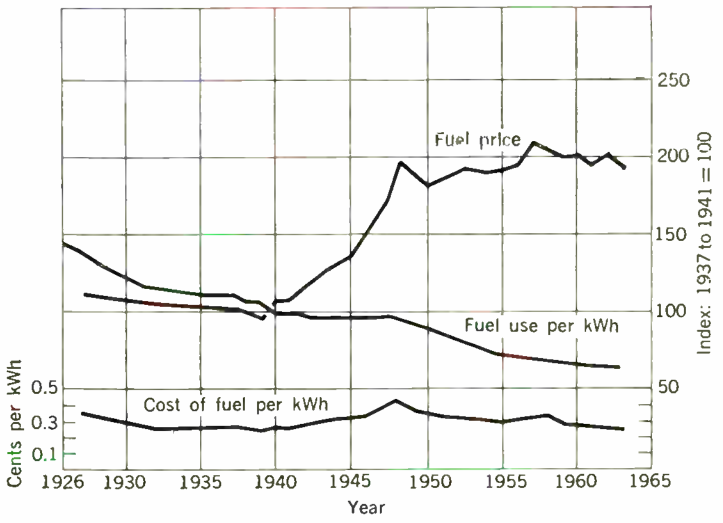


Fig. 6. Fuel prices and efficiencies, 1926–1963. Improved efficiencies counterbalance increased fuel prices.

matic control has played an important role in the achievement of these improved efficiencies.

The supercritical pressure unit. As part of the continuous search for improved operating efficiencies, design pressures and temperatures of steam-generating units have been steadily increased over the years. As a most noteworthy advance in this field, several units have been built and placed into operation within the past five years which operate in the supercritical range. Most units in the 500-MW and above size are or will be in this category.

When operating above critical pressure—3206 psi—steam and water do not exist as a mixture. A steam generator of this type is therefore of the "once-through" design. It has no steam drum with its storage effects, and drum level is therefore not available as a control reference as in conventional boilers. Its response characteristics and degree of self-regulation differ markedly from conventional units. It includes a very large number of manipulated variables, many of which have major interacting effects on output parameters. Its operating complexities are manifold. It has created the need for markedly new concepts and executions in an automatic control system that will provide stable coordinated regulation over the full range of "light-off" to rated load, under both steady-state and varying load conditions.

The solutions developed for such boilers are representative of the most advanced state of the art in this facet of power plant control.

In turning to more detailed comments on in-plant controls, I think it will be helpful to consider two aspects of such applications separately, even though they are to some degree interrelated, namely: (1) continuous operating functions, including on-line automatic control, performance computation, and safety monitoring; and (2) automatic start-up and shutdown functions.

Continuous plant controls

Use of control theory. In the development of present-day control systems, such as those now applied to once-through boilers, modern control theory and simulation techniques have been used, to a degree, to replace or supplement the essentially empirical approaches of earlier years. Simulation in particular, using both analog and digital computers, has been helpful in dynamic modeling,

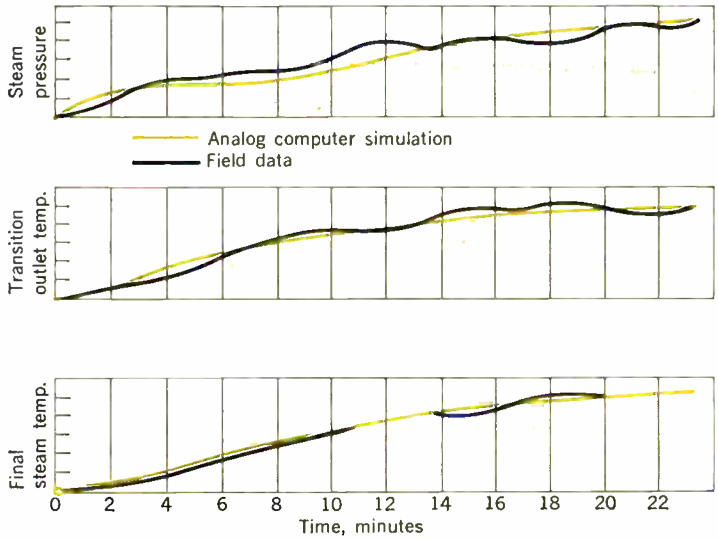
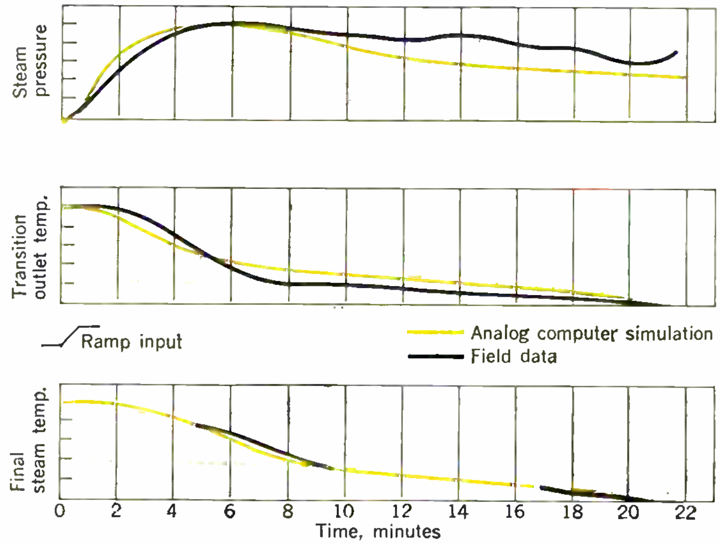


Fig. 7. Responses to step change in fuel and air at full load. Comparison of L&N simulation with field data.

Fig. 8. Responses to ramp change in feedwater. Comparison of L&N simulation with field data.



in the development of advanced control concepts, and in the synthesis of multivariable control systems.[4-7]

Several companies feel that here, at least, a gap has been effectively bridged and that there have been productive exchanges between engineers with long-time practical power plant field experience and scientists in computer laboratories.

Simulations from theoretical design data of complex once-through units have proved to be reasonable when checked against subsequently available field data. Typical comparisons of predicted variations in output parameters for step function changes in input variables, based on a theoretical simulation of a supercritical once-through boiler from its design data, with subsequently available field data are shown in Figs. 7 and 8.

These simulations were conducted on an analog computer having 170 operational amplifiers, and, together with similar simulations, were helpful in carrying out significant studies and in reaching decisions on the relative merits of proposed alternative control arrangements. This manufacturer is studying supercritical unit responses more extensively on a large digital computer, and subsequently performing the control studies on an analog computer. With this approach, it has been possible to study all of the significant process inputs and outputs to represent all of the major control loops.

In addition to simulation, use is being made in modern control systems of noninteracting concepts, of feed-forward techniques, and of adaptive arrangements to adjust controller settings for nonlinear control responses at varying loads and with different operating combinations.

Where direct digital control techniques have been undertaken, available knowledge of sampled data theory has been used to establish sampling rates properly related to input noise conditions and to process control dynamics.[8]

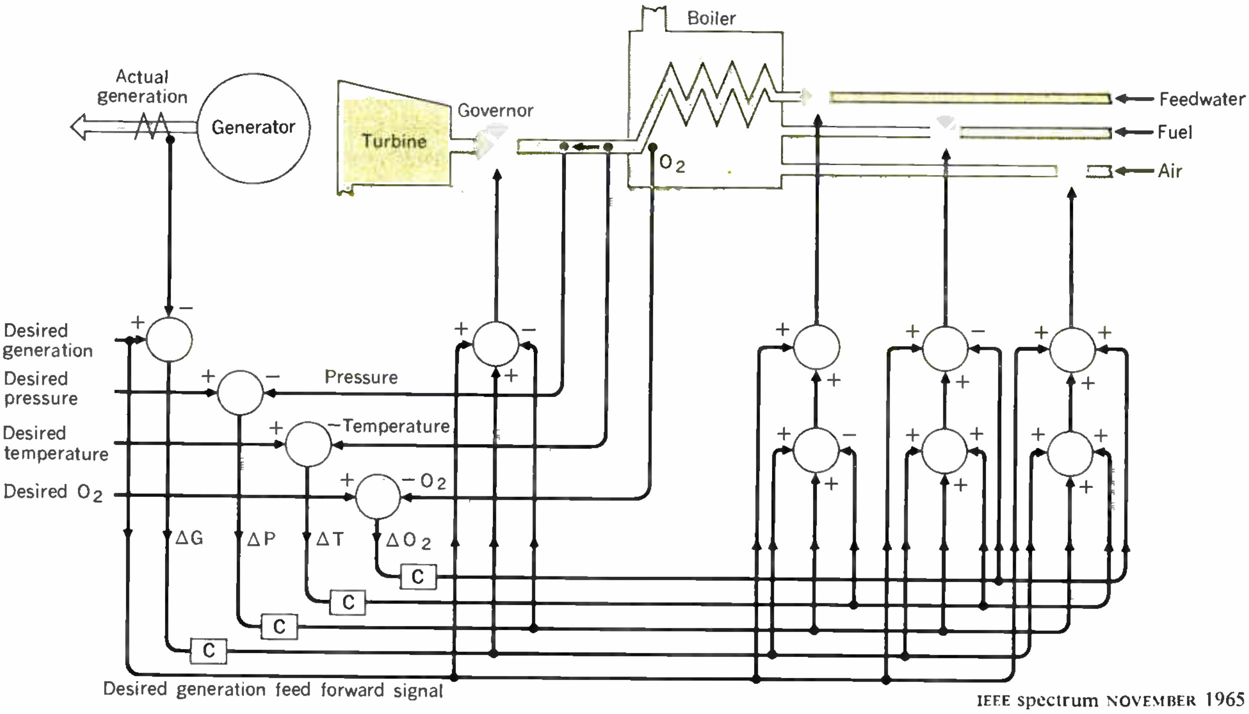
In general, manufacturers feel they are making commendable progress in the development of control concepts as coordinated noninteracting control systems to meet the exacting requirements of complex present-day plants. They might well be the first to grant, however, that not too much of the extensive control theories being developed, particularly in academic circles, finds use in present-day installations. Much that is done remains empirical or experimental.

Empiricism and experimentation. In the context of comparisons between theory and practice, it seems appropriate at this point to say a few words about empiricism, its practitioners, and its relation to control applications.

Empiricism should not necessarily be downgraded. Indeed, when it takes place in the most advanced of experimental laboratories it is usually called "science." In the development and application of control systems, empiricism is unscientific only when the attitude is obtuse and narrow, and when available applicable contemporary knowledge is not fully used.

Theorists should recognize that it is the empiricist, the "practical" engineer, who is largely responsible for the control systems that are installed and operating so well in complex generating plants and on widespread interconnected systems today. Typically, he has gathered much of his information and understanding from field observations and experiences, from adjustment of control systems in customer plants, and from cut-and-try techniques for improving their performance. He has sought to absorb and utilize all the applicable theory he can understand. In addition, the most effective empiricists have listened with respect to the more theoretically minded individuals at their plant headquarters who

Fig. 9. Simplified schematic of a coordinated control system for once-through boilers. Major coordinating controllers are marked "C."



have been able to demonstrate better ways of anticipating and solving field problems and better ways of executing recognized control principles.

But there is one view from which the practical engineer cannot depart. Today's control problems need solutions today. Customer commitments must be satisfactorily resolved with contemporarily available tools. Tomorrow's knowledge will not be today's until tomorrow, and will not become fully useful until then.

The practical engineer recognizes, however, the importance of innovation, and he encourages all activity that will improve the state of the art. But he also recognizes that newness does not necessarily equate with progress. He welcomes innovation, but requires that what is new be proved, in actual operation, to have appropriate qualities of reliability and improved performance before it qualifies for general acceptance as a contribution to the art.

I am certain that all manufacturers are on the alert for, and ready to welcome, all theoretical contributions, from within and outside their organizations, that will help them do a better practical applications job.

A coordinated control concept. Let us turn to the synthesis of a coordinated control system for a complex multivariable application. One control now in use and being supplied for new projects, derived from both theoretical considerations and field experimentation,[4] is shown in highly simplified form in Fig. 9.

The large-sized once-through units to which this system is currently being applied have as many as 90 or more manipulated variables to be placed under coordinated automatic control. The diagram of Fig. 9 does not by any means begin to show the extent of the control problem, with its multiple fuel, air, and feedwater inputs, its reheat steam cycle, and its complicated, almost endless details. The diagram is intended only to show how the major input variables are acted on in coordinated fashion by pertinent measured, set, and computed parameters, in some cases in the same sense, in others in the opposite sense.

Feedforward from desired output, itself manually set at the station or automatically set by a remote dispatching computer, is utilized. Appropriate limits for ranges and rates of response are provided, as are automatic runbacks on loss of major auxiliaries. Each individual control action is conditioned to give weight to its influence on process output parameters, to varying response characteristics, and to varying time lags. These sophistications, essential to coordinated nonhunting and safe regulation, are not shown, but perhaps this brief reference to them will help to establish the dimensions of the control problem.

Analog executions. Virtually all major plant control systems currently in operation or in the process of installation are analog in nature. A recent trend has been to all-electric and electronic executions, though a number of the new large plants still favor pneumatic or electronic–pneumatic assemblies. Electric–electronic systems are felt by many to have the advantages of speed and flexibility, and they coordinate well with digital data and computing systems.

The newest analog systems make extensive use of solid-state technology. Increasingly, SCR power switches are replacing electromechanical contactors for operation of large electric actuators. Characterizable contact-free transmitters are replacing potentiometers for generating actuator feedback signals.

There have been important improvements in the accuracy and reliability of flow and pressure transmitters, but even greater performance capabilities are being requested by users.

Digital techniques. Power companies have been traditionally alert to the need for collecting data for operator guidance and for evaluation and improvement of plant performance. Where a company's fuel bill runs into many millions of dollars per year, big savings can be achieved by even modest improvements in plant efficiency.

Several years ago, conventional measuring and recording instruments began to be supplemented, and in some instances replaced, by digital data gathering assemblies. Some of the systems included modest computing capability. Pertinent information was in this way presented to operators in a more centralized and coordinated fashion, hopefully resulting in more rapid corrective steps when such were required.

With the advent of the digital computer, centralized data gathering systems were expanded to include additional functions.[9]

One objective was to provide the operator with concurrent computations of cycle and plant efficiencies instead of the previously available historical analysis. Another was to provide more extensive monitoring and alarm functions, which would aid in preventing both minor and major shutdowns. Efforts to extend the computer to plant control functions soon followed.

In addition to these essentially continuous plant functions, computers were also installed to fully automate plant start-up and shutdown without human intervention, as will be additionally referred to in a section that follows.

The pioneer on-line solid-state digital computer installation was made in 1958. Its functions were logging of approximately 100 key variables, alarm scanning, performance calculations, and closed-loop direct digital control of two auxiliary temperatures.

Since then, it is estimated that about 65 or 70 computers have been installed in steam plants throughout the country and additional ones are in the process of installation.

As experience has been gained, and new generations of computers have become available, functions have been extended to larger numbers of points scanned, alarmed, and logged, to more meaningful and useful performance computations, to logical sequence control functions and—in a few cases—to more extensive direct digital control.

There is by no means agreement in the industry at this point, however, on the functions that can and should be assigned to a plant computer.

One example of current practice is shown in Fig. 10. This is an artist's sketch of the control room for a large plant now under construction. For each of two 900-MW units, control will be of the analog electric–electronic type, and a digital computer will perform monitoring, performance computation, alarm, and logging functions. Start-up and shutdown switching functions will be manually executed, but the computer will provide sequence and safety monitoring instructions and checkback for operator guidance. The screen for projecting monitoring messages to the operator can be seen in the center of the figure.

Another comprehensive installation, scheduled for operation this year, and exemplary of the present state of the applications art for steam-plant computers, will include the following functions: off-normal alarming, performance computation, logging, trend recording, on-demand display of stored history of plant variables, trip sequence monitoring, some start–stop functions, digital data control for several temperature and level loops that completely replace analog loops for these functions, and digital override of major analog loops for control of feedwater, combustion, and steam temperature.

Design, installation, and operating experiences with computer installations have been well documented.[10–14] (References 10 and 14 are particularly helpful in portraying the present state of this art.)

In general, I think it is clear from available documentation that there has been much to learn in applying on-line computers to power plants. In many cases, the experience has been time consuming and expensive, for manufacturer and user alike.

One manufacturer, in providing information for this survey, has cited a number of typical problem areas encountered with field installations. For most problems, he points out, solutions have been provided. For others, he notes, solutions still require verification.

The problem areas cited are: input signal noise, system reliability (now felt to be of a high order), expansion capabilities, computer speed (solved with presently available units), transducer failures and errors, high cost and excessive time required to define, code, and check out programs (emphasized as a continuing real and major problem), and poor operator/computer communication.

Start-up and shutdown functions. An understandable objective in the operation of steam plants has been to extend the use of the digital computer beyond continuous monitoring, computation, and control functions to extensive start–stop functions, thereby achieving full plant automation.

One of the pioneering utilities in this aspect of computer application has stated in the following way the full degree of automation that it hoped to achieve: "The boiler and turbine–generator should be capable of being safely and reliably started, operated automatically at optimum efficiency, and automatically shut down without benefit of manual operator assistance."

References 11 and 13 document this company's and its consultant's experiences, and detail the extensive complications and problems encountered in undertaking so comprehensive an objective. While indicating that concrete evidence had not yet been developed that a digital computer system is the most economical method of automating a steam plant, they do call attention to benefits gained from experiences with efforts to achieve such full plant automation.

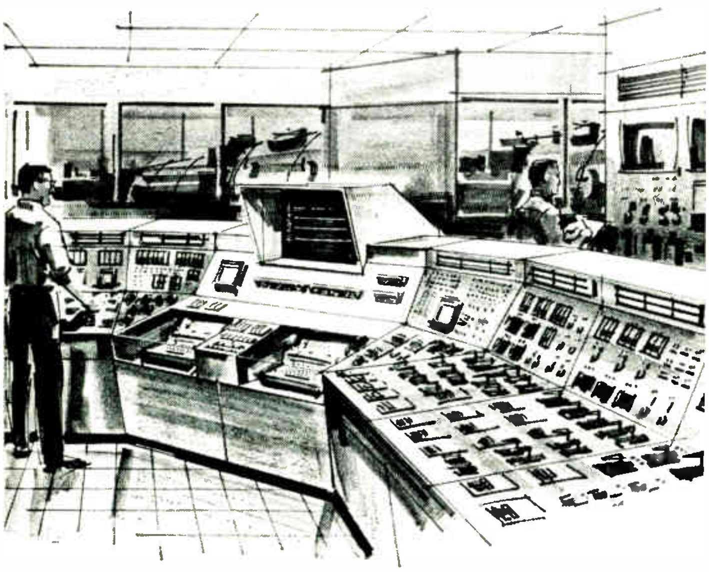


Fig. 10. Centralized control and monitoring, large supercritical unit.

Prevailing views

There is not, at this point, a unanimity of views among users and their consultants concerning the place of digital computers in steam plants. Performance of present installations is being appraised. Technical and economic considerations with respect to future plants are being evaluated. Here are excerpts from comments obtained from major consultants and operating companies for this survey article.

Consulting engineers. One consultant says: "Analog systems will continue to be used for automatic boiler control. There does not appear to be justification from the standpoint of initial cost or improved efficiency to encourage development of digital techniques in this area.

"It is for on-line up-to-date performance computation and safety monitoring that the computer initially derives its justification. Eventually, performance calculations will be standardized on a national basis, after which it is expected that such computers will be considered standard equipment for new projects.

"Due to the high equipment cost and complexity of programming for intermittent start-up and shutdown functions, and based upon reports of operating experience in this area, we cannot find justification for providing computer equipment for this purpose on an overall unit basis. We do recommend that consideration be given to computer start-up and shutdown in some areas, such as the turbine–generator combination, where programs have been successfully applied.

"Solid-state logic circuitry lends itself to start-up–shutdown functions as exemplified by progress in the burner light-off area.

"Overall start-up and shutdown appear to be a job for solid-state switching circuitry working in parallel with a computer."

Another consultant writes: "A direct economic justification by savings in efficiency and safety is almost impossible to prove. Another approach is that of demonstrating how small an increment of efficiency is sufficient to cover the cost of a computer installation, and assuming that the potential for such savings is inherent in a modern on-line installation.

"Once this concession is made, it would appear reasonable to justify an on-line computer for a large station by the many protective possibilities it presents in addition to performance calculation.

"While computer automated stations have yet to prove their worth, there is little doubt that this is the way the wind blows. A great deal of work remains to make sensors more reliable, and to develop systematic methods for flow charting operations."

Still another consultant writes: "Any increase in the extent of automation must contribute to greater safety to both personnel and equipment, improvement of operating and operator efficiency, increase in station availability, and reduction of maintenance.

"All of the automation equipment must be justified by such criteria. When we consider highly sophisticated digital computing systems, justification tends to be based on more of the intangible advantages. It is extremely difficult to assign tangible values to such things as preventing catastrophic failures.

"Complete automation will be an integrated overall approach where some systems are independent and others are supervised by a stored program computer.

"Wide acceptance of advanced automation must develop slowly, and must be based on sound economic justification."

One consultant sees real potential worth of expected benefits from full automation, on a basis of fuel economy, minimization of manpower needs, reduction in maintenance, and reduction in both major and minor mishaps. "Expected savings," he points out, "can vary considerably with staffing practices, unit characteristics, and care in operation. For the same size units savings may vary by a factor of 3. Individual study is therefore essential."

He feels that direct digital control has promise, and cites the possibility of digital programs being used protectively to catch analog control failures before great upsets occur.

"Efforts to compute efficiency and heat rate are restricted by lack of solid understanding of heat storage dynamics. We need a full range nonlinear simulation. We live with imperfect sensors and position switches. A major problem is getting people with the right temperament, knowledge, and interest to work at bridging the gaps. We're still in R & D for the next couple of jobs."

Users. One of the users writes: "There are three drawbacks to computer control at present. They are the high cost of equipment, the high cost and effort required for programming, and lack of reliable sensing devices for many applications.

"We have not seriously considered digital computers for continuous control functions. We have felt that the most promising application is the continued use of analog loops with the digital computer used to control the time sequence of major operating steps and to make certain logical decisions."

Another user furnished a copy of reference 14, in which he comments about the future this way: "It is hoped that the two-year slippage of computer-controlled start-up at [Plant P] will be over in mid-1965. It is also hoped that experience will be achieved earlier at [Plant B]; however, the general inability of boiler, turbogenerator, and other contractors to produce on time the necessary information for analysis and flow-charting has already delayed completion of logic diagrams by 17 months. Programming for control has not yet begun [February 1, 1965], and the 12 to 13 months estimated for this work cannot now be completed by the commercial operation date. These comments are an acknowledgment of underestimating the job and overestimating ability in varying degrees by all participants. The worst effect is not getting any practical operating experience in computer control before having to proceed with another unit installation. In short, we have so far been unable to prove monetary savings equal to or exceeding cost of the systems. Information on costs however seems to accumulate steadily. Automation in various forms and degrees will continue to be applied until further experience and operating data dictate the requirements in a more adequate manner."

Another user, who has pioneered in plant automation, writes: "With regard to our present policy concerning automation, we are only making provisions for the future addition of computers. Conventional control systems are used. Automation features are included, but as wired logic subloops.

"We have retrogressed somewhat from our initial automation philosophy which was fully automatic start-up and shutdown programs with absolutely no manual interventions, to a more comfortable position which allows operators to perform most of the on–off type functions.

"It is true our new unit design lacks the degree of checks and balances afforded by complex computer programming, but with the automation we are providing in new units, the operator has at his disposal more control apparatus with which to circumvent plant hardware or control equipment troubles. Where set computer control programs provide a start-up procedure, increased remote manual control provides a start-up flexibility that has been lacking in all computer control programs to date."

Finally, still another user has this view: "More reliable primary sensors are needed to eliminate paralleling for redundancy.

"A great deal of effort should be expended toward application of digital techniques to present analog control functions. Other power plant processes which are at present inadequately sensed and controlled should be studied for digital control application."

It is clear from the foregoing summary of viewpoints that widespread differences of opinion currently prevail as to the degree of steam plant automation that is justifiable or desirable, and the extent to which it should be analog or digital or both.

Probably the best way to appraise the state of this facet of the art is simply to say that it is in a state of flux.

Views have certainly not yet hardened. Utilities and their consultants, to their credit, have encouraged experimentation. Not all the approaches or innovations have been the same, and not all the results have been satisfactory. Such uncertainty and differences of view are as good an indication as any that progress is being made. Work, in many plants, involving many manufacturers and consultants, continues. Inevitably, better clarity will emerge in the years ahead, and more universally shared views will doubtless develop.

Interconnected systems

Increasingly, over the past four decades, adjacent power companies have interconnected with one another for parallel operation. By this means, generation and reserves can be shared. Advantage is taken of load diversity and of time-zone differences to transfer generation over interconnecting tie lines from an area of low demand to one of high demand. Larger, more efficient units can be purchased and their outputs shared, and rotating reserves in a given area reduced. Overall operating economies are correspondingly achieved.

In earlier years, interconnections extended over relatively limited areas. As operating problems were analyzed and resolved, and parallel operation technologies were developed, interconnections have been steadily expanded. Today, five operating interconnections account for the entire country. The largest interconnection extends to the east from the Rocky Mountains, and includes the Midwest, the Gulf Coast, the Eastern Seaboard, and eastern Canada. Constituent groups within this single interconnection are the Interconnected Systems Group (ISG) of 115 operating utilities, private and public, the Pennsylvania–New Jersey–Maryland pool (PJM) of 12 operating companies, and the Canadian–Eastern United States group (CANUSE), which has 31 operating utilities.

The more than 150 utilities of this interconnection, having a total peak load greater than 130 million kW, operate continuously in parallel, smoothly and cooperatively. Automatic control makes that possible.

Similar parallel operation is achieved and automatic control is similarly utilized in the four other interconnections.

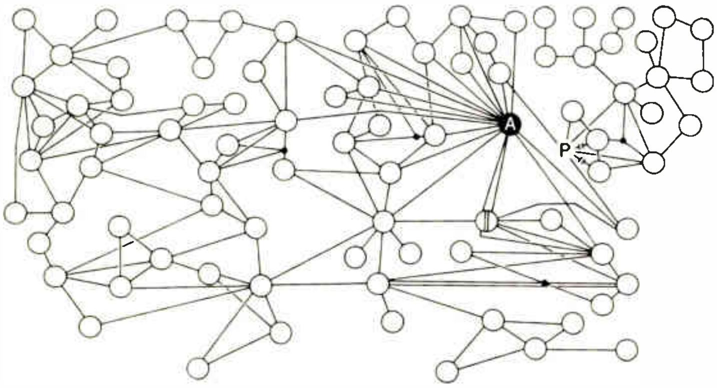
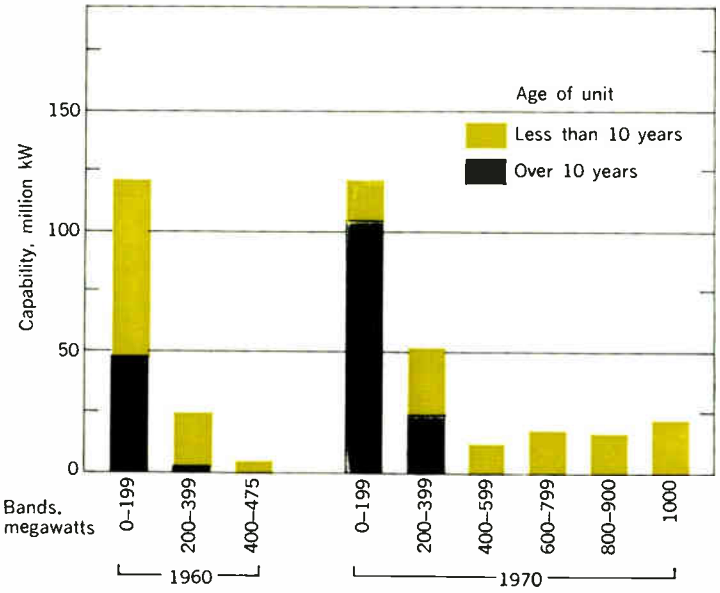


Fig. 11. Control areas of the country's largest interconnection (ISG, PJM, and CANUSE).

Fig. 12. Varying sizes and ages of available generators. Distributing of thermal generating units.



Some of the five interconnections have undertaken short-term test periods of parallel operation with each other. It is generally anticipated that by about the end of this decade requisite new tie lines will have been built and closed, permitting all five interconnections to operate as a single interconnection covering the entire United States and portions of neighboring nations.

The control problem

Coordinated control is essential to successful parallel operation. Concepts for system regulation and optimization have been well developed over the years, and are in widespread use within the limits of present-day equipment and technologies.[15]

Control requirements are twofold:

Area regulation. Total generation within an operating area must be adjusted to follow the moment-to-moment load changes within that area, in suitable coordination with generation and load changes in all other operating areas, so that scheduled tie-line interchanges with adjacent areas, system frequency, and system synchronous time are all properly maintained. This function is referred to as "area regulation."

Economic dispatch. Optimal assignment of the total generation required at any moment from an area should be made among the many plants and units within that area to achieve optimum economy consistent with safe operation. This objective is identified as "economic dispatch."

Let us explore briefly the nature of these two functions, and the present state of the art in achieving them.

Area regulation

The word "area" probably needs to be explained. An "area" can be a part of a company, a whole company, or a group of adjacent companies, which operate, from the viewpoint of interconnection, as a single entity. It schedules and maintains levels of tie-line interchange with its neighbors, but permits tie lines *within* the area to be free flowing; i.e., no effort is made to maintain them at any scheduled levels. All load changes within the area, regardless of where they occur, are treated alike insofar as automatic control is concerned.

A first objective of area regulation is to automatically adjust total generation to match total load changes within the area. A second objective is to adjust area generation when required to assist on a preprogrammed basis any other area of the interconnection that may be in trouble, and which cannot at the moment fulfill its own area regulation obligations.

The universally accepted technique by which coordinated neighborly area regulation fulfilling both of these objectives is achieved is known as "net interchange tie-line bias control."

The country's largest interconnection (ISG, PJM, and CANUSE) has some 88 control areas for its 115 operating utilities. These areas, with their major tie-line interconnections, are shown in Fig. 11. It will be understood that each circle is a control area, and may include, as several of them do, a number of companies "pooled" together to operate as a single entity from the viewpoint of area regulation and economic dispatch. Also, each line between two areas may represent many tie lines, and not just a single tie.

This interconnection extends into Quebec in the North-east, Florida in the Southeast, a portion of Texas in the Southwest, and Montana and the Dakotas in the Northwest.

All 88 of the operating areas shown in Fig. 11 are equipped for net interchange tie-line bias control.

The tie-line telemetering required for the automatic computation of an area's net interchange with the interconnected system is largely analog, although in recent times digital techniques have also been used. Telemetering transmission has increasingly been by microwave.

Almost all of the area controllers, including most of those that have been recently installed, are of the analog type, the newest using solid-state components. One or two on this interconnection, and a similar number on the Pacific Southwest–New Mexico interconnection, use digital control techniques for area control function; these will be referred to further in discussing the use of digital computers for the economic dispatch function.

Area regulation performance. Area regulation performance on the interconnection of Fig. 11, though by no means perfect, has been very good. A commendable job is being done, permitting the areas of this widespread network to achieve the benefits of parallel operation and to stay together in operating synchronism, even during periods of large system disturbances.

It is no mean task to assure that 88 controllers, spread out over thousands of square miles of area—each in an independent privately or publicly owned utility, each depending on widespread telemetering networks, each requiring frequency and tie-line schedule settings coordinated on a system-wide basis, each requiring appropriate "bias" settings, each to be backed up by adequate and responsive generating capacity, each to be adjusted so that it corrects errors and does not create them, and all operating simultaneously on a single integrated network—will effectively fulfill their individual objectives and obligations and at the same time contribute to the common overall network objective of sustained, stable parallel operation.

That these complex control objectives are achieved as well as they are is a credit not only to the state of the applicable control art, but also to the operating people around the interconnection who are charged with making the system and its equipment work.

For many years there have been informal, voluntary operating and test committees on the various pools and interconnections who have appraised performance, analyzed problems, and established operating guides, thereby contributing immeasurably to the results currently being achieved. More recently, an informal, voluntary nationwide group, the North American Power Systems Interconnection Committee (NAPSIC) has been formed, with representation from all operating regions of the country, to deal on a national basis with the coordination problems of massive networks. This committee will make important contributions to improved system operations.

With regard to area regulation control performance, the refinements still to be achieved are: better and more rapid responses in some areas to changes in demand within the area; minimizing the regulating assistance required from other areas; fuller coordination of tie-line schedules; better telemetering channels for more sustained communications between tie lines and control, and between control and regulated generators; better coordination of frequency settings for time-error correction.

Improvement in all of these factors will decrease present levels of "inadvertent" interchange—i.e., deviations from scheduled interchanges between areas—and will assure equitable distribution of system regulating burdens.

Economic dispatch

In the execution of area regulation, generation is automatically adjusted within the area to match area load changes. Clearly, it would be advantageous to assign each required generation change to sources within the area that can most economically absorb it. If we take into consideration the different ages and sizes of units (Fig. 12), the resultant differences in their efficiencies, and their different locations and consequent differences in transmission loss factors to load centers, there is opportunity for substantial economies by loading them optimally with respect to one another. This is economic dispatch. It is achieved when generating sources within the area are loaded to equal incremental costs of delivered power. For fuel-burning plants the well-known coordination equation for such optimization is

$$\lambda = \frac{\dfrac{dH_n f_n}{dP_n}}{1 - \dfrac{\partial P_L}{\partial P_n}} \tag{1}$$

where

λ is the incremental cost of power delivered for the area

$\dfrac{dF_n}{dP_n}$ is the incremental cost of power generated at source n

$\dfrac{\partial P_L}{\partial P_n}$ is the incremental transmission loss for source n

$\dfrac{dH_n}{dP_n}$ is the incremental heat rate for source n

f_n is the cost of incremental fuel for source n, adjusted to include other varying costs at source n

There has been an interesting evolution in the automatic control equipment used to achieve economic dispatch. A brief summary of some of its highlights and comments on the present state of the art follows. Those interested in fuller details of early steps in this evolution and in information concerning the derivation and applications background of Eq. (1) are referred to papers listed in the bibliography of Ref. 15.

Flexible loading consoles. The first areawide automatic economic dispatch systems date back to the early 1950s. Kilowatt loading schedules for each controlled source of the area as a function of total area generation were computed in advance, and were manually programmed into a centralized computer-control console. As area demand varied, the centralized console and its auxiliary equipment would compute and maintain the proper loading level for each generator of the area, and in the process would fulfill the area regulating requirements.

A unique and important feature of these control assemblies was the use of a feedforward signal from area control error, which, when combined with feedback from prevailing area generation, provided a reference for predictively computing the loading assignment for each source. This assignment was then independent of the rate at which other participating sources responded to their control assignments.

Another important feature involved arrangements for overriding economic dispatch when the area regulating requirement would not be fulfilled rapidly enough by the sources responding to economic dispatch.

A large number of these early consoles are still in use, and a number of new ones have been installed in quite recent times, some for predominately hydro areas[16] where the flexibility of wide-range schedule setters is very useful, and others for coordinated use with digital computers, as will be noted later. The newer assemblies utilize solid-state circuitry in place of the electromechanical elements of earlier units.

Analog desired-generation computers. An advance from the flexible loading consoles occurred in the late 1950s with the introduction of analog-computer-control assemblies based on the coordination relationships of Eq. (1). Here desired generation for each available source was computed on a continuous basis from the following:

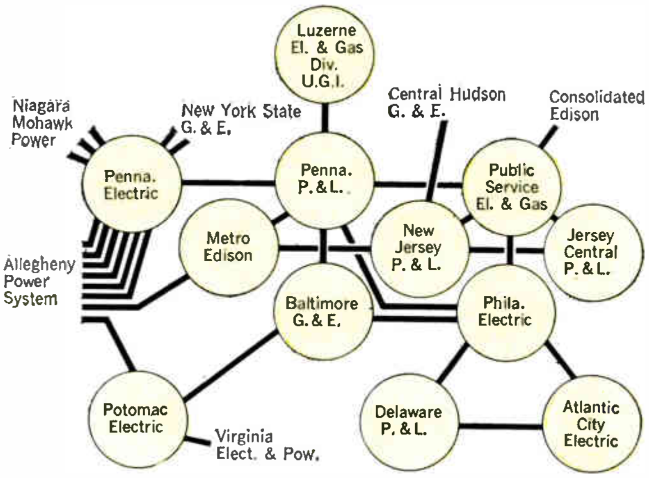
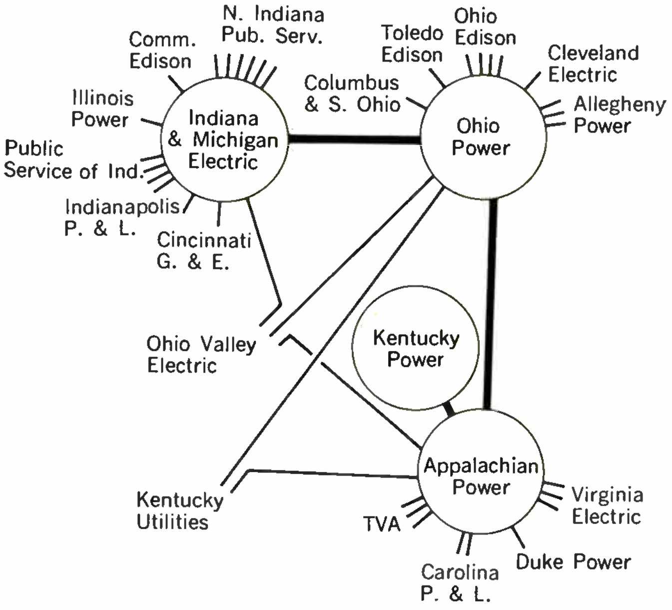


Fig. 13. Operating companies and ties of the circle marked "P" in Fig. 11. Pennsylvania–New Jersey–Maryland pool.

Fig. 14. Major operating companies and ties of the circle marked "A" in Fig. 11. American Electric Power System.



1. Stored information of its incremental heat rate vs. output relationship.

2. Incremental transmission losses for its station, computed dynamically from continuous measurement of prevailing area generations and power flows and from stored constants related to the area configuration.

3. A continuously computed lambda value that would yield an economic dispatch whose total generation would satisfy the prevailing area needs.

Some two dozen or so large centralized analog computer controls of this general type are currently in operation, or in the process of installation. A combination of feedforward and feedback, as with the flexible loading consoles, provides a predictive lambda computation and contributes to nonhunting simultaneous control of area sources.

Digitally directed analog control. A relatively recent development has been the inclusion of digital computers in centralized economic-dispatch control systems. One technique is to link the digital computer to an analog console of the general type discussed earlier.[17-19] With this arrangement, the digital computer at appropriate intervals executes the economy dispatch computations, and transmits the resultant desired generation levels for the controlled sources to setting devices in the analog console. The latter executes the control assignment, achieving the economic dispatch while simultaneously fulfilling the area regulation obligation.

The digital computer can advantageously be programmed for other on-line functions, such as determining the appropriate time to bring generators on the line or take time off as peak load goes through its daily peak and valley cycles, checking reserves and imposing security restraints for various parts of the area, evaluating possible advantageous interchanges for neighboring areas, optimizing pumped hydro operation, checking area voltages, and logging pertinent operations and measurements data.

When the digital computer is not available for economic dispatch because of off-line use, or because of maintenance or malfunctioning, the analog console provides continuity of multiple-unit area regulation while executing manually programmed economic dispatch.

Several digitally directed analog systems have recently been placed in operation or are presently being installed.

Direct digital control. An alternative technique when utilizing a digital computer is to apply it directly for area regulation and economic dispatch, without the use of an intermediate analog control console. At the present state of the art, a suitable stand-by analog control would probably be retained, or made available, for area regulation.

Initial installations of this type are now in operation,[20,21] and are reported to be performing satisfactorily.

Typical installations

It may be of interest at this point to look briefly at two major recent installations, which will illustrate a number of the points made in this discussion of interconnected systems controls.

Pennsylvania–New Jersey–Maryland pool. The control area marked P in Fig. 11 is the Pennsylvania–New Jersey–Maryland pool. Companies of this group were pioneers of the "pooling" concept, in which member companies operate as a single control area with free-flowing ties and a common economic dispatch.

The 12 independently owned companies of this pool, and their intrapool and external ties to neighboring utilities, are shown in Fig. 13.

Control execution for this pool is hierarchical. At the pool headquarters in Philadelphia a net interchange tie-line bias controller acts with an analog computer unit to establish a pool lambda that will satisfy area generation requirements, and will simultaneously maintain scheduled interchanges over the 16 northern, southern, and western tie points to the utilities with which the pool interconnects.

The computer control at the central headquarters communicates this lambda value to computer-control assemblies located at the dispatch centers of the respective member companies, which in turn compute and execute corresponding economic dispatch assignments for their generating units.

American Electric Power System. The circle marked A in Fig. 11 represents the American Electric Power System. A closer look at this system and its major tie points with its principal neighbors is provided by Fig. 14.

This system, the country's largest investor-owned electric-energy producer, has pioneered in interconnected operation, as is apparent from its many ties with other utilities. Here a group of adjacent companies having common ownership operate as a single control area. Intrasystem ties are free flowing. Schedules for advantageous interchange are established and maintained for the 40 major tie points with 19 other utilities, and economic dispatch for the 38 principal generators of the system is automatically computed and maintained, all from one central location.

A new digitally directed analog system[22,23] to fulfill these functions was placed into operation late in 1964 at the company's new power control center in Canton, Ohio. Control commands are routed directly from Canton over microwave to the participating generators of the operating companies.

This installation, with its solid-state analog console, its digital computer, its individual unit approach, its use of antihunting concepts, its display arrangements for unit conditions, its arrangements for computing advantageous interchanges with its many neighbors, its tie-in with a large billing computer, and its extensive use of microwave telemetering, reflects well the present start of the art in interconnected power system controls.

I should like to acknowledge my indebtedness to a number of my associates at the Leeds & Northrup Company and to individuals of the following organizations for information helpful in the preparation of this paper: American Electric Power Service Corp., Bailey Meter Co., Control Data Corp., Ebasco Services, Inc., General Electric Co., Gilbert Associates, Hagan Controls Corp., IBM Corp., Metropolitan Edison Co., North American Power Systems Interconnection Committee, Sargent & Lundy, Southern California Edison Co., Stone & Webster Engineering Corp., Tennessee Valley Authority, and Westinghouse Electric Corp.

Figs. 1, 4, 5, and 12 are derived from reference 1; Figs. 2, 3, and 6 from reference 2; Fig. 11 is reproduced, with permission, from material of the North American Systems Interconnection Committee.

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A review of radar astronomy—Part II

In the conclusion of this article the rotational and surface characteristics of several planets, particularly Venus, are considered. Most of the immediate future research will involve the moon, Mercury, Venus, and Mars

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Rotation of Venus

The determination of the axial rotational rate of Venus has long been an objective of planetary astronomers. It may be surprising to learn that we know the rotational period of all the planets in the solar system, even the most distant planet Pluto, with the exception of the planet that comes nearest to us, Venus! This anomaly fundamentally arose for two reasons: (1) Venus is shrouded with a thick, almost featureless cloud cover that prevents us from seeing its surface; and (2) Venus rotates very slowly. If the surface could be seen, we could track the motion of various markings and thus determine the rotation; or if Venus' rotation were faster, we could observe the relative Doppler shift of the lines in its optical spectrum resulting from the difference in velocity between its approaching and receding limbs. We could then compute the period from this velocity. Unfortunately, Venus appears to rotate so slowly that the errors in the classical velocity measurements have been as great as the velocity actually measured.

The most recent attempt to find the rotation of Venus by spectroscopic means was made by R. L. Richardson at Mount Wilson Observatory in 1956. He obtained a period of 14 days retrograde, but with a very large probable error. Interestingly, his results were consistent with two earlier spectroscopic measurements made in 1903 and 1922, which also gave a slow retrograde rotation, but again with a very large probable error. Moreover, the astronomers making these measurements felt it unlikely that Venus' rotation could be opposite to that of the earth and Mars. As a matter of fact, six of the seven planets whose direction of rotation is known rotate forward—that is, in the same direction as the earth. Only the planet Uranus is retrograde, and it is a rather particular case because its rotational axis is nearly in the plane of its orbit. Although Pluto's direction of rotation is unknown, its period is thought to be about 6.4 days, as determined by periodic variations in its brightness.

The rotation of Venus has significance beyond its own intrinsic value as knowledge. For example, in the study of Venus' atmosphere the rotation period determines its solar heating cycle. The passive microwave temperature measurements indicate that the night side is almost as hot as the day side. If Venus rotates slowly, there must be an efficient heat-transfer mechanism in its atmosphere to maintain the high nighttime temperature. The rotation also plays an important role in mapping the surface of Venus. Radar spectra have indicated the presence of several features, believed to be caused by different physiographic areas on the surface of the planet. Once the rotation period is known, the position of these areas in Venus' latitude and longitude can be found by studying the motion of the features across the Venus disk. A more far-reaching reason for determining the rotation of Venus is the implication in connection with the origin and evolution of the solar system. If Venus does rotate in a retrograde direction, as the radar data now strongly suggest, how could this have come about?

The first unequivocal detection of Venus by radar was made during the conjunction of 1961. Observations were made by at least five groups: the Jet Propulsion Laboratory, Lincoln Laboratory, Radio Corporation of America, Jodrell Bank in England, and the U.S.S.R. Of these, JPL, Lincoln Laboratory, and the U.S.S.R. were able to draw some conclusions regarding the rotation and reflecting characteristics of Venus. All groups made contributions regarding the determination of the astronomical unit. Both Lincoln Laboratory and JPL concluded that Venus must be rotating very slowly and possibly that its rotation was synchronous.[10-12] Nevertheless, even at that time inconsistencies were found that suggested a slow retrograde rotation.[13,14] The results obtained in the U.S.S.R. were in disagreement with the results found in the United States, however, and suggested a much shorter period of about ten days.[15] The U.S. observations also suggested that the reflectivity is about 11 percent and that the surface is relatively smooth, comparable to or perhaps smoother than that of the moon.

In 1962, when Venus was again near the earth, radar observations were made with considerably more refined equipment, and over a wide range of frequencies. A thorough discussion of the U.S. results may be found in the February 1964 issue of the *Astronomical Journal*.

Five separate approaches were used in an effort to determine Venus' rotation:

1. The large 50-Mc/s antenna array of the Jicamarca Radar Observatory in Peru was used to observe the fading characteristics of Venus echoes.[16] From a comparison of the echo power, using pulses of long and short duration, the Jicamarca group determined that less than 1/40 of the disk of Venus contributed almost all of the reflected power. Using this information and the fading fluctuation frequency, they arrived at a rotation period of between 180 and 280 days. They could not ascertain the direction of rotation, however.

2. At JPL, a series of range-gated spectra were obtained extending over a two-month period around conjunction. From these spectra the velocity of a known geometric region on Venus can be found and thus the apparent angular velocity computed. These computations suggest a period of about 250 days retrograde.[17]

3. Another experiment at JPL obtained high-resolution spectra of the reflection from Venus of a CW signal. The frequency resolution of the spectra was 1 c/s, and since the transmitter frequency was 2388 Mc/s (λ = 12.5 cm), the minimum velocity resolution was about 0.063 m/s. This resolution is to be compared with the minimum velocity resolution obtained by Richardson by optical spectroscopy of 33 m/s, which was the overall standard error of his measurements. Measurements of the width of the base of the radar spectra and the way in which they changed versus date lead to a period of about 266 days retrograde.[18]

4. An unexpected discovery concerning the CW spectra furnished the opportunity for the fourth method. A small protrusion or feature was found on the CW spectra that moved slowly from day to day. The persistence of the feature suggests that it was caused by some kind of rough area on Venus' surface and that its motion was due to the planet's rotation. Assuming that this is the case, the motion of the feature suggested a rotation period of about 230 days retrograde.[18]

5. If the way in which the surface of Venus scatters radar signals were known, then one could compute the radar spectra for several different rotation rates and compare them with observations. The computed spectrum that best matches the observations would then yield the rotation. Unfortunately, the backscattering function of Venus is poorly known. Nevertheless, by making certain plausible assumptions about the statistics of Venus' surface another researcher at JPL derived theoretical spectra that were matched to the observed spectra.[19] The results indicated that Venus rotated between 570 days forward and 250 days retrograde.

Scientists in the U.S.S.R. also conducted an extensive series of observations of Venus in 1962.[20] To determine the rotation, they used a method, similar to type 2 above, in which the velocity of a known geometric region on Venus was measured. Their frequency resolution was about 1 c/s. Since their transmitting frequency was 700 Mc/s (λ = 43 cm), their minimum velocity resolution was 0.21 m/s. They concluded that the rotation of Venus was between 200 and 300 days retrograde.

It is apparent that the 1962 observations suggest rather conclusively that Venus rotates retrograde with a period of approximately 250 days. Observations of the JPL group in 1964 strongly support this conclusion.

Surface of Venus

In addition to determining the rotation of Venus, radar techniques allow us to penetrate the planet's thick atmosphere and learn something of its surface characteristics. In fact radar may be the only way to explore the surface of Venus for many years, since we cannot see the surface visually and its temperature is apparently so high that the building of a landing package would present formidable engineering problems.

The radar cross section of Venus ($g\eta$) is about 11 percent of its geometric cross section at 12.5 cm. We cannot say for certain what the reflectivity of the surface material is because we do not exactly know the directivity. Analysis indicates that it is apparently near unity, which implies that the true reflectivity is near 11 percent.[19] By means of Eq. (4)

$$\eta = \left[\frac{1 - \sqrt{\epsilon}}{1 + \sqrt{\epsilon}}\right]^2 \tag{4}$$

we can compute the dielectric constant of the surface material as approximately 4. This result suggests that, on the average, Venus has a dry, sandy, or rocky surface. There can be no large oceans as we know them or the reflectivity would have been near 100 percent when such a surface was under the subradar point.

Measurements[11] made at 38 Mc/s also indicated a reflectivity of about 11 percent most of the time, which strongly suggests that reflections were received from the surface and not from a critically dense ionosphere. Muhleman[21] has shown that the effect of a dense Venusian ionosphere is inconsistent with the radar data. There were some anomalous high reflectivities at 38 Mc/s, which may have been due to the appearance of solar plasma in interplanetary space or to changes on Venus that were not observed at higher frequencies.[22]

At 50 Mc/s ($\lambda = 6$ m) Venus appears to be considerably smoother than the moon.[16] As mentioned earlier, echoes were received from an area less than about 1/40 of the visible disk of Venus, while the Jicamarca group found that for the moon the area is not much less than 1/20 of the visible disk.

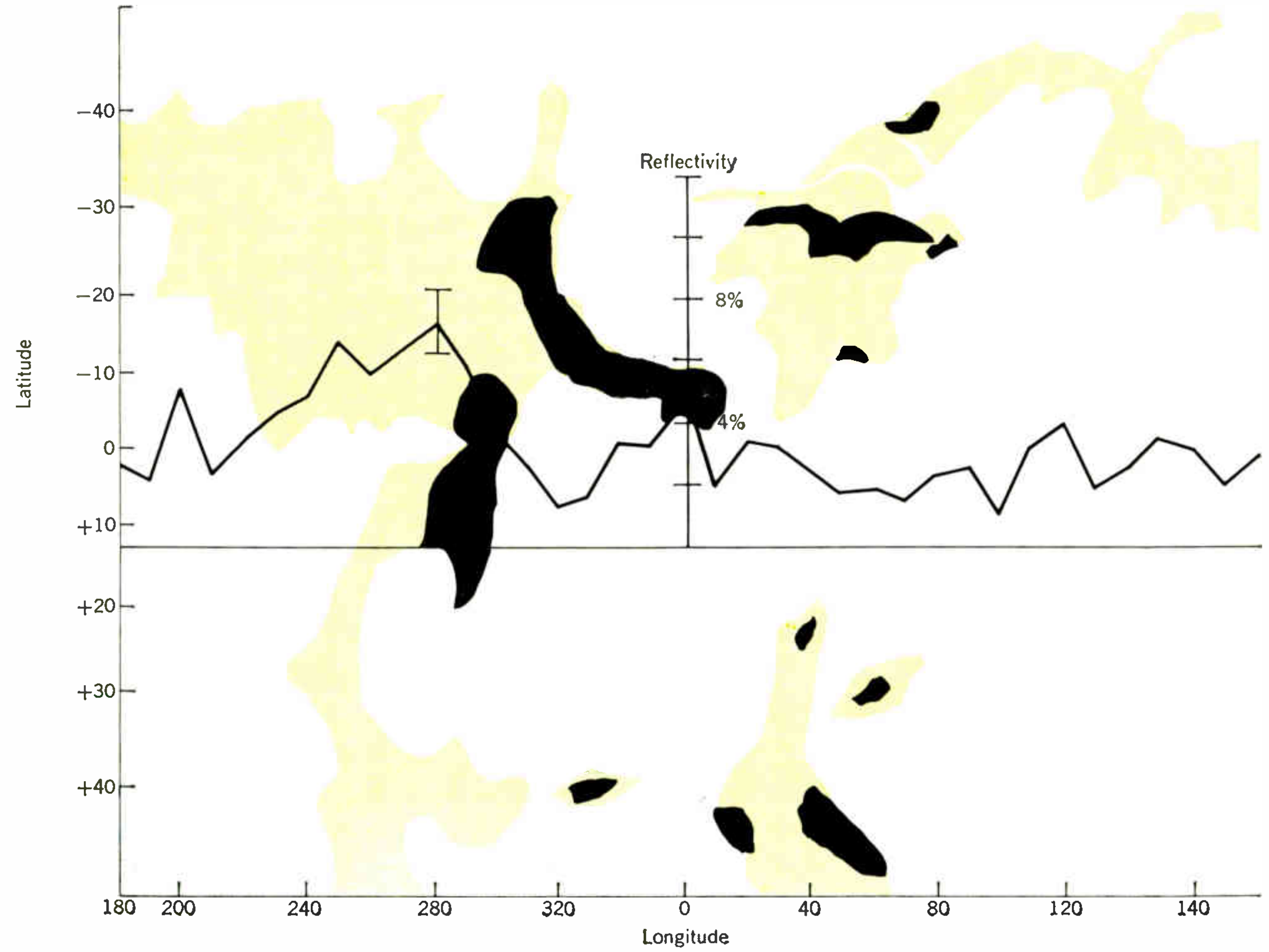
At 12.5 cm the backscattering function of Venus appears to consist of two parts. There is a strong quasi-specular part that drops rapidly with increasing angles of incidence and a diffuse part that drops much more slowly.[18, 19] The nature of the scattering of radar signals from a rough surface is not well understood at present. It appears possible, however, to associate the quasi-specular component of the echo with reflections from regions that appear to be smoother than the moon, but more data are needed before we can say this with certainty.

There are two essentially different approaches to the statistical description of a surface that have been used to interpret the Venus radar data. One is to assume that the surface can be approximated by a series of facets of varying size and inclination.[19] The backscattering of the surface is then determined by the relative number of facets that are oriented perpendicular to the line of sight. The other approach is to assume that the surface fluctuates randomly in elevation as a function of position. The surface is then specified by giving the probability distribution of heights, difference in heights, and the spatial correlation function. This last function is the correlation between the heights of a pair of points on the surface as a function of their separation.[23]

Both approaches were used to estimate the overall mean slope of Venus' surface. Using the former approach (randomly oriented facets) a mean slope of between 2.3° and 7.4° was obtained.[19] The mean slope obtained for the moon by the same procedure was 16°. Using the random surface approach an rms slope between 4° and 7° was obtained.[18] For the moon this approach gives approximately 6.5°.[23]

An exciting result of the 1962 experiment was the detection of an anomalous feature on the spectra that moved slowly with time.[18] Evidence suggests that it was caused by an unusual physiographic area on Venus' surface and that its motion was the result of the planet's rotation. The area's true nature can only be guessed; however, the anomaly can be considered as an increase in the local value of $g\eta$ and could result from a high value of g (roughness) or a high value of η (reflectivity or dielectric constant). Roughness does not necessarily imply the presence of mountains, but merely that the region is rough to a scale of 12.5 cm, the radar wavelength. Observations of Venus, during its 1964

Fig. 14. Radar reflectivity of Mars and its correlation with the visual markings on the planet's surface, at 12.5-cm wavelength.



conjunction, with a radar system ten times more powerful than that used in 1962 have substantiated the existence of features. About a half dozen have now been found. A study of their motion should lead to a precise rotation period of Venus in the same sense that visual features determine the rotation of the other planets, and hopefully to the first radar maps of the planet's surface.

Mars

Mars is a far more difficult radar target than Venus. Part of this difficulty arises from the geometry of the situation, since the cross-sectional area of Mars is smaller by a factor of almost two and the distance of closest approach is greater by a factor of two to three. When these two factors are placed in the radar equation

$$P_{r_{\text{iso}}} = \frac{P_t}{(4\pi)^3} \frac{G^2\lambda^2}{r^4} \pi R^2 \qquad (1)$$

the echo power from Mars relative to Venus is down by a factor of 95. But this is only part of the loss. Compared with Venus, Mars rotates quite rapidly, so the bandwidth of the echo is broadened and the signal-to-noise ratio is degraded accordingly. If Mars and Venus were equally rough, the bandwidth ratio at conjunction would be 230 to 1.

Because of this extremely low signal-to-noise ratio, only total power measurement and spectral analysis have been attempted for Mars. More complicated signal processing, such as frequency–time mapping, will have to await greater radar capability.

Mars was observed at the JPL radar observatory during the opposition of February 1963.[24] The wavelength used was 12.5 cm. Spectrograms show that Mars is somewhat smoother than Venus, and most of the detectable power reflected from Mars returns from a small area of about 250 miles in diameter, centered about the subearth point.

A total of 65 hours of spectral data was taken, representing more than 350 runs. Each run consisted of an 11-minute transmission (the round-trip time of flight to Mars) followed by an 11-minute reception. As Mars rotated, each successive run illuminated an area about 200 miles farther westward on the Martian 13° north parallel. Throughout the nights of the experiment, each 250-mile disk was illuminated about seven times. The average signal power for each of these areas defines a radar "brightness" map for the 13° parallel, which is presented in Fig. 14. The error flag on the reflectance curve was determined experimentally by measuring the standard deviation of the observations with only noise applied to the receiver. A map of some of the visible features on the Martian surface serves as a background to Fig. 14. It is interesting to note that the regions near Syrtis Major appear bright to radar but dark to visual observations.

Since echo power was measured through a 400-c/s predetection filter, the darkness of an area may be due either to poor reflectivity or to roughness, which spreads the echo power beyond the detector pass band.

Jupiter

Jupiter is even more difficult than Mars to study by radar. When the cross-sectional area and the distance of closest approach of Jupiter are substituted into the radar equation, the calculated echo power is less than that for Mars by a factor of three. However, the greatest part of the difficulty arises from the rapid rotation of Jupiter. The bandwidth for Jupiter, other things being equal, is 50 times greater than for Mars and 11 500 times greater than for Venus.

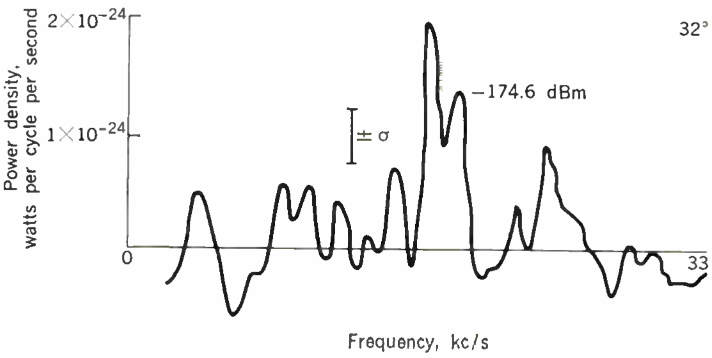
As was the case for Mars, only total power measurement and spectral analysis have been attempted for the radar studies of Jupiter.[25] These observations were carried out at JPL during the opposition of the fall of 1963. Over 100 hours of data were taken, divided into about 100 runs. A run consisted of transmitting a wave of high spectral purity for the round-trip time of flight (1 hour, 6 minutes) and then switching to the receive mode for an equal period, followed by processing the echo as to its spectral composition. Most of the individual runs showed no evidence of an echo. Occasionally, however, a run would indicate the presence of a statistically significant return.

It was noticed that the time intervals between "significant" runs were most often multiples of the rotation period of Jupiter. (The rotation period of System I is 9.841 hours; there was found to be negligible correlation with Systems II and III.) This suggested that a single localized area on Jupiter was both a good and a smooth reflector. To investigate this possibility, Jupiter was divided into eight "time zones" and all of the runs that illuminated a given time zone were averaged together. Eight zones were chosen because Jupiter rotates about 1/8 revolution during a run. The zone centered about the Jovian longitude of 32° gave a statistically significant response, the echo peak being almost eight times the standard deviation. The other zones show little, if any, echo, and the average of all runs shows negligible return.

The echo bandwidth, from the 32° longitude spectrogram (displayed in Fig. 15), is approximately 3.3 kc/s. This corresponds to reflections from a disk on Jupiter, centered about the subearth point, of 730 miles diameter. The actual reflecting area may be much larger than this, but because of the smoothness, echoes originating outside of this disk would not be directed back toward the earth.

The spectrogram presents the echo approximately 2 kc/s higher in frequency than predicted from the earth and Jupiter ephemerides. This shift is far too large to be accounted for by an error in the ephemeris velocity of

Fig. 15. Radar spectrum of Jupiter at 12.5-cm wavelength. Echo bandwidth is about 3.3 kc/s.



Jupiter. (The echo from Venus was always within a few cycles per second of the predicted frequency.) The discrepancy may have been caused by a slight slope of the reflecting surface, since a slope of only 1.0 percent would account for the frequency shift observed.

Mercury

Mercury is a target similar to Mars, geometrically. However, its long rotation period of 88 days produces a maximum echo bandwidth of only 75 c/s (at 2388 Mc/s), which is close to the Venus bandwidth. Hence, on an overall basis, Mercury is a much more detectable target than Mars.

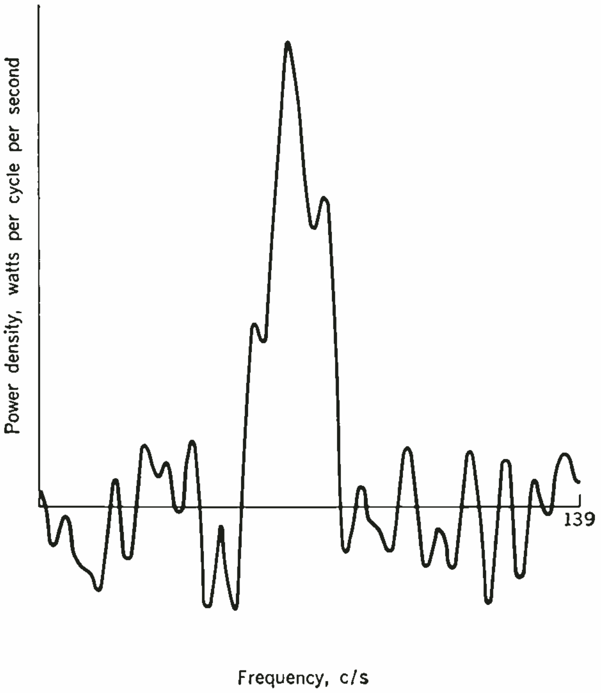
A series of radar observations of Mercury was made at JPL's Goldstone Observatory during the inferior conjunction of the spring of 1963.[26] Measurements were made of the total power received, the spectral composition of the total power, and the spectra reflected from slices of Mercury which were isolated by range gates.

The total power received was, typically, 5×10^{-22} watt, which corresponds to a radar cross section of 5 percent for Mercury, as compared to 10 percent for Venus.

The spectrograms are quite similar to those obtained from Venus. They are slightly wider (compared with the limb-to-limb width), however, which suggests that Mercury has somewhat greater surface roughness than Venus.

Range depths of 178 km were used for the range-gate experiments. Four hours of received signal were processed for the sample spectrogram of the front cap of Mercury shown in Fig. 16. Data of this kind were used to measure the distance to Mercury. The distance measurements have an internal consistency good to within 20 miles and provide a striking confirmation of the astronomical unit which was based on radar observations of Venus during the conjunctions of 1961 and 1962.

Fig. 16. Sample radar spectrogram of Mercury using the range-gated signal from the first zone, at a wavelength of 12.5 cm.



The moon

The moon has been more intensively investigated by radar techniques than any other extraterrestrial body. Clearly, this circumstance arises because the moon is a relatively easy target to detect by radar; for example, the reflected lunar signal is about seven orders of magnitude stronger than that obtained from Venus using the same instrumentation. Meaningful scientific radar experiments concerning the moon were first carried out by Browne *et al.* in 1956,[1] and there has been a rapid increase since that date paralleling the development of high-gain antenna systems, improved detection techniques, etc. Until about 1962 observations were made using antenna beams that were large compared with the solid angle of the lunar disk, and resolution on the lunar surface was achieved using the range-ring Doppler-strip techniques described previously. Only recently have narrow-beam systems been utilized to illuminate selected regions of the lunar surface.[27,28] However, the full benefits of these techniques have not as yet been utilized due to the difficulties of accounting for the (often poorly known) details of the antenna patterns; consequently, the most useful scientific data presently available are in the form of Doppler-range maps centered on the subearth point.

The scientific interpretation of the lunar radar observations divides into two somewhat independent parts: the determination of total power reflectivity and the study of the lunar surface scattering law as a function of radar wavelength. The interpretation of the power reflectivity is somewhat dependent on the scattering law of the lunar surface by virtue of the surface backscatter gain or directivity as shown in Eq. (2). It is necessary, therefore, to obtain a measure of the backscatter law before one can interpret the measured total power in terms of the surface reflectivity and, in turn, the electrical parameters of the lunar surface materials.

The lunar backscatter function can be directly measured by illuminating the moon with narrow pulses as shown in Eqs. (5) through (13); see Part I. Accurate measurements of this type have been obtained from the moon at 68 cm by Pettengill,[3] at 3.6 cm by Evans,[27] and at 10 cm by Hughes[29]; less accurate measurements at 8.7 mm have been made by Lynn *et al.*[30] Only in the 68-cm data is a measurement given all the way to the lunar limbs—that is, to grazing angles. The pulse responses at these various wavelengths all exhibit the same mathematical form, consisting of a rapid decrease in power with increasing delay for small delays (small values of τ) followed by a flattening at longer delays—i.e., toward the lunar limb. However, the height of the initial peak is a strong function of wavelength and the response is more peaked (or "specular") at the longer wavelengths. This can be qualitatively understood from the following argument. The shape of the pulse response is a function of the lunar surface roughness. The effect of a given wavelength is to average the roughness over distances comparable to the wavelength. Hence the moon appears smoother to longer wavelengths and consequently behaves more as a mirror surface, thus giving rise to a more spectral return at the longer wavelengths.

Efforts to obtain a quantitative understanding of the scattering process have been extensive and date back to Rayleigh's theoretical investigations of the reflection of light from corrugated and random surfaces. The problem has been attacked with both wave-optics and ray-optics techniques. The wave treatments have been relatively unsuccessful in explaining the lunar radar response, apparently due to the mathematical difficulties associated with the statistics of a real random surface. (See Ref. 31 for a recent application of these techniques.) The ray-optics approach, although less realistic physically, has been relatively more successful. Muhleman[19] has obtained a mathematical formulation that accurately predicts the radar response of the moon over the entire disk. This treatment assumes that the surface of the moon may be considered as made up of mirrorlike facets, large compared with the radar wavelength, with random tilts to the mean lunar surface. He was able to show that in the limit of ray optics the backscatter function is identical to the probability distribution of slopes of the facets relative to the mean surface. The backscatter function (or its equivalent, the pulse response) involves a single parameter α, called the effective mean slope, which increases for decreasing wavelengths. The α parameter is actually the mean absolute slope averaged over distances of the order of the given wavelength along a one-dimensional contour of the lunar surface. Its relationship to true mean slope of the two-dimensional lunar surface is not, as yet, completely clear.

Rhea *et al.*[32] have extended this approach to obtain an estimate of the lunar directivity by utilizing the measured pulse response of the moon at 68 cm as the density function of the slopes in an integration equivalent to our Eq. (14):

$$g = 4\pi \frac{c}{R} \int_0^{2R/c} S[\phi(\tau)]d\tau \qquad (14)$$

They obtained $g = 1.15$. Muhleman, in an unpublished work, reported the same value from his backscatter function with $\alpha = 0.145$ (mean one-dimensional tilt of 8.3°) obtained from a fit of the 68-cm data. Thus, it appears that the lunar directivity is well established, at least for 68-cm radar.

If one accepts the value of g at 68 cm he may compute the actual surface reflectivity from the total power measurements.[2] The mean value obtained is $g\eta = 0.074$, which gives $\eta = 0.064$ with $g \approx 1.15$. Then, from Eq. (4), for the dielectric constant we obtain $\epsilon = 2.8$.

The accuracy of this result is very difficult to estimate; however, it appears conservative to state that the dielectric constant lies in the interval $2.5 \leq \epsilon \leq 3.0$. A number of investigators have attempted an interpretation of this result in terms of the material constituents of the lunar surface. There are, however, a small number of terrestrial materials that are suspected of existing in quantity on the lunar surface and exhibit dielectric constants in this range in their natural dense states—for example, pumice. But if the lunar surface materials exist in underdense states (granulations, dust, etc.), a host of materials are possible. The problem cannot be resolved until a good measure of density of the materials in the upper few meters of the surface is available.

Pettengill and Henry[33] have discovered that certain small regions of the lunar surface yield high values of $g\eta$. They obtained these measurements by using the mapping techniques described earlier. In each case they found the region of high $g\eta$ associated with so-called "rayed craters," such as Tycho, which are believed to be relatively young features of the lunar surface. It is not clear, however, whether these anomalous returns are due to values of directivity significantly greater than unity or values of η significantly greater than 7.4 percent. An increase in directivity could arise due to the focusing nature of the craters or to increased roughness in the crater. Higher values of reflectivity would arise if the young craters were relatively free of underdense material (dust), in which case the reflections would occur from dense material exhibiting a higher dielectric constant.

Apparently, the interpretation of the radar reflectivity measurements can best be carried out in conjunction with the lunar microwave black body emission measurements. A discussion of these data is beyond the scope of this article. An initial attempt in this direction can be found in Ref. 34.

Astronomical constants

The primary reason for undertaking highly expensive planetary radar experiments was to establish a single astronomical constant—the astronomical unit. In this regard the results have been more than impressive. Indeed, the measurement of range and Doppler velocity radarmetrically has revitalized and, perhaps, revolutionized the study of planetary motions in their orbits about the sun. This comes about for two different reasons.

First of all, the material on which the theory of planetary motion and orbits is based consists of measurements of the angular position of a planet among the "almost" fixed stars or of the time of events, such as the passage of a planet across the edge of the solar disk. The precision of these measurements is difficult to evaluate. The difficulty arises from the finite angular size of a planet relative to the earth; for example, Venus subtends an angle of about 50″ at the point of closest approach to the earth (inferior conjunction). It is the task of the observer to find the center of this disk while the planet moves through its lighting phase from full phase to a vanishing crescent. This phenomenon not only leads to noiselike errors in measurements but invariably results in biases that are highly correlated with the planet in question and the earth. The resulting measurements are accurate to about 1.0″ and are always systematically biased.

In turn, the radar measurements are free of these effects—the biases in particular. The radar measurements of Venus obtained in 1964 are accurate to about 25 km in range and about 0.1 m/s in range rate. An intuitive estimate of the equivalent angular accuracy of such measurements can be obtained from the angle subtended by 25 km at the earth–Venus distance at inferior conjunction of about 50 million km, which amounts to 0.1″ and which is, furthermore, uncorrelated with the orbital positions of the earth and Venus. Clearly, this is not the complete picture. Because of the nearly coplanar nature of the planetary orbits with respect to the orbit of the earth, certain orbital parameters, such as orbital inclination, are poorly determined by radar (which does yield strong solutions for eccentricities, semimajor axes, and perihelion positions). Consequently, the total orbital problem is best solved by combining radar and angular observations.

The second unique advantage of the radar observations is perhaps more subtle. Angular measurements do not involve units. Consequently, planetary theories based on such measurements are independent of a scale of length. Early workers merely defined the mean distance of the earth from the sun as unity, and all distances are expressed in terms of this "astronomical unit," or "AU." The distance in kilometers or light-seconds corresponding to this unit must be supplied to give the position of a planet relative to the earth in a way that is meaningful for, say, space navigation. Clearly, this can be accomplished by measuring any quantity connecting the orbit of the earth and a planet involving the kilometer or light-second—for example, distance, velocity, or acceleration. In practice many such measurements are required but not because of the uncertainty of a single measurement. The difficulty involves our knowledge of the orbits of the earth and planets. This can be made clear by considering the nature of planetary theory.

The theory of motion of a given planet such as the earth is the solution of the Newtonian equations of motion utilizing exhaustive perturbation techniques. Angular observations of a given planet have been used in the past to obtain the specific parameters in the theory for the planet in question, which results in an angular ephemeris for the planet with distances expressed in astronomical units. Observables such as range may be computed from this ephemeris *after* one has inserted a "guessed" value of the AU. Such an observable is then compared with a corresponding observation. The difference between the observable and the observation is due to the error in the initial value of the AU and the errors in all of the empirical parameters contained in the angular ephemeris. Consequently, it is necessary to combine radar measurements over a great portion of the orbits of the earth and Venus, for example, and to solve simultaneously for corrections to all of the empirical parameters from the resulting differences between observations and observables. Measurements in the near vicinity of inferior conjunction are insufficient.

We have obtained extensive radar observations of Venus for several months around the 1961, 1962, and 1964 inferior conjunctions of Venus, resulting in about 50 000 observations of range and Doppler velocity. Muhleman[35] obtained a preliminary solution for the AU and orbital parameters of the earth and Venus from these data. A complete discussion of these results is beyond the scope of this article, but the resulting values of the AU are shown in Table I. The table also includes previous values of the AU obtained by radar investigators, as well as the best value obtained by a classical angular-measurement technique, which is obviously grossly in error.

Significant parameters of the earth–moon system have been obtained by radar methods.[36] An extensive radar observational program of the moon is currently in progress by the JPL group for improving the estimates of these parameters, which include the semimajor axis of the lunar orbit, the ratio of the mass of the earth to that of the moon, and the radius of the moon.

Future experiments

We showed in Eq. (1) that, for a given radar system, the echo signal strength depends directly on the cross-sectional area of the target and inversely on the fourth power of the distance from the radar. The noise power depends on the square root of the system bandwidth, which in turn is directly proportional to $\sqrt{R\omega_a}$. Thus, we can define the detectability of a solar system target relative to, say, Venus by the expression

$$D = \left(\frac{r_{♀}}{r}\right)^4 \left(\frac{r}{r_{♀}}\right)^{3/2} \left(\frac{P}{P_{♀}}\right)^{1/2} \qquad (36)$$

where $(P/P_{♀})$ is the ratio of the bodies' rotational period to that of Venus (equivalently, $\omega_{♀}/\omega$). The detectability of some of the solar system members (relative to Venus) is shown in Table II. The present capability of the JPL radar system, which is about +35 dB relative to Venus, may be considerably extended by going to extremely long integration times (weeks) when the motion of the body relative to the earth allows such an operation. Consequently, only Mercury and Mars are readily available for meaningful astronomical experiments (beyond Venus and the moon). However, it is quite likely that Jupiter and/or one of its satellites will be unequivocally detected. Ultimately, radar experiments with Jupiter should yield significant information concerning the existence and characteristics of its solid body, atmosphere absorption in the radio domain, and the character of its magnetic field. The possibility of detection of the III and IV satellites of Jupiter suggests a powerful technique for probing the Jovian atmosphere. If a measurable signal can be obtained from one of these satellites it will be observable throughout its orbit around Jupiter. Consequently, the radar signal will twice traverse the Jovian

I. Astronomical unit determinations from radar observations of Venus*

Source	AU, kilometers	Parallax ($\pi_{\odot}$), seconds of arc
Good radar methods†		
D. Muhleman et al.	149 598 640 ± 250	8.794 137 9 ± 0.000 015
G. Pettengill et al.	149 597 850 ± 400	8.794 184 9 ± 0.000 026
D. Muhleman (revision of Pettengill's value)	149 598 100 ± 400	8.794 170 5 ± 0.000 026
Marginal radar methods		
Thomson et al.	149 601 000 ± 5000	8.7940 ± 0.003
Maron et al.	149 596 000	8.7943
Kotelnikov	149 599 500 ± 800	8.7941 ± 0.000 05

* From doctoral dissertation, D. Muhleman, 1963.

† Good radar methods are those that observed Venus over a sufficiently long arc to remove the major part of the errors from the ephemerides.

II. Detectability relative to Venus* for some solar-system bodies, all referred to closest approach

Body	Detectability, dB
Mercury	−21
Mars	−27
Phobos (Mars satellite)†	−58
Jupiter	−43
J-III Ganymede (Jupiter satellite)	−60
J-IV Callisto (Jupiter satellite)	−59
Saturn	−57
10-mile comet nucleus at 0.5 AU‡	−57

* Present capability is Venus plus about 35 dB.
† Assuming a 2-c/s postdetection bandwidth at 2388 Mc/s.
‡ Assuming a 3-c/s postdetection bandwidth at 2388 Mc/s.
Note: Venus may be regarded as a 10-percent reflector.

atmosphere as the satellite passes behind Jupiter at each revolution. Accurate total power and Doppler frequency measurements would yield considerable information on the density profile of the Jovian atmosphere.

We have included a hypothetical comet in Table II to suggest another area of future radar astronomy research. Radar observations of comets would be of considerable interest to workers in the astrophysics of comets, particularly if the diameter of the nucleus could be obtained. Equally important would be precise tracking data for the computation of cometary orbits. Unfortunately, the near passage of such comets is relatively rare. The detectability shown in Table II would, of course, also apply to an asteroid.

The bulk of the research in the immediate future will involve the moon, Venus, Mercury, and Mars. The careful cataloguing of range and Doppler observations of these bodies will supply remarkably accurate orbital information for these bodies and, most important of all, for the earth. This information will supply vital empirical checks on the planetary theory of motion, the constants of the solar system, and Einstein's Theory of Gravitation. The current data are greatly motivating theoretical research in these areas. An important side result of the observations will be measurements of interplanetary electron densities, solar winds, magnetic fields, and solar coronal effects.

The excellent detectability of the moon (70 dB greater than Venus) is yielding detailed information on the roughness and dielectric properties of the lunar surface in resolved regions as small as 40-km squares through Doppler-range mapping. Individual craters are being examined by means of these techniques.

Similar experiments involving somewhat grosser surface area resolution are being carried out for Venus. The radar technique, in conjunction with passive radio emission measurements, is the only method available for obtaining this information because of the Venusian cloud cover. Venus remains the primary radar target.

Investigations of Mercury and Mars will proceed at a somewhat slower pace. Detailed radar mapping of the Martian surface should yield vital information concerning topography and possibly the existence and properties of vegetation on Mars. The latter apparently can be obtained through measurements of the variation of surface reflectivity across the Martian disk and variations with Martian seasons. Radar polarization measurements could yield information concerning a Martian ionosphere and magnetic field.

We have not touched upon the subject of solar radar astronomy, which is still in its infancy. This field, too, promises a nearly endless series of research problems.

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Memories in present and future generations of computers

Automatic fabrication can now produce core memories of several-million-bit capacity. Coming up are integrated batch-fabricated developments, such as the monolithic ferrite and superconductive memories. And possibilities exist of an all-semiconductor thin-film transistor memory

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The importance of the internal memory in computers cannot be overemphasized. The very fact that all information as to what to do, how to do it, and on what data to do it is in memory makes the computer a general processor that can be adapted to any specific task. The universality of the computer has extended its usefulness to practically all activities of men.

Already explosive, the impact of electronic processing of information has been heightened by the feasibility of distributing computer power through communication networks to a large number of users. Essential to all these applications is the ability to store electric signals in order to permit their manipulation. Obviously, how many signals can be stored, how conveniently and at what speed they can be accessed, and at what price are crucial questions underlying the whole field of data processing.

Ideally, most desirable would be the possibility of storing a vast amount of information in nonvolatile form so that it could be kept on record, for years if necessary, and yet be accessible electronically at high speed and with great versatility. Revolutionary indeed would be an economical shoebox-sized device containing 10^{12} bits accessible at random or through selected content in nanoseconds!

Unfortunately, we are far from this ideal. Instead we must resort to a hierarchy of different types of information stores: large-capacity record-keeping magnetic tapes, random-access electromechanical memories such as the magnetic card memory (RCA 3488), rotating disks and drums, the main internal memory of the computer itself, which is typically a core memory, an ultrafast scratch-pad memory, and banks of registers within the computer. A general trade-off of storage capacity and speed characterizes this hierarchy.[1] The merit of this multilevel storage scheme is that, with judicial store partitioning, computer organization, and software, the benefits of enormous storage capacity at extremely fast speed have in fact been realized. The demerit, apart from the complexity, is the impossibility of universally optimizing the mix of stores, and above all the overhead in extra processing that must be paid due to the necessity of swapping information from one form of store to another. This overhead severely limits the throughput and is an essential limitation in multiple-accessed time-shared computer systems.

The electronic random-access memories occupy an important—perhaps the most important—place in the hierarchy of memories. This article is limited to that type. First, a few examples of the state of the art of internal and scratch-pad memories are described. This is followed by a discussion of two developments in integrated techniques that may prove to be an important step toward the ideal store: the monolithic ferrite memory and the superconductive memory. In addition, all-semiconductor, content-addressable and fixed, read-only memories are briefly considered.

Core memories

The ferrite core memory has become standard in commercial computers. Storage capacities from hundreds of thousands to several million bits and cycle times of a fraction of one microsecond to several microseconds are common. Since its inception about 15 years ago,[2,3] the core memory's capacity and speed have been constantly increasing and the cost constantly decreasing.

A nearly ideal solution to the problem explains this success. The core is a one-bit register that requires no power for storing and is capable of being rapidly switched. At the same time the core is its own addressing gate with three inputs—two additive x and y ANDs, and one inhibiting z NAND. The necessary conditions for the analog threshold gating and low read noise and power waste in nonswitched cores are rectangularity of the hysteresis loop and similarity of properties from core to core. The loop rectangularity is inherent in the nature of the selected material and processing. Uniformity results in part from the simple expedient of thorough mixing of the complex constituents used. More important, uniformity results from sorting after a test of each core. The degree of uniformity obtained surpasses that of most manufactured electric components. Automatic molding and testing of cores at rates of about ten per second together with ingenious aids to manual wiring or semiautomatic wiring are mostly responsible for the relative economy of these large aggregates of elements that are made one at a time.

Illustrative of the advances that have been realized are the standard current-coincident core memories. These are found, for example, in the RCA Spectra 70 family of computers, in which modular compatible design is utilized. Table I summarizes the main characteristics.

These memories operate in the classical current-coin-

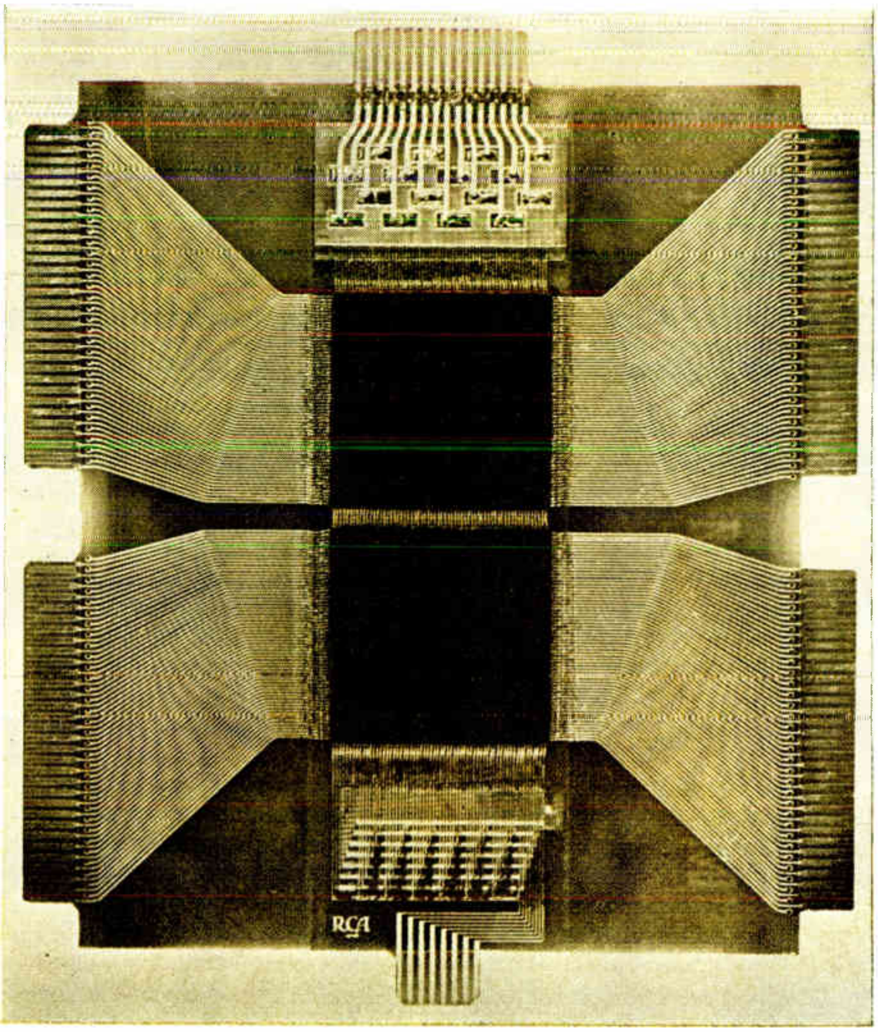


Fig. 1. Monolithic ferrite memory module (RCA MF 2100) comprising two 64 × 64 wafers and integrated diode selection.

cident mode in arrays with four wires: x, y, inhibit z, and a sense. Half-select currents in the model 70/45, which utilizes cores of 30 mils OD and 18 mils ID, are 350 mA and have a rise time of 100 ns. In model 70/55, the cores are of 20 mils OD and 12 mils ID, and the half-select currents are 450 mA with a rise time of 50 ns.

The high performance of the Spectra 70 current-coincident memories (cycle time as short as 840 ns and a capacity of more than 4 million bits) is the result of great advances since the first core memories were made. Cycle times of 8 μs and capacities of 40 000 bits were typical a decade ago. This progress was achieved through the use of smaller cores (from 80–30 to 20–12), better materials, more uniform processing, the use of ever-improved transistors, and a great deal of improvement in the memory system.

Very fast core memories can be made that use a word-organized system of selection. All cores belonging to a given bit are driven by a single word-selection line—in contrast to two x and y lines used in current-coincident selection. Digit lines link all cores of a given bit belonging to all words and are generally used both for writing and sensing. For reading, the word current alone switches all cores of a given word and therefore can be of arbitrarily high amplitude. This results in very fast core switching. For writing, the word current is reversed and currents are applied in coincidence to the digit windings. Various systems of so-called "digiting" can be employed. A system leading to the fastest cycle time is utilized in the Spectra 70 scratch-pad memory. It uses two cores per bit and energizes one or the other of pairs of digit windings. One of the cores will experience both the word-write current (of lower amplitude than the word-read current) and the digit current, while the other will experience the word current only. Therefore, the two cores are brought from the saturated state to which they were delivered during the read cycle to unequal, partially switched states. On subsequent read, the difference in the change of flux of the two cores, as they are brought to saturation, produces the output signal. Clearly, the digit current cannot be arbitrarily high since it could disturb cores on nonselected word lines. However, the switching of the core is very fast despite this limitation.

The Spectra 70 scratch-pad fast memories use stacks of 128 words of 34 bits or 68 cores each. The cores are 30 mils OD and 10 mils ID. The small inner diameter permits fast switching with modest currents: I_R = 400 mA, I_W = 220 mA, I_D = 70 mA. The cycle time is 300 ns, and the access time for reading is only 120 ns.

The Spectra 70 main current-coincident and word-organized scratch-pad memories illustrate the most advanced types of what may be termed classical core memo-

I. Current-coincident core main memories in RCA Spectra 70 computers

Processor	One-Bank Storage Capacity, eight-bit bytes	Cycle Time, seconds	Experimental Range Banks	Maximum Storage Capacity, kilobits
70/15	4 096	2.00	1, 2	74
70/25	16 384	1.50	1, 2, 4	590
70/45	69 632	1.44	¼, ½, 1, 2, 4	2396
70/55	135 168	0.84	½, 1, 2, 4	4359

ries. Their high performance represents the culmination of a long series of gradual improvements. Will progress continue without change in system or basic technology merely through further refinements? It probably will to some degree; however, major improvements are more likely to result from a major change. An interesting example of a system that may offer significant cost advantage is that of a core memory organized in an intermediate way between current coincidence and word select.

The cost of the standard core memory is divided between that of the array and that of the associated electronic addressing and sensing circuits. The ratio of the cost of the stack to the entire system varies, in the present state of the art, from about one tenth for a total capacity of only a thousand bits to about half for a capacity of a million bits to about eight tenths for a capacity of ten million bits. Clearly, to make very large capacities economical the price of the magnetic structure must be greatly reduced. Systems, colloquially referred to as 2½D, have been described[4] which achieve this reduction in cost by using large arrays of conventional cores with only two x and y wires instead of the four normally used in current-coincident memories. In this system the y lines are grouped into m groups of q lines each. A given y line is selected in each of the m groups and is energized with an enabling half-selected current. The y lines are used also for sensing so that sufficient time is allowed for transients, caused by these currents, to decay. This waiting period constitutes a sacrifice of speed for the sake of economy. Next, a selected x line is energized, and produces sense voltages in the m-enabled y lines. In the following cycle these outputs, or alternatively new inputs, are used in a conventional way to rewrite or write in the memory by reversing the direction of the x and y drives applied simultaneously. The system requires the switching of the m amplifiers to the proper q lines in each group. Despite this additional circuit cost, there appears to be an overall saving in cost for the entire system.

Integrated magnetic memories

Cores that are singly made, tested, and wired by automatic techniques, combined with individually wired associated transistor circuits, are at the apex of present-day nonintegrated electronics. However, an integrated method for making the highly regular memory array by a single process seems a natural way to avoid a multitude of steps and at the same time to make elements that are smaller, and thereby faster and less power consuming, than is practicable in the more conventional method where elements are handled as separate objects. For more than a decade, various integrated methods, including ferrite technologies and metallic thin magnetic films, have been investigated. While no integrated memory has succeeded so far in breaking into the dominance of the nonintegrated core memory, integration still represents the best hope for order-of-magnitude improvements.

The difficulty is that so far no element made by integrated methods has had an overall performance equal to that of the singly made core. Most integrated elements—film patches on plates or wires, regions surrounding holes or wires in ferrites—do not permit current-coincident operation, as there is seemingly unavoidable erosion of sharpness and uniformity of switching properties of the element. Therefore, integrated memories must be word organized in order to demand from the storing element only a modest participation in the selection function: that of analog switching by word and digit coincidence during the writing cycle only. Word organization entails, of course, the use of a larger external switch to select one line among 2^n than the ensemble of two switches, each selecting one line among $2^{n/2}$, that is required in current-coincident operation.

The word-addressing switch can be magnetic, such as an array of dc-biased cores. However, the lack of perfect saturation, the relative power inefficiency, and the difficulty of integration make magnetic switching unsuitable for the very large size at which integration becomes significant. Semiconductor gates are far better switches than magnetic elements, and arrays of diodes, the simplest semiconductor, are commonly used for addressing word-organized memories. The cost of a singly made diode is low enough so that submicrosecond word-organized memories of about 16 000 words are approximately equal in cost to equivalent current-coincident memories. However, for larger capacities the cost of diodes dominates. The only hope is in integrating the switch. Clearly then, a magnetic integrated structure, itself very economical, that is driven by integrated diodes may be the first really economical integrated memory. The monolithic ferrite memory is precisely so designed.

Monolithic ferrite memory

Ferrite slurry is spread by means of a blade into sheets. During this operation, conducting parallel lines of refractory metal are made within the sheets. Two such sheets, with their conductors at right angles, face each other and are separated by a third ferrite spacer sheet, with no embedded conductors, to form a sandwich. The laminated structure is then hot-pressed and, finally, sintered to produce a monolithic structure containing conductive lines integral within its volume. These lines define the storing elements at their crossovers and at the same time constitute the necessary windings. In the recently announced commercial monolithic ferrite memory model (RCA MF2100), the distance between the lines is 15 mils and the equivalent diameter of the "virtual cores" is only 5 mils. A pulse applied to a digit conductor, in time coincidence with a write pulse, switches a component of flux common to both word and digit conductors at the corresponding crossover point. The application of a word pulse, of opposite polarity to the write pulse, switches the mutual flux and induces a sense voltage in the digit windings.

The diodes have been integrated by a glass encapsulation technique, which isolates the individual silicon p-n junctions. The diodes are spaced at the same distance as the lines in the monolithic ferrite and are interconnected on a printed board (Fig. 1).

The new model has the following characteristics: word-drive currents, read 400 mA, write 100 to 150 mA; digit currents ±30 mA, sense outputs 30 to 45 mV; element switching time 35 ns, typical cycle time 200 to 800 ns. The 64-word × 64-bit module comprises two monolithic ferrite wafers that are approximately one inch square and five mils thick. The wafers are 64 × 64 and the system operates with "two interactions per bit." Memories of large capacities are made by connecting a number of modules.

In its present form the monolithic ferrite is already showing great promise for high-speed, compact, and relatively large capacity memories. Good uniformity in many 64 × 64 wafers was obtained with reasonably high yield. Tests with memories containing 16 of the wafers (that is, 64 × 64 × 16 = 65 536 intersections), as well as tests with a few wafers used as very fast scratch pad, are proceeding successfully.

Furthermore, in the laboratory many experimental laminated monolithic 256 × 64 wafers have been made with slightly finer structures (lines 10 mils apart). The X-ray photograph of Fig. 2 shows the conductors within the ferrite. It may also be possible to replace the two diodes required at each word line for the read and write currents of opposite polarity by a single storage diode. Finally, integrated sense amplifiers may be used, which would lead to a fully integrated magnetic-semiconductor monolithic memory system.

Transistor rather than diode addressing is preferable in many respects, particularly in that it results in less stack noise. However, transistors integrated on the scale required for word addressing are still beyond the present art, but may be available in the not too distant future. Great strides have been made in the past year in the development of the field-effect transistor, particularly the metal oxide semiconductor (MOS) type, and these simpler devices may permit the integration of the entire address switch, including complete decoders.

Progress with the monolithic ferrite memory is thus seen to be dependent on the progress in intergrated circuits, which is extremely rapid at the present time. Clearly, integrated circuits will improve other forms of integrated magnetic memories, such as thin-film memories, and even the standard core memory itself. Very likely, partially integrated memories of various forms will pave an evolutionary road. The integrated diode–monolithic ferrite memory is likely to be a first significant milestone on this road.

All-semiconductor memories

The broader question arises as to whether semiconductor integration techniques can advance to the point where magnetics will be dispensed with altogether. Experimental integrated MOS memories have already been reported.[6] The most interesting approach consists in using for storage cells complementary symmetry flip-flops[7] made by loading an n-type transistor by a p-type and vice versa. These storing cells consume negligible power for storage and can easily be gated by other MOS transistors. Integrated MOS memories are likely to be significant for high-speed small-capacity types (e.g., 256 words, 50-ns cycle time), as their magnetic counterparts consist almost entirely of semiconductors.

For larger capacities, the required scale of integration is unlikely to be achieved by means of one-inch silicon chips on which MOS transistors are made. More likely to succeed are thin-film transistors (TFTs),[7,8] which are field-effect transistors[9] similar to the MOS and usable in the same circuit configurations. The TFTs are fabricated by evaporation of the metal electrodes and the semiconductor materials, and can be made on large areas. The memory would consist of an array of complementary symmetry flip-flop addressing and sensing circuits, all composed of TFTs. The evaporating process for forming the TFTs would also form all connections. However, the thin-film transistor is barely emerging from the laboratory and it may require several years before it becomes a serious contender for use in integrated all-transistor random-access memories of large capacities. A first memory application of TFTs is more likely to be for content-addressable memories, as this technique is particularly convenient for providing the mixture of logic and storage necessary for that type of memory organization.

Content-addressable or associative memories

A few comments on CAM-type memories may be in order here. The main feature is that access is through the stored content itself rather than through an address that codes the physical location, as is the case in random-access memories. The essence of content addressability is to compare simultaneously a given set of querying bits of a word with all the stored words in the memory, and detect perfect match where it occurs. The matching signal or signals provide a means to retrieve the remainder of the bits of the word associated with the querying bits at the matching locations. Nondestructive readout is essential since the whole memory is being interrogated. Indeed, content-addressable memories have been built with transfluxors, biaxes, and bicores as the main components. The prototypes have up to 4000 words of 20 to 50 bits and operate with cycle times of a few microseconds. Because CAMs require the intimate mixing of storage with logic, proportionally many more semiconductor devices are necessary than in random-access memories, a fact that raises their cost by one to two orders of magnitude. Clearly, the reasons for integration and miniaturization that were indicated for random-access memories apply even more strongly for content-addressable memories.

Concurrent with these hardware developments, the actual place of the CAM in the general field of data processing is undergoing scrutiny. At first it was thought that CAMs would eliminate the need for ordering, sorting, or merging, or at least would greatly simplify these functions. Because these functions can be performed with ever-growing efficiency by proper programming of present-day computers, the advantages of the CAM at this second look do not appear as great as first believed two to three years ago, at least for the small-capacity CAMs realizable today. However, when larger and more economical CAMs become available and their unique properties fully analyzed, content-addressable memories will no doubt find a place in data processing.

Superconductive memories

Superconductive thin films may be used to make large numbers of storing elements as well as all the addressing circuits necessary for a memory. A single technique is thus available for integrating, on a grand scale, the entire memory system. Storing results from persistent currents in loops with associated trapped flux and is really a natural form of hysteretic storage, just as is the permanent flux in magnetic memories. Addressing can be obtained by cryotrons, which are ideal steering switches with perfect isolation between input and output. Furthermore, superconductive techniques lead to extremely low power requirements and lend themselves to various ingenious arrangements for very high signal-to-noise memory output signals. Clearly, the cost and relative inconvenience of the necessary cooling equipment are justified only for extremely large storage capacities, upward of ten million bits. It is precisely for this purpose that the potentiality of grand-scale integration becomes important.

A very simple densely packed memory was evolved to fulfill these potentialities,[10-12] It consists of a continuous sheet of tin superimposed with two orthogonal sets of uniformly spaced x and y selecting lead conductors. Persistent storing currents are induced in the sheet at the selected intersection as the results of coincident currents of appropriate amplitude in the corresponding x and y lines. Their polarity determines the stored bit. The readout is destructive as in current-coincident core memories. The sense voltage is induced in a winding linking all intersections.

This elegant arrangement was found to operate quite well. However, it is difficult to control the uniformity of the tin film properties so as to avoid deleterious variations in the threshold of switching of the storing elements. As inherent in any integrated fabrication, uniformity cannot be achieved by sorting individual elements; rather, it depends on perfection of processing. Much less dependence on film properties results from using a more complicated geometry than a mere crossing of two orthogonal lines. With such geometries, which still preserve high packing densities, uniform operation with reasonable tolerances can be expected.

The drive currents are steered to the selected x and y lines by a network of cryotrons arranged in binary decoding trees. At every bifurcation one of the cryotrons is superconductive and the other is resistive, according to the value of the corresponding address bit.

The cryotrons, the memory structure, and all connections are constructed by a single integration technique. Thin films of tin, lead, and silicon monoxide are evaporated. The desired patterns are obtained through appropriate evaporating masks or through selective etching.

Superconductive techniques promise to provide memories of hundreds of millions to billions of bits with access times measured in microseconds. Such storage capacities are achieved today in electromechanical memories that have access times of many milliseconds.

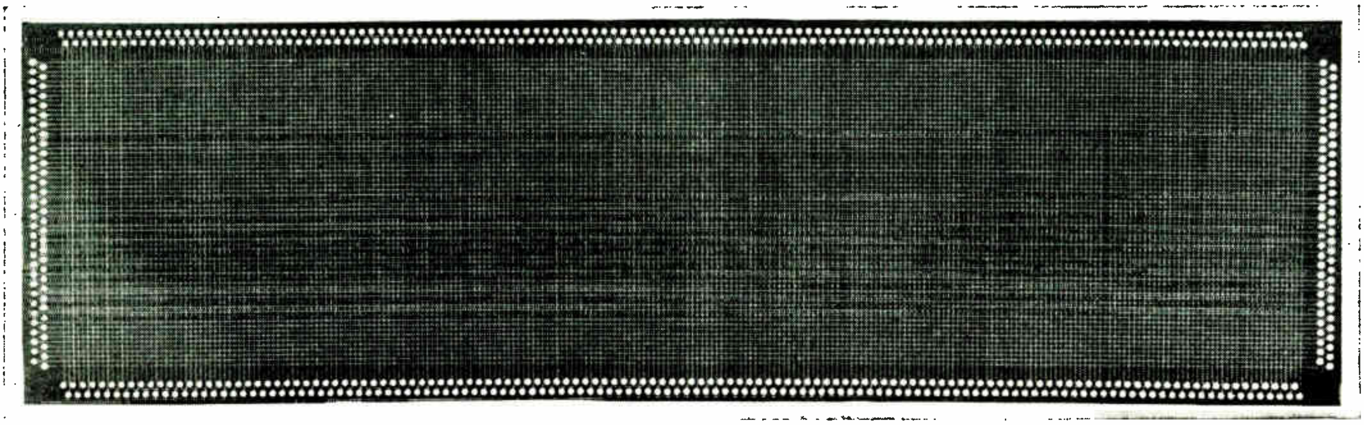
Fixed or read-only memories

Fixed or read-only memories are really code converters, converting input to output codes in predetermined fashion. They are analogous to the conventional electrically addressable memories in that they consist of a regular array of elements and are addressed through similar decoders.

The read-only memory can be used—as in the Spectra 70 computers—for the function previously performed by logic circuits. It stores the elementary operations that combine to establish the instruction complement of the computer. It replaces wired-in logic, which is relatively chaotic and difficult to alter, by a more orderly and more flexible arrangement. It allows the instruction complement either to expand or to contract with relative ease, allowing the tailoring of the order codes to specific computation tasks. The read-only memory also permits the emulation of various computers on a given one by translating and transforming the order codes. Additional uses of fixed memories are: the extension of the main memory to store relatively permanent information; indexing and recording of files in peripheral equipment; general translating in many telephone applications, etc.

Read-only memories consist of two sets of octagonal conductors at the intersection of which various forms of couplings are physically made according to patterns defining the desired code conversion. The couplings can be inductive, capacitive, or conductive.

Fig. 2. X-ray photograph of experimental monolithic ferrite laminate with 256 × 64 = 16 384 intersections spaced 10 000 to the square inch.



Illustrative of a particularly convenient type is the *E*-core read-only memory of the Spectra 70 computers. The *E* cores are made of a soft ferrite material and act as linear transformers. The magnetic path is closed by using two *E* cores face to face. There are as many *E* cores as digits in the word (53 in the current models). Each core has a winding on its central leg that provides the output. There are also as many windings linking every *E* core as there are words (1024 in the current models). On each core these word windings link one or the other window and thus determine whether a positive or negative voltage will be induced on the sensing central-leg winding when a particular word winding is energized. A word current of 50 mA produces a signal of about one volt in the multiturn sense winding. The signal is large enough to drive a standard logic gate directly. No sense amplifiers are necessary. The present cycle time is 960 ns, but with the two stacks used alternately the effective cycle time is 480 ns. Data are available at the processor 360 ns after a command.

A number of read-only memory types have been described. Inductively coupled types, in addition to the *E* core of the Spectra 70, include ferrite rod arrays,[13] the twistor permanent memory in which cards with a pattern of permanent magnets annul the switching action of the twistor wire at selected locations,[14] and eddy-current shielding loop cards.[15] Capacitive coupling has been used in certain forms of punched cards with preprinted arrays of capacitors[16] and in punched cards' capacitive shields.[17] Of interest also are content-addressable fixed memories: a magnetic type resembling the *E* core,[18] diode types,[19] and resistive-card types.[20]

It is very likely that the usage of read-only memories will expand. They provide a systematic method for obtaining the desired logic with all the advantages of a single design for many different tasks. Wired-in logic especially optimized for a given code conversion will contain, in general, fewer gates than are necessary in a read-only memory, which is adaptable to any code. However, such economy in number of gates, particularly with the advent of integrated circuits, is a small advantage compared with the orderly and flexible arrangement provided by the read-only memory. An engineering challenge exists for making read-only low-cost memories of very high speed, which are conveniently changeable. There is no doubt that this challenge will be met.

Conclusion

Because the memory is such an essential part of data-processing systems, continuing efforts are being devoted to improve it. As a result, the classical core memory has already reached considerable maturity. With cores made and tested singly by automatic machines at high speed, it has become possible to realize storage capacities of millions of bits. In the meantime, integrated rather than automated fabrication techniques have progressed considerably and although they have as yet not definitely shown economic or other advantages, they are likely to provide the next important improvement. The monolithic ferrites with integrated diodes and superconductive memories are the most promising forms of integrated memories. Another contender is the all-semiconductor memory, at present in an earlier development stage.

The orderly techniques of the electrically addressable memories are being extended to fixed read-only memories, which will make simpler, more versatile, and more economical computers.

In addition, entirely different approaches are being investigated in the laboratory. The advent of the laser and improvements in electrooptical devices open possibilities of optical memories. Interesting is the idea of using some natural scanning mechanism in a magnetic material—such as domain wall motion or sound—rather than constructing discrete storing cells by automation or integration.

The importance of the memory problem, the imagination, and the magnitude of the effort devoted to it will undoubtedly result in great progress. Integrated techniques are likely to provide the next important order-of-magnitude increase in economically obtainable storage capacities.

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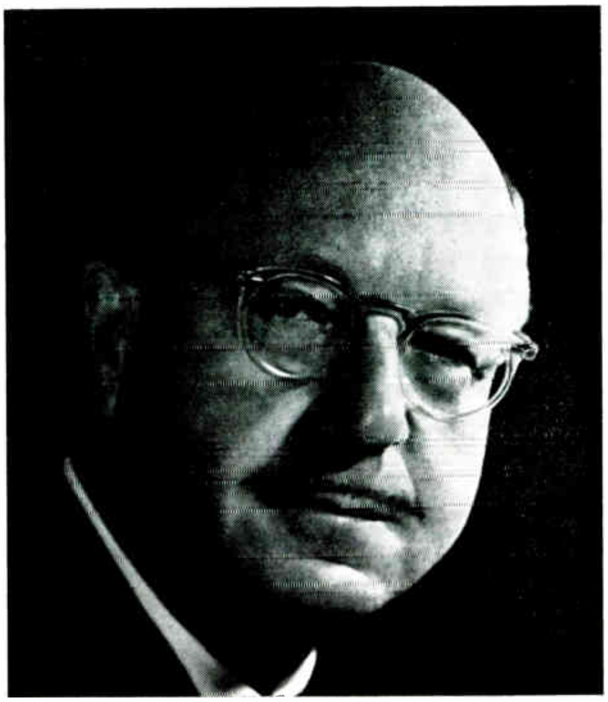

The professor, the industrialist, and the painter

An interview with one of the distinguished leaders of the electronics industry

For many years a professor of mathematics and electrical engineering, as well as consultant, Dr. Daniel Noble, Vice-Chairman of the Board of Motorola, Inc., is one of those unusual men who at the right time turned his intellectual capacities to the successful direction of what has become a major and revolutionary new industry—that which has grown out of solid-state electronics. He is now responsible for a complex of facilities at Phoenix, Ariz., involving three divisions and more than 10 000 employees, as well as the Communications Division in Chicago. Dr. Noble is distinguished in many more ways than there is space to list: he pioneered the application of FM to two-way mobile radio communications systems, he is a Fellow and, former Director of both the IRE and the IEEE, and, in 1962, he received the Western Electronics Manufacturers Association's Medal of Achievement for his accomplishments as a scientist, business executive, educator, and civic leader. Not so well known as yet, perhaps, is the fact that he has recently turned his gifts to painting.

The Motorola Semiconductor plant, set out from Phoenix in a desert landscape under a curious hot sienna outcrop of mountainous rock, is attractive to approach, and we learned subsequently that Dr. Noble had a great hand in its setting and distinctive design. His private office, too, is marked by a cultivated taste in Indian and Mexican *objets*—sculptures, pottery, tapestries, and rugs. After the intense 103-degree Arizona heat, one could not imagine a more pleasant place in which to listen to Dr. Noble's reflections on the beginnings, growth, and problems of the integrated circuits industry, and on his art and its relation to what he characterizes as the field of his major concern—the science of electronics.—*N.L.*

The need for a new equipment design philosophy

Dr. Noble, in your address to the International Electronic Circuit Packaging Symposium in San Francisco this August, you stressed the problems of the integrated circuits manufacturers vis-à-vis the equipment and systems designers, and you urged the adoption of a new design philosophy. What is the significance of this new philosophy?

Our future design of equipment and the design of integrated circuits for our linear systems must be based upon a conservative design philosophy, if we ever expect to achieve low-cost, integrated circuit mass production.

Conservative design means less-critical design. While it is true that conservative design will require the use of more integrated circuits for each equipment, or more elements in each circuit, the increased circuit module yield resulting from the decreased tolerances can be so overwhelmingly persuasive in reducing costs that the increased number of units used is not significant. Equipment using integrated circuits must be designed for the widest possible circuit tolerances, and the tolerance freedom must be increased as the number of equivalent components *is increased in each integrated circuit. Failure to understand the necessity for a new design philosophy can forever relegate the linear integrated circuit to a limited, specialized area of application, where the improved reliability, size, weight, and power consumption factors are more important than cost reduction. Cost reduction to the phenomenally low potential implicit in the new art can be achieved only if we learn how to design systems that can be assembled with wide-tolerance, high-yield integrated circuits.*

If I succeed in getting no other ideas across, I hope that my suggestion will be taken very seriously (which means that engineers will try to do something about it): Integrated circuit and equipment designers must communicate effectively; they must work very closely together if we are to make any real progress in both the package design for efficient equipment fabrication and in the design of equipment to make use of circuits with broad tolerances in order that high circuit manufacturing yield may be possible.

You said that, in your own eyes, the single most important statement in your San Francisco address was this: "The equipment and systems designers must abandon the traditional component approach to the design of equipment." Would you amplify your views further on this question?

Yes. As we approach the design of equipment that will make use of integrated circuits, we must adopt a new design philosophy. I tried to emphasize in my address the fact that the key to low-cost production of integrated circuits must be high yield. It is possible at present to design equipment using prototype integrated circuits, but too frequently when the equipment is constructed and you wish to mass-produce 10 000 units you find that you cannot get acceptable yields on circuits equivalent to the integrated circuit prototypes.

Most of the equipment built thus far has been related to digital circuitry, and while the yield problem does apply to digital circuitry, it applies to a much greater degree to linear circuitry or analog circuitry. You see, as I pointed out in my San Francisco talk, the engineers using component circuitry always used 5 or 10 percent tolerances on the components; but if you're building an integrated circuit with 50 components and you must try to hold that many components to such tolerances, you have an intolerable job ahead of you. You could always make just a few to start with, but when you must produce thousands of circuits, your yield may be 5 percent, whereas you need a 90 percent yield to hit the low-cost jackpot.

But it is *possible, with a design philosophy which you could call conservative, to design the equipment with additional circuits so that it isn't necessary to balance everything to the peak of performance in order to meet the specifications. There must be a change in attitude on the part of the equipment designers and the systems designers. They need a better understanding of the integrated circuitry problem and the yield problem. Likewise, there must be a better understanding of the problems of mass reproduction on the part of the integrated circuits people. We tend to have specialists in the semiconductor field, and in integrated circuits, who have had very little experience with mass-produced equipment. Conversely, the equipment people have had comparatively little experience in integrated circuit technology and so you have these two groups going down the line separated by a no man's land, that is, with a complete lack of understanding of each other's problems.*

We understand that you and your company have tackled this communication problem in various ways—through publications, speeches, and editorials, and even by giving courses to your customer–engineers. Has this effort helped?

It certainly has helped a great deal, but it doesn't give a complete answer. You always encounter equipment people who buy integrated circuits and make up equipment without understanding the need for conservative design, and then they come back and say, "We want 10 000 of these integrated circuits and here are the tolerances." And they set tolerances that are too tight for a good, high yield. Equipment people don't think in terms of integrated circuit production. They think in terms of the 50 years of component-oriented design tradition, and setting plus or minus 10 percent tolerances on components is almost an automatic reflex. It's difficult to upset a philosophy of this kind; 50 years of background isn't changed overnight. The point is that the problem needs to be talked about and aired completely and thoroughly.

I'm also constantly hitting our own engineers with the communications problem—both the integrated circuits people and our systems people. We're always attempting to bring them together to work out viable patterns. For example, the other day I looked at one of our reports concerning a system upon which our men had worked. They ended up with something like 48 integrated circuits, which required seven or eight masks to produce. After going through a redesign program for conservative design to solve the problem, they reduced the circuits to 35 and the masks to two or three. Going around again through another redesign schedule, they still needed 35 amplifiers but they accomplished the processing with only one *mask and they could make both n-p-n and p-n-p units and could vary the amplifier characteristics with changes in the rates of diffusion. We finally ended up with a conservative design in which you could cascade the n-p-n and p-n-p without coupling units, with one mask to process all the circuits for all of the amplifiers. This is the sort of thing that must be done. If they had stopped at the first design, they would have had something that worked, but the cost would have been high and the yield would have been impossible. The whole design would have been impractical from a cost point of view. It is this reaching for mature conservative design, and for the maximum possible tolerances for each individual integrated circuit, that is absolutely necessary if we are going to achieve low-cost production.*

There are two things that I had hoped for from integrated circuits beyond everything else.

1. The improved reliability *of the systems using integrated circuits, because as our systems increased in* *complexity, unless we introduced a radical step-function change in technology, away from components, development would eventually have been stopped by the rising pattern of failures. A complete change in the technology was called for to give us orders-of-magnitude improvement in reliability.*

2. It is possible to achieve phenomenal cost reduction for mass-produced equipment when we develop integrated circuits fully. The fact that a whole circuit complex involving dozens of components can be made for a few cents when we learn how to produce circuits with high yield makes this statement obvious. As a bonus, we get reduction in size, weight, and power consumption, but the two major *integrated circuit contributions with which I am concerned are improved reliability and reduction of cost. We can never realize these two extraordinary advantages unless we change our equipment design philosophy to one of conservative design which will make it possible to specify the widest possible tolerances for the integrated circuits in order to facilitate high yield production. Even if we use* more *integrated circuits to achieve the high yield, the ultimate result will be reduction of cost.*

Couldn't this conservative design philosophy be thought of as a form of redundancy?

It isn't as simple as that. To give you an oversimplified explanation: Suppose you must build an amplifier that is to have certain minimum and maximum gain levels. To save materials, the component people would put in just the right number of tubes and components and specify the tolerances so that in the normal course of events performance would be within the specified range of amplification. Well, there's another way of doing this if you have wide variations in the amplifier itself. With an integrated circuit, you could add more transistors to the circuit to make sure you had adequate gain. However, you'd probably also have to include automatic gain control in the system so that the gain wouldn't exceed the maximum specified level. This would give you a factor of safety. Components have been added to the circuit, but it's a conservative design. For the maximum variation in production, this integrated circuit would never fall below the minimum amplifying requirements nor would the automatic gain control allow it to exceed the maximum. So, you would have rolling off the line an amplifier that always stayed within the limits. You built extra gain into the circuit and the tolerances are so wide that your yield might be 90 to 95 percent. This is what we mean by conservative design.

Solid state: the new industry force

It is always interesting to trace the inception—the "moment of recognition"—of a new idea or field of action, whether it be in art, science, or industry. Could you tell us how and when you first came to recognize the real potential of solid-state electronics?

I'm proud of the fact that I did anticipate the trend toward solid-state electronics. Back in '47 and '48, when I was talking with our Chairman of the Board, Paul Galvin, I remember saying that in general the next 50 years of electronics was going to be oriented toward solid-state electronics. My view was a result of various discussions and experiences at the Radiation Lab (M.I.T.) and other places during the war, and an awareness of the growing attention to atomic energy research. There was also the feeling that while we had explored the liquid and gaseous states, solid state, because of limited technology, had been neglected; but with available new techniques it was destined soon to become a "bandwagon" area of research. As soon as the transistor, especially the junction transistor, was invented, solid-state electronics became a reality.

I came to Phoenix with the specific intention of setting our research moving toward solid-state electronics. At that time, I didn't know exactly what the total solid-state electronics pattern would turn out to be, but I knew it was going to be a powerful force in the industry and that solid-state electronics would characterize the product flow of the entire electronics industry for the next 50 years or more.

I selected Phoenix because I felt that here we could collect the kind of brain power we needed. In the past, electronics engineers were circuit people. They were concerned with component circuitry, and there were specialists in each *equipment area. You could get a TV specialist or a communication specialist or a specialist in radar circuitry. It was my conviction that the new pattern would have a number of disciplines that must be integrated. I knew that we would need metallurgists, mathematicians, and chemists, as well as electronics engineers, mechanical engineers, and physicists. I was convinced that highly qualified professional people would like to live in the Phoenix area. My conviction has proved to be valid.*

We have organized here, I'm sure, one of the best teams in the world, and we have more than double the number of these specialists that I anticipated we would need. We were fortunate in being able to bring in exceptional leadership. Our Phoenix operations are managed by a bunch of former professors. I was a professor. Dr. C. Lester Hogan, who runs the Semiconductor Products Division and who is a very able scientist and engineer as well as an able businessman, was professor of applied physics at Harvard. Dr. Bill Welch, who heads our Controls Division, was a professor of electrical engineering at the University of Michigan. Joe Chambers, who runs our Military Division, wasn't a professor, but he ran a consulting firm in Washington, D.C., before he joined us.

Should the moral be drawn from this that professors are much sharper about the business world than they're supposed to be?

Well, professors are people, and you will find some professors who are good businessmen and some who are not, the same as you do in any selection of people. The tendency to generalize that engineers are this, or professors are that, is a public attitude that has no validity.

Digital and linear integrated circuits: state of the art

In general terms, how do you view the evolution of the integrated circuits field? Has the industry matured a great deal, as much as you had expected?

In the digital field, yes. All of the major computer manufacturers are moving toward the design and ultimate production of computers with integrated circuitry. There has been very substantial, and I think reasonably rapid, progress in the adapting of integrated circuits for digital computers in digital systems. In the linear field, progress is very, very slow. Since you don't have a large number of circuits that are standard, identifiable, and redundant, in linear equipment, the problem of working out acceptable prototypes that will have general use is very, very difficult. There needs to be some standardization, but we can't have standardization of detail; it must be standardization of the input and output of black boxes, so to speak. And I'm sure that the rise in the use of integrated circuitry in linear systems is going to be slow despite anything we do. It's unfortunate because integrated circuitry has much to offer in this field. Digital, of course, was a "natural" because of the tremendous redundancy and the comparatively simple function—switching a circuit on and off. But linear circuitry is extremely complex: I've characterized it as infinite switching with control of amplitude at the same time. Of course, any survey of equipment utilizing circuits will show that there are something like 30 to 35 basic circuits involved, and only a few of these are digital. All the others are analog. When you get away from computers, the great mass of equipment produced by industry is analog, and this field is comparatively untouched by integrated circuitry today. Thus, a big body of the industry is not moving very rapidly toward the adaptation of integrated circuits.

Consequently, we're constantly exploring the use of integrated circuits for linear applications in our own R & D. They're needed for military applications, of course; and in these new fields only the military can afford them. One fact that hasn't been understood fully by the people concerned with setting up governmental contracts is that industry is not going to develop linear circuitry on its own because there is no easily defined market, and because of the lack of standardization, and the uniqueness of most analog circuitry applications. There must be a very substantial pattern of governmental contracting for development of linear integrated circuitry if the military or NASA or any of our governmental departments expect to have available the advantages of integrated circuitry for linear applications. The linear field is an extremely complex field, and there's no simple solution to the problem of introducing integrated circuitry.

On becoming a painter

Dr. Noble, we have been told that, not long ago, you took up nonobjective painting, and that in February you will have a one-man show, and that other shows are in the offing. Would you tell us something about how you took up painting, and how you view it in relation to your professional career?

I've been experimenting with art all my life. I have been drawing pictures from the time I was five and I painted from time to time but in no serious way. However, I have always reached for an understanding of art. I spent a lot of time looking at pictures, and painting some. Over the last few years, I had in mind the development of a personal modern art exploratory pattern, partly in an attempt to understand modern art and possibly with a little tongue in cheek about the whole idea. I hoped to produce ten paintings and, if they had any validity or acceptance, I was going to do an essay on modern art. When I came back from a month in Geneva, just a little over a year ago, I decided that it was the time for action. I brought out my paints and started working in the modern or nonobjective mode. I enjoyed painting and kept on going. I was hooked! I had a feeling that there was some significance to the pattern I was creating. When I had completed about 20, some of my friends who were interested in art and some of the galleries' people and some of the art museum people saw the works and they surprised me, both by becoming intensely interested and by their statements to the effect that my paintings represented original and important work. So with this encouragement I continued to paint. Since September of last year I've produced more than 50 paintings.

James Harithas, the curator of modern art for the Phoenix Art Museum, became so interested, and brought other people who were collectors and critics to see the work, that the decision was finally made to give me a one-man show at the Phoenix Art Museum simultaneously with a *show at the Stable Gallery in Phoenix.*

This has somewhat confused and delighted me. Collectors have already earmarked two pieces for purchase prior to going into the show. I confess that I don't quite know where I stand on the matter of artistic validity and value but I'm pleased and interested that the experts find the stuff worthwhile, and I am quite willing to go along for the ride. I'm having a lot of fun.

I have one painting called "Integrated Circuitry," which is a free-wheeling interpretation. There's nothing literal about it, but anybody who knows integrated circuits can at least get a feel for it. My canvases include: "Walk in Space" and "Proliferation of Space Consciousness." Still another is "Organic Computer Confused by the Problems of Visual Conception at a Modern Art Exhibit." You see, science is bound to creep in.

Some of the paintings I mentioned are examples of my effort to relate my scientific and artistic interests. In general, I paint what I want to paint and end up fighting each canvas until I achieve a subtle state of equilibrium which I call unity. The simplest way to explain unity is by the statement that when the painting has unity I no longer feel the impulse to change color, line, mass, or composition. If I paint something and it doesn't have such unity, there is a tremendous impulse to change the picture.

In any case, the experience is interesting, and I'm going to ride out the show in February until I find out what the professional critics think about my work.

My primary interest concerns electronics and the science of electronics, but perhaps art will introduce some new parameters and some new degrees of freedom for the interpretation of man's relationship to the new scientific revolution.

The organic computer

Would you tell us more about how you imagine this relation between science and art?

I'm sure that everybody who makes decisions is conscious of the fact that these decisions come as a result of subconscious correlation of all the disciplined bits stored in the organic computer. It's quite a common experience for me to have something come up that's fairly complex, and with all the related facts brought together, I'll say, "This is what we should do," and say it with conviction, and I am asked, "Why?" It may take me quite a long time to find the reasons why. The decision has been subconscious and there has been an effective correlation. I'm sure that everybody experiences that sort of mental processing. If the facts do not go together and I can't get a subconscious correlation, then I have no feeling for a decision and I hold it up.

Now, why shouldn't a similar thing take place when you look at a painting if you are deeply interested in art? If you correlate and store art-oriented bits all your life, when you start to paint it seems reasonable to assume that there should be a subconscious correlation of all disciplined bits. The artists have a name for this—they call it action painting. But, action painting isn't going to be effective unless there are a hell of a lot of good disciplined stored bits in the computer as points of reference for the subconscious correlation of creative combinations. In other words, you can't have subconscious correlation if you don't have anything to correlate. I think that when somebody just starts daubing, hoping something will come out, the chances of it happening are rather poor unless there have been some long periods of accumulation and disciplining of information that is relevant to the concept in hand.

The brain can be pretty stupid in many areas, but it still makes the digital computer an imbecile by comparison when it comes to a simple thing like pattern recognition or visual perception. This visual perception capability of our organic computer is truly magnificient.

If you were to write the letter M, for example, you could form it in 50 different ways—narrow, skinny, long, short—but in context you would recognize it instantly. You recognize a person. You don't do it by analyzing a, b, c, d, and then concluding that therefore it's somebody; but rather you instantly infer who it is even if you see a side of a face moving away from you. This is visual perception at work.

If you orient your painting to a model, say a dog or a horse, you're stuck with the dog and the horse reference; but if the painting is not model-oriented, its composition, color, and line are free-wheeling, without limited symbolism. Without the models your visual perception is free to generate a response impact without the limiting influence of a model.

Of course, each observer is going to see something a bit different from others because of the difference in the stored bits in each computer. I don't claim that I understand the reaction. I'm still trying to reach for an understanding.

Brain modeling

Have you directed any of Motorola's research efforts toward artificial neurons or similar elements for biological-like computers?

I have an intellectual interest in this field, though I haven't explored it to the extent that I feel competent in discussing it; but I do feel that we must depart from the counting approach that we use in the digital field. We must use artificial neurons or some other equivalent approach because, with the computer design we have at present, we'll never achieve any notable success in pattern recognition and visual perception areas, or even manage to resolve some comparatively simple problems not related to the digital approach. There must be new approaches to adaptive processing; we must learn much more about the function of the neuron; and eventually we must develop something nearly equivalent to the brain, but more effective than the brain in some areas.

Although we're working with customers in many fields, we are not working on neurons, because none of our customers are reaching in this direction.

As I said earlier, one of the things we are giving our greatest attention to is the challenge of working with the customers in such a way that their understanding of equipment and systems interacts constructively with our understanding of integrated circuits. Our main areas of integrated circuit development are directly related to the current customer interests, and although some of the interest has to do with the development of specialized linear integrated circuits, most of it at this time is concerned with the development of digital systems.

Special
Conference
Report

IEEE Annual Communications Convention

P. T. Sproul *Bell Telephone Laboratories*

The first IEEE Annual Communications Convention, sponsored by the IEEE Communications Technology Group, was held in Boulder, Colo., June 7–9, 1965. A wide range of communication subjects was covered.

Five papers were presented at a session on "Switching System Maintenance and Testing," sponsored by the Communication Switching Committee of the IEEE. Of special interest was "Maintenance Planning of No. 1 ESS" by L. S. Tuomenoksa, Bell Telephone Laboratories. The Bell Laboratories exercises great care in diagnosing problems that could be encountered with ESS No. 1. Actual faults were put into a system to determine the effect of these faults upon system performance and capability. Results of these tests were then put into a dictionary from which the trouble indicated and the proper corrective measure could easily be ascertained and the difficulty thus corrected by the maintenance man on ESS No. 1.

Another interesting paper was presented by A. L. Fleming of Bell Telephone Laboratories: "An Automatic Call-Through Test Set for Step-by-Step Systems." This subject is of particular interest due to the upgrading of the nationwide switching system required by direct distance dialing (DDD). The paper described a test set that would automatically routine step-by-step offices and locate and indicate problem areas which hitherto have only been picked up by routine maintenance testing using manual methods. This type of automatic testing is particularly important in view of the problems encountered with the DDD system.

At the session on "New Switching Systems," two papers described a new development of the International Business Machines Corporation that improves the service to telephone customers who reach numbers which for one reason or another are out of service. This development, known as the Automatic Telephone Intercept System, produces a recorded message to inform the customer of the status of the number he has called. The intercept operator keys the number into the system, which is composed of business machine computers and audio response units.

A. A. Kunze presented a paper on new concepts in time division switching with the objective of setting new patterns for future research in the switching field.

A small crossbar community dial system, the SA1, described by J. M. Long, Bell Telephone Company of Canada, and A. Vennos, Northern Electric Company, serves small numbers of lines with common control equipment. To accomplish this purpose, a simple plan and the ability to operate with a nonduplicated control are necessary. Success of the system is attested by its installation in some 160 locations.

E. U. Cohler described the planning of a store and forward data switching system that applies the new concept of multiple processors with the inherent capability of parallel message handling.

A session on "Simulation of Communications Networks" was organized as a panel discussion, which was preceded by a set of short talks by the panelists. Although the purposes of the several simulations described were in many cases different, all speakers concerned themselves with the trade-off between efficiency of program execution and ease of programming and program modification. Another item of general interest was the determination of the reliability of the results, in terms of statistical sampling error.

The panel discussion was centered upon the problems of accuracy and validation of the simulation models and programs. The question of the kind of problem that can best be solved by using simulation was also raised. The predominant view was that simulation is most useful as a means for developing principles of design and operation, and that it has occasional usefulness as a tool for evaluation of particular system configurations.

Massachusetts Institute of Technology Lincoln Laboratory staff members—D. C. MacLellan, H. Sherman,

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Reviews for this conference report were submitted by the following: R. K. Hellman, Hazeltine Corp.; D. C. MacLellan, H. Sherman, P. Waldrow, M.I.T.; and S. B. Weiner, Stromberg-Carlson Corp. P. T. Sproul edited the material.

and P. Waldrow—described the first two of a new series of experimental satellites launched on Feb. 11 and May 6, 1965. LES-1 and LES-2 are the first microwave communication satellites to be constructed entirely of solid-state components; they are also the first active satellites to receive and radiate in the assigned communication satellite band at 8 Gc/s.

LES-1 and LES-2 carry a novel experimental switched antenna system. The receiver and transmitter are connected, through a diplexer and a set of microwave switches, to that one of eight microwave horns which points most closely toward the center of the observed earth. The switching is carried out by a cascade of one two-pole switch and two four-pole switches. The means for establishing the pointing reference is a lightweight optical earth sensor followed by appropriate digital logic to choose the correct X-band antenna.

The outputs of miscellaneous transducers for measuring temperatures, power levels, continuity, and generally the operational status of the satellite are relayed to the ground by means of a 60-channel telemetry system. The telemetry logic employs low-power circuits which require a typical power drain of 66 μW per flip-flop. The TLM transmitter uses a highly efficient circuit for generating the transmitted carrier and a modulation system (biphase modulation) that puts all of this power into useful, information-carrying sidebands. The combination of these techniques permits one to operate a 60-channel PCM telemetry system at 100 bits per second with a total dc power drain of 2.055 watts, of which 0.85 watt is available for useful radiation to the ground.

LES-1 and LES-2 each carries an electromagnet that is designed to precess the satellite spin axis and hold it normal to the satellite–sun line. The precession system weighs 200 grams, consumes 500 mW of power, and operates without command from the ground. Because of spin axis conversion associated with the failure of LES-1 ordnance circuitry, the electromagnets in LES-1 changed the satellite spin rate rather than its spin axis position. LES-2 spun correctly, and the torquing system has performed in accordance with expectations.

The dip-brazed tubular frame that forms the basic structure for LES-2 weighs 3.5 pounds. This structure carries the total satellite weight of about 80 pounds and was successfully tested in the laboratory to 156 percent of the Titan III vibration and shock requirements. The ratio of the frame weight to the total satellite weight is 4.5 percent.

The LES-2 was launched into a 1500–8000-nautical-mile orbit on May 6. All systems are functioning as designed.

Many excellent papers were presented in the information theory sessions, which were divided into three parts: "The Information Theory Symposium on Time-Varying Channels," "General Information Theory Topics," and a panel discussion on "Adaptive and Learning Systems."

One of the sessions in the symposium on time-varying channels described two basic types of channel simulators:

1. An essentially tapped delay line with randomly varied tapped weights. In one variation of this concept, randomness was obtained through the use of suitable noise voltages. In another, the tapped weights were physically varied by means of a pseudorandom mechanical system.
2. A nonreverberant water tank acoustic medium containing input and output sonic transducers that are separated by many acoustic wavelengths. Signals are scattered from the input to the output transducer through the introduction of bubbles, or through scattering objects in the medium.

A tutorial discussion of underwater acoustics was presented as part of this symposium. The authors discussed boundary scattering effects and underwater propagation, characterization of undersea channels, and several optimum receivers to be used to detect signals passed through underwater channels.

A tutorial session on seismic channels was also presented. The session discussed the properties of the earth as a seismic channel and general properties of seismic arrays. The closing paper in this session indicated that an average power of 630 MW would be needed to sustain a bit rate of one bit per 10 seconds at 5000 km.

Other sessions discussed optimum demodulation and channel characterization for various time-varying channels.

A session on low-noise amplifiers presented an excellent up-to-date picture on recent developments in low-noise amplifiers, including masers, tunnel diodes, traveling-wave tubes, low-noise transistors, and parametric amplifiers. Boyd P. Israelsen described several compact low-noise traveling-wave amplifiers that have found areas of application. Norman Chasek reported progress in tunnel-diode amplifier design, anticipating considerable use of this device. The saturating power output of the tunnel-diode amplifier has been increased by 10 dB. Masers, as reported by J. J. Degan, are still the ultimate to which all other amplifiers are compared. A feature not generally appreciated is the linear characteristic under overload conditions. Substantial improvement in the noise figure of cooled parametric amplifiers was reported by J. G. Josenhans in an experimental setup. The temperature of 10°K for the overall amplifier having a 400-Mc/s bandwidth was achieved when it was cooled to 4.2°K.

Another session emphasized practical means for attaining improved reliability of microwave systems. The results of three papers and a panel discussion could be summed up as follows: Frequency diversity is felt to be essential if a high degree of system reliability is to be achieved. However, the contributions of solid-state components with equipment operating from batteries and conservative transmission design were stressed as being of equal importance. Last, and not to be dismissed, is operation and maintenance by trained personnel equipped with adequate testing facilities. Adequate alarms should also be built into this system, with circuits especially arranged for test communications. Protection circuit arrangements are desirable for systems with large circuit cross sections.

Radiocommunication problems of particular interest were covered in another session. Also, a portable microwave radio link complete with multiplex equipment was described by I. A. Egger of Telefunken. This system is designed to supplement communications or to replace systems that have been disabled. A versatile high-speed radio path protection system was described by F. S. Beale.

Error control

One error control session, chaired by G. W. Gilman, included a series of four tutorial papers on the philosophy and use of error control. It began with an overall survey by R. G. Gallager of M.I.T. Block and convolution coding were discussed with respect to principles, techniques, and application.

S. Sussman presented a paper on results of measurements on working channels and on models useful for representing telephone and radio circuits. The paper included statistics of error occurrences observed in the field and mathematical models for these.

A paper by A. H. Frey, Jr., discussed the problems involved in a satisfactory comparison of different modes of error control. He reached the conclusion that, for most practical applications, system design and operation considerations rather than information theory will be the deciding factor.

A paper by A. E. Fein *et al.* discussed time spread coding. It covered (1) the concept itself, (2) an experimental evaluation of this technique, and (3) methods for empirically characterizing digital channels. About two orders of magnitude improvement is said to have been obtained in a field test of this technique.

There were also a series of papers on the most recent work in the field of error detection and correction. Each of the authors discussed his most recent work, including Dr. Ray-Chaudhuri of IBM who covered the problems and successes experienced in his work on upper bounds and lower bounds on minimum redundancy in an error-correcting group code. This group of papers was by specialists in the field who were offered an opportunity through this convention to exchange notes on their most recent work. It was not possible for the individual authors to cover their work completely in the 30 minutes allocated to each paper.

A second error control session, chaired by W. P. Bethke of RADC, was devoted to visual communication. Many distinctive types of large computer-driven displays are available today. However, matching equipments to the requirements must not neglect certain "trade-off" considerations that may influence the ultimate equipments. Such factors as reliability, operating costs (long term) vs. initial costs, and reponse time are typical "trade-off considerations."

Certainly no system can neglect the man–machine interface. Psychophysical factors as well as information content are essential to proper data and display organization. There is a definite hierarchy existing in display systems. An airport traffic controller has a direct and immediate link with the system. He reacts to data displayed and actually affects the display. On the other end of the scale, displays are simple, clean, and usually in nonreal time. In addition, the "reactors" (Commander) are much more remote from the system.

The impetus provided by the military developments in this area produced certain "civilian" by-products. Such devices as traffic controller displays, vehicular traffic handling systems, and stock market quotation devices are representative examples.

In another session covering signal detection, the papers exhibited a common thread: problems involving random parameters on the signals and noise in contrast to the situation of known conditions. The speakers agreed that optimum detectors generally include parameter estimates within the detector structure, and thus could be called "adaptive" if desired. However, the parameter estimations are the result of implementing the detection operations, and not the result of specifying extraction as well as detection, so that the accuracy of the estimates is suspect. This was emphasized in the paper by F. F. Fulton on nonorthogonal signal reception, where the engineering realization of the receiver is of such a form that phase estimates are not even accessible. As a contrast, the paper by D. L. Schilling on phase-locked loops was concerned directly with extraction and showed adjustment techniques based on a novel equivalent circuit that permits obtaining very low thresholds.

Signal processing

Two advances were noted in a session on signal processing analysis. The first was described in "The Transmission of Frequency-Modulated Signals Through Linear Systems," a paper by D. D. Weiner and B. J. Leon. They presented a concept of quasi-stationary response and used this to simplify the solution of linear systems excited by arbitrary frequency-modulated waves. An exact response is obtained by using the quasi-stationary solution plus a correction term. This approach, presented by Weiner, is more straightforward and simpler than prior methods of analysis described in the literature.

The other advance in signal processing analysis was reported in the paper, "Time Compression in Recording of Errors" by L. M. Small, who described a technique that appears to be convenient and economical in the use of recording tape. The data come out in a form suitable for immediate machine processing. This technique, worked out in detail but not yet fully implemented, could provide very valuable error characteristics of all types of digital communication links.

Another session on signal processing presented a series of papers on the latest work in the signal processing field by several of its active workers. These are briefly summarized as follows:

R. Hove, in his paper on matched filters using *RC* active delay networks, filled a gap by providing a needed and feasible answer to practical processor implementation where low-frequency long-direction signals are of interest.

The effects of misalignment between pseudorandom carrier and its reference in a correlation receiver were described by W. Gill, who used a decomposition property that permits easy determination of the power spectra and hence of the correlation properties.

C. V. Ramamoorthy, by a graphic theoretic approach, attempted to demonstrate that improvements in data transmission are likely to come about by the application of the growing technology in the signal coding field.

D. W. Tufts and P. Trafton conducted extensive experimental investigations which show that some of the theoretical results in the distribution and moments at the filtered detection outputs are in agreement, while for some detector–filter combinations there is divergence for some part of the interesting range of the parameters.

R. Gagliardi showed the usefulness of applying vector space analysis to common communication system design problems involving the transformation of a data signal into a transmission signal and subsequently recovering the data within prescribed constraints on the transmission signal, the signal processors, and the channel.

E. Gorog presented a noniterative technique for time-domain equalization using nonlinear filtering in combination with linear filtering to enhance data transmission efficiency over distorting channels.

Special Conference Report

Aerospace Technical Conference

Arnold A. Sorensen *The Martin Company*

An opportunity to visit NASA's Manned Spacecraft Center and to attend technical sessions covering the breadth of aerospace technology marked the 1965 Aerospace Technical Conference and Exhibit, held at the Shamrock Hilton Hotel in Houston, Tex., from June 21 to 24. The conference was sponsored by the Aerospace Group and the Houston Section of the IEEE and was also supported by the Society of Automotive Engineers, ASME, and the Society of Value Engineers.

At the luncheon on Monday, the keynote speaker, Paul E. Purser, special assistant to the director of the NASA Manned Spacecraft Center, was introduced by the IEEE Director of the region, Carl Wishmeyer. Mr. Purser spoke of the Center's mission and the technical facilities being prepared to meet the challenge. He encouraged the technical societies in their program of advancing the state of the art by information exchange.

Guest speaker at the Wednesday night banquet was Lester C. Van Atta, assistant director of electromagnetic research at the NASA Electronics Research Center. (Dr. Van Atta is also chairman of the newly formed Group on Aerospace and Electronic Systems.) In his talk on "Preparing for Future Accomplishments in Space" he discussed deep-space communications problems associated with interplanetary exploration. New techniques will be needed to obtain the useful RF power and large antenna apertures needed to achieve the high information bit rates foreseen for new programs.

Twenty-six sessions were scheduled at which 102 technical papers were presented and three panel discussions held. These panels covered engineering education, moderated by R. T. Smith, assistant director of Southwest Research Institute; value engineering control, moderated by Dan Lewis, chairman of the Houston Section of the Society of Value Engineers; and some electrical/electronic areas requiring emphasis in preparation for future space programs, moderated by R. L. Johnson, vice president–director of manned spacecraft programs for Douglas Aircraft Corporation.

Interplanetary probes

Mr. Johnson stated that space undertakings in the decade ahead can be divided into the three broad categories of manned and unmanned lunar and earth orbital operations and unmanned interplanetary probes. These raise problem areas whose solutions will demand our highest skills. These areas were reflected in the topics assigned to the panel members. John L. Mason, chief engineer, AiResearch Manufacturing Company, described three different life-support systems. He stated that the major obstacle for long-duration manned space flight is the unavailability of suitable power sources in the 5-kW class. N. V. Petro, vice president, Defense and Space Center, Aerospace Division, Westinghouse Electric Corporation, outlined objectives and requirements of communications technology required to support the national space program. His discussion ranged from the idea of global control of manned orbital stations via satellite to operational problems involving relativistic time observation and mass increase involved with the idea of an unmanned probe to a distant star. In covering his topic of navigation, H. J. Woll, chief engineer, Aerospace Systems Division, RCA, spoke of the strides made in sensors and computer systems. He stated that implementation of lunar missions, interplanetary fly-by, space rendezvous, resupply, and rescue not only will provide evolutionary improvements but also will stimulate man's creativity into larger steps. G. L. Hansen, vice president and Centaur Program director, General Dynamics/Astronautics, said that optimization of system integration effort requires task structuring within the framework of environment expected in the 1965–1975 period. This includes not just the physical and technological, but also the managerial and governmental environments. D. C. Regan, head, Instrumentation Reliability Section, Manned Spacecraft Center, in discussing reliability stated that many items have performed better than predicted. However, more valid failure-rate information is needed. The reliability engineer must be the jack of all trades and the master of one. He must learn system engineering as a discipline.

Technical papers were presented in 23 sessions devoted to aerospace power generation and conversion equipment, electronics, electrical design, cryogenic systems, liquid-metal systems, electromagnetic compatibility control, radiation techniques, and human engineering. One session was devoted to a description of the Houston Manned Spacecraft Center, supplementing information received during tours of the Center.

Rotating machinery

Emphasizing the continuing interest in rotating machinery, one session was devoted to theoretical analyses and design methods required in the aerospace field, because of the use of high frequencies and harmonic producing loads. In other sessions descriptions were given of development and tests of a potassium-cooled 50-kW generator developed for the SNAP 50/SPUR system, problems encountered in the design of rotating machines for extreme environments, the static exciter–regulator for the SNAP-8 space power system, investigation of high-frequency power conversion and generator techniques, and power transmission at frequencies up to 5000 c/s.

Hardware was described for speed and torque control of an induction motor by means of a solid-state cycloconverter frequency change. Supplying the motor with controlled frequency and voltage in a closed feedback system permits complete control.

A number of papers were devoted to static power converters. These included the analytical optimization of magnetics, use of synchronized complementary converters to minimize ripple and filtering problems, tests of capacitors for inverter space applications, and application factors affecting their weight. Low-voltage converter–regulators have been developed to the point where it is possible to boost the low-voltage level of thermionic, fuel-cell, thermoelectric, and electrochemical single-cell sources to usable levels with efficiencies between 70 and 90 percent.

A study of secondary power systems for a 12-man logistic spacecraft showed the hydrogen–oxygen fuel-cell system to be attractive. The reactant supply system would include supercritical storage of the cryogens for the launch and 24-hour orbital space flight mission phase and gaseous storage for the six-month orbital storage period prior to entry and landing.

Solar cells

A noncontact surface analyzer for defining a three-dimensional solar concentrator surface contour was described in one paper, continuing a series on the development of concentrating solar-cell panels. Another paper described a method of reducing solar absorptance by constructing the solar cell so that it will reflect the infrared part of the solar spectrum. Several papers were devoted to analysis and development of a flat-plate solar thermoelectric generator capable of providing 3 W/ft^2 with a weight factor of 30 W/lb for the couple and 15 W/lb for the panel form. These offer promise of lower-cost space power systems with special adaptability to missions not suited to photovoltaic cells.

The impact of microcircuits upon the design of communication, data handling, and guidance electronics was obvious in papers presented in the two sessions on electronics. It was stated that much existing equipment can be converted to microelectronics without extensive redesign, without sacrificing reliability, and without increasing circuit fabrication costs. Extensive use of semiconductor networks is being made in the advanced orbiting solar observatory scheduled for launch in 1969. During the design stage a decision was made to incorporate integrated circuits into the Apollo guidance computer. As a result, it represents the most extensive use of any single integrated circuit. The mean time between failures was observed to be 7500 hours, a number four or five times greater than predicted. A portable television camera employing microcircuits is to be used on board the Apollo spacecraft and on the lunar surface. The primary objective of this system is to provide real-time television pictures of lunar scenes, which are suitable for viewing on commercial television receivers. Also presented was a paper on establishing and evaluating models of circuits in a radiation environment, using flow-graph techniques.

Provisions being made for the astronauts who are first to step out on the lunar surface were described in a paper on lunar-suit telemetry and voice communications. Transmission of physiological data as well as space-suit environmental and performance data will be monitored on earth. Some of the hardware implementation problems, including suit antenna considerations, were discussed. Size and weight reduction of antennas by ferrite loading and the development of fiber-reinforced ceramics for electromagnetic window applications to 2500°F were covered in other papers.

In the area of electrical design, papers focused on the behavior of electric discharges at altitudes between 70 000 and 250 000 feet, faults caused by conductive dendrites occurring under wet conditions, and performance in space of electrical contacts lubricated with niobium diselenide.

Development of a micrometeoroid detector analyzer consisting of a modified ballistic pendicular for momentum measurement and capacitive foils for velocity measurement, an evaporative system for space environmental thermal control of electronic components having high power density, and illumination requirements for vision on the lunar surface were described. Vacuum-insulated switches for application to large nuclear space power systems have been designed to operate at high temperatures and to be radiation resistant.

A session was devoted to the Saturn S-IV cryogenic system. Four papers were devoted to propellant utilization, weigh operations, environmental control, and safety. Described were methods to achieve precise loading and minimum residuals, use of electronic force transducers, calibration with a digital weigh system for computer control, frost prevention, and selection of hydrogen and oxygen detectors. The last paper, presenting the electric system used to drive the chill-down motor pumps, described the circuitry of two functionally identical 1.5-kVA inverters designed to supply 400-c/s power to the motors. Included were comparisons of the two inverters, one using germanium transistors in the output stage and the other using silicon transistors.

Liquid-metal systems

In the session on liquid-metal systems the development status of the potassium-cooled induction generator for the SNAP 50/SPUR system was discussed. The experimental program to select and develop the journal bearing configuration for use at 24 000 r/min, the fabrication techniques employing electron beam welding, and development of liquid and vapor screw seals to separate the bearing and rotor cavity were described. In another session, A. P. Waterfall, Royal Aircraft Establishment, Farnborough, England, related results obtained with an automatic technique, utilizing a large high-speed computer for the analysis of data obtained from the re-entry vehicles of the Black Knight rocket. In a paper on an asymmetrical spinning space station, an analysis was presented of control by use of a gyroscopic element. The controller provides nutation damping and limited precession control.

In the session on electromagnetic compatibility control, an experimental evaluation was presented of a technique for predicting intrasystem interference compatibility by means of a digital computer. All electronic components are classified either as sources or receptors of electric energy. For input data taken under controlled conditions, the comparison of laboratory measurements and computed data showed very good correlation.

Work carried out in conjunction with the Falcon missile has shown that the 1-ampere 1-watt power rating for pyrotechnic devices is incomplete and has no direct relationship to threshold energy levels, and that a magnitude improvement in safety records can be gained by opening rather than short-circuiting squib leads prior to actuation. The experimental portion of the Aerospace Corporation program for the determination of radio-frequency interference at orbital altitudes was described. Historically, aircraft X-band RFI measurements were vital in the redesign of the BOMARC missile electronics and have also been used to solve certain Nike problems. Hardware for the new program includes antennas, preselectors, and crystal video logarithmic receivers. Results from the first experiment will be available later this year.

Electroexplosive devices

The first paper in the session on electroexplosive devices pointed out that the sensitivity testing methods currently being used to evaluate the increasing reliability levels are clearly being misapplied. It analyzed techniques used to estimate the reliability of "one-shot" devices, discussed current practices which can produce suspect data, and suggested remedial action involving a serious investigation of statistical models of modern items. The second paper presented the philosophy for using the pulse reflection test method for checking the characteristics of exploding bridgewire ordnance devices. The third paper showed the heat transfer analysis made of a typical ordnance header to derive the relationship between the various parameters that determine thermo-dissipative characteristics of the device. Computer solutions allow one to design hardware to have a wide range of all-fire characteristics for any designated no-fire characteristic. Stray RF fields that couple sufficient energy into electroexplosive device wiring to sensitize or detonate the device was the concern of the last paper. A thin-film thermocouple detector to evaluate safety was described. Bismuth and tellurium were used to produce a temperature element for sensing the change in bridgewire temperature. The rapid response time and sensitivity provided an accurate means of determining the effects of stray RF pickup.

Thin films were also employed in a new technique for measuring thermal radiation, described at another session. It was conceived to aid in the evaluation of the base heating experienced by rocket vehicles due to radiation from the exhaust plumes. A heat meter based on thin-film resistance thermometry functions on the basis of the sudden application of a heat pulse. Heat pulsing is accomplished by actuating a shutter interposed before the sensing element. Radioisotope techniques for the determination of heat-sublimation and surface recession during an atmospheric re-entry were the subject of another paper. Accuracies exceeding 90 percent are obtainable by the use of miniaturized nuclear counters to monitor decrease in source activity. A radioactive "line" source embedded in the heat-shield material sublimes and ablates at the same rate as the heat shield.

Human engineering

Papers in the session on human engineering ranged from recommending the composition of various teams for the management of this discipline to comply with system management contractual obligations, now being called out in new government documents, to designating the key factors for implementing on-board maintenance for manned spacecraft designed for long lifetimes in space. One paper showed that a reliable correspondence exists between the location of display stimulus and the control response in orthogonal, rectangular, and alternate arrangements. A paper from the Manned Spacecraft Center propounded the philosophy behind the design of a sensing and data collection system for the handling of low-potential physiological signals used in the determination of the astronaut's well-being. Experience gained from the Mercury program has been helpful in establishing the ground rules for the design of the medical instrumentation system for the manned Gemini missions. A high reliability factor and maintenance of signal fidelity for 14 days are required. Advances in the state of the art in electronic components and fabrication techniques have made this possible.

Abstracts of papers presented at this conference appear in the June 1965 issue of IEEE TRANSACTIONS ON AEROSPACE, vol. AS-3, no. 2. The papers are published in full in a special supplement to this issue.

Authors

Dankwart Koehler (SM) received the Dipl.-Ing. degree from the Technische Hochschule, Stuttgart, Germany, and later received a Georgia Institute of Technology World Student Fund Scholarship and Fulbright Travel Grant to study at Georgia Tech, from which he received the M.S. degree in electrical engineering in 1955. His subsequent research work in the field of relaxation effects in ferrites at the Institute for Communication Engineering, Technische Hochschule, Stuttgart, led to the degree of Doctor of Engineering in 1958.

In 1957 he joined the research laboratories of Telefunken in Ulm, Germany, where he worked on transistorized nuclear radiation detection equipment. Three years later he became an assistant professor at Georgia Tech. Since 1961 he has been with Bell Telephone Laboratories. At present he is supervisor in charge of a high-speed-circuits group. Dr. Koehler has written several published articles on relaxation effects in ferrites, nuclear radiation monitoring, high-speed circuits, and charge-control models. He is a member of Sigma Xi.

Nathan Cohn (F) received the S.B. degree in electrochemical engineering from the Massachusetts Institute of Technology in 1927, after which he joined the Leeds & Northrup Company. He became district manager of the company's Technical Division, San Francisco, in 1929 and held this post until 1936. Later he was successively district manager, Technical Division, Chicago; manager of the company's West Central Region; and manager of the Market Development Division, Philadelphia. In 1958 he was advanced to the position of vice president, technical affairs. He was appointed to his present position, senior vice president, technical affairs, in June 1965.

An internationally known authority on power systems controls, Mr. Cohn has written numerous papers and received several patents on automatic control of electric power generation in interconnected systems. He is a Fellow and past president of the Instrument Society of America. He is a director of the Foundation for Instrumentation Education and Research, and a member of the National Research Council of the National Academy of Science. He is also a member of Sigma Xi, Tau Beta Pi, and Eta Kappa Nu.

Duane O. Muhleman, Richard Goldstein, and Roland Carpenter. Biographical sketches of these authors appear on page 98 of the October issue.

Jan A. Rajchman (F) developed the magnetic-core memory system that is now the standard information storage device in modern computers, and is responsible for pioneering contributions to the development of the electron multiplier tube. He attended the College of Geneva, Switzerland, and the Swiss Federal Institute of Technology, from which he received the Diploma E.E. in 1934 and the Doctor of Science degree in 1938. In 1936 he joined the RCA Manufacturing Company, Camden, N.J., as a research engineer. In 1942 he was transferred to the RCA Research Laboratories in Princeton. He became associate director, Systems Research Laboratory, in 1959, and assumed his present position of director, Computer Research Laboratory, in 1961.

In 1947 Dr. Rajchman was corecipient of the Levy Medal, Franklin Institute, for his work on the betatron. He received the 1960 Morris Liebmann Memorial Award from IRE "for his contributions to the development of magnetic devices for information processing." He also is the recipient of three RCA Achievement Awards. He holds 98 U.S. patents, of which 68 are in the computer field. He is a member of American Physical Society, Association of Computing Machinery, and Sigma Xi.

Air Traffic Control

People needed in MITRE's Washington, D. C. office to provide system engineering assistance to the Federal Aviation Agency. Work areas include broad level system design, computer program operational specification, configuration management, system integration and system test planning.

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Sensor Systems

People needed to support theoretical and experimental programs on advanced radar and optical detection and tracking systems; feasibility and technique analysis, systems synthesis and performance evaluation.

Telemetry

Engineers are needed to work with telemetry and instrumentation. Particular work areas include telemetry standards, systems, and techniques for both airborne and ground applications. Experience should include design or analysis of telemetry systems as well as modulation theory, RF techniques and receiving and transmitting antenna systems.

Range Data Transmission

Engineers are needed to work on range data transmission. Particular work areas include digital data transmission systems analysis and testing. Experience with switching systems, modulation and information theory, and coding is desired.

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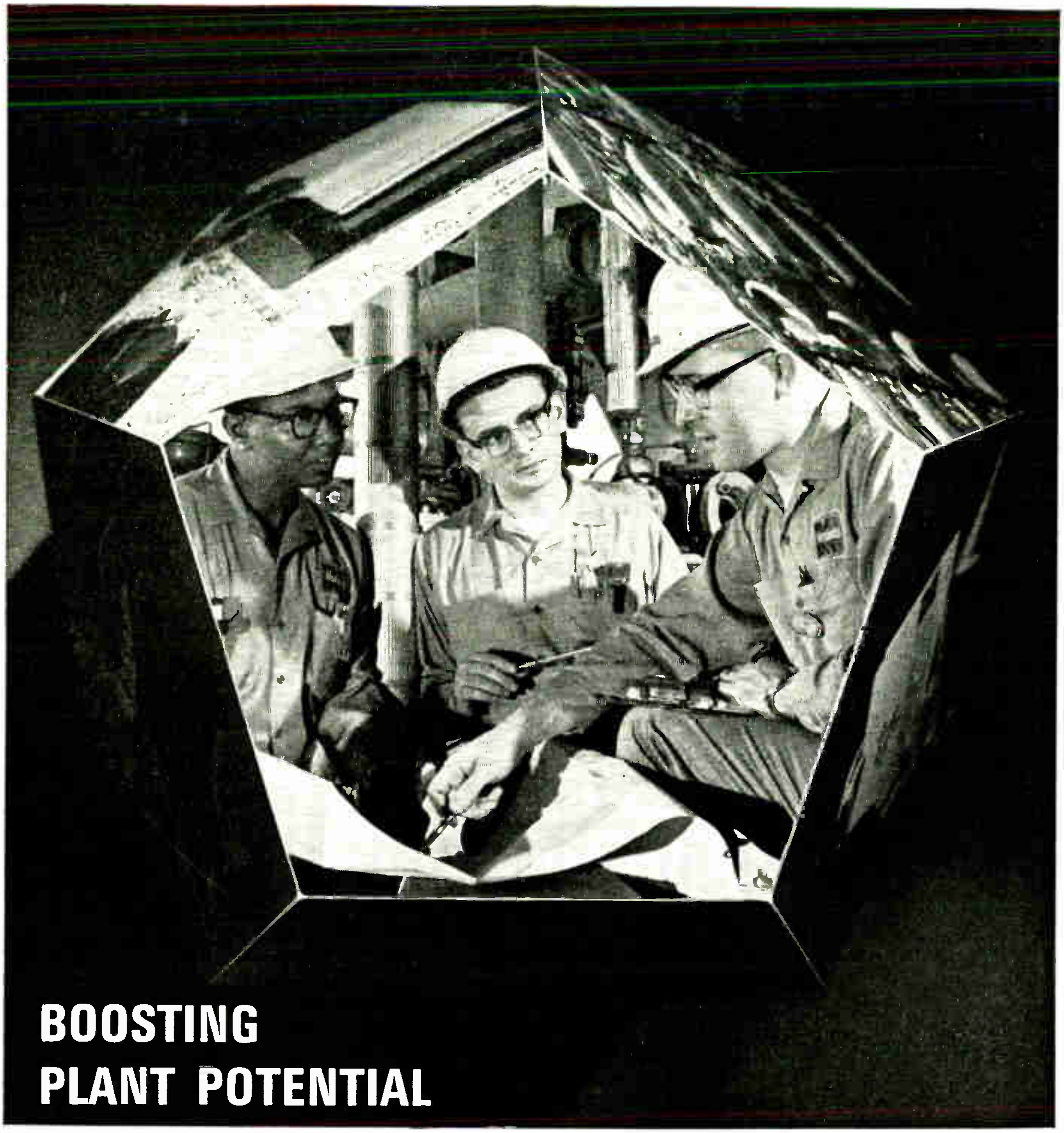

News of the IEEE

calendar
people
obituaries

18th Annual Conference and Exhibit on Engineering in Medicine and Biology slated

The 18th Annual Conference and Exhibit on Engineering in Medicine and Biology will be held in Philadelphia at the Sheraton Hotel from November 10 to 12. The meeting is cosponsored by IEEE, through its Group on Bio-Medical Electronics, and the Instrument Society of America, with the participation of the American Society of Mechanical Engineers.

The objective of the conference is to contribute to the further advancement of the interdisciplinary area between the engineering, medical, and biological sciences, both from an applied and basic standpoint. It will comprise tutorial papers in selected areas of current interest in biomedical engineering, special sessions, contributed papers, informal discussion sessions in the evenings, and commercial and scientific exhibits. Chairmen of the special sessions were invited to select leaders in the fields to present current work.

The registration fee prior to the conference will be $8, and at the conference, $10. Students will pay $5, those attending one day, $5, and wives of registrants may attend free of charge.

Tutorial sessions will be given prior to the regular morning sessions. The tentative program of tutorial sessions follows:

Hemodynamics. *A. Noordergraaf, Moore School, Univ. of Pa.* (Wednesday, 9:00 a.m.)
Physics of Electrical Transmission in Nerves. *J. W. Moore, Duke Univ.* (Wednesday, 9:00 a.m.; Thursday, 8:30 a.m.; Friday, 8:30 a.m.)
The Mechanics and Energetics of Muscle Contraction. *R. E. Davies, School of Veterinary Medicine, Univ. of Pa.* (Wednesday, 9:00 a.m.; Friday 8:30 a.m.)
Integrated Electronic Structures. *J. W. Lathrop, Tex. Instr.* (Wednesday, 9:00 a.m.)
Design Criteria for Heart Function Support Devices. *A. Kantrowitz, Maimonides Hospital; A. Kantrowitz, Avco Corp.* (Thursday, 8:30 a.m.)
Mathematical Analysis of Electrophysiological Data from Single Neurons. *G. L. Gerstein, Univ. of Pa.* (Thursday, 8:30 a.m.)
Excitation—Contraction Coupling. *Alexander Sandow, Inst. for Muscle Disease* (Thursday, 8:30 a.m.)
Vision Under Weak Illumination. *Albert Rose, RCA Labs.* (Thursday, 8:30 a.m.)
Oneiromancy in Cardiovascular Instrumentation. *R. F. Rushmer, Cardiovascular Instrumentation Program, Univ. of Wash.* (Friday, 8:30 a.m.)
Field Effect Devices. *Richard Lee, Siliconix* (Friday, 8:30 a.m.)

The evening workshops, which are informal discussion groups, will be held on Wednesday and Thursday, November 10 and 11, starting at 8:30 p.m. Workshop topics may include:

1. Modeling the Cardiovascular System
2. Impedance Measurement of Biological System
3. Patient Monitoring
4. ECG and UCG
5. Applications of Ultrasound to Diagnosis
6. Ultrasonic Image Converters
7. Integrated Circuits and New Devices
8. Electrical Measurements in Single Nerve Cells
9. Computer Simulation
10. Analysis of Dico Mole Samples
11. Pattern Recognition
12. Artificial Kidney Techniques
13. Computer–Data Interfaces
14. Models of Nervous Activity
15. Measurements of Eye Movements
16. Artificial Membranes

The principal speaker at the Thursday evening banquet will be L. T. Terry, formerly Surgeon General of the Public Health Service and now vice president for medical affairs, University of Pennsylvania.

Laboratories of institutions in the area which will be open to visitors include: The Johnson Foundation for Biophysics and Physical Biochemistry, University of Pennsylvania; Department of Biomedical Engineering, Moore School of Electrical Engineering, University of Pennsylvania; Research Institute of the Presbyterian Hospital; Biomedical Engineering Laboratory of the Drexel Institute of Technology.

The tentative program of contributed papers and special sessions follows:

WEDNESDAY, NOVEMBER 10
10:20 a.m. Sessions

Hemodynamics—I

Chairman: G. O. Barnett
Wave Propagation in the Arterial Tree.* *D. McDonald, Presbyterian Hospital, Philadelphia*
A Method of Determining the Nature of Wave Propagation in Arteries.* *U. Gessner, D. H. Frederick, Johns Hopkins Univ. Medical School*
Preliminary Report on Longitudinal Tethering of the Aorta.* *D. J. Patel, D. L. Fry, Natl. Heart Inst.*
Pulse Contour Changes in Carotid and Vertebral Arterial Systems. *W. A. Himwich, H. A. Spurgeon, Galesburg State Res. Hospital*
The Pattern of Blood Flow in the Pulmonary Veins of the Dog. *E. Morkin, R. Skalak, A. P. Fishman, Columbia Univ., Coll. of Physicians and Surgeons, and School of Engg. and Mines*
Continuous Measurement of Left Ventricular Volume in the Canine Heart. *M. E. Sanmardo, C. M. Philips, J. C. Davila, Temple Univ. Medical Center*

Physiological Control Systems—I

Chairman: D. G. Fleming
Modulation Transfer Function from Spatial Resolution of the Human Visual System. *A. S. Patel, Elec. Engg. Dept., Northwestern Univ.*
Intensity as a Parameter of the Eye Movement Control Center. *L. L. Wheeless, Jr., G. H. Cohen, R. M. Boynton, Bausch & Lomb and Univ. of Rochester*
A Mathematical Model for the Neck Receptors—Ocular Reflex. *J. L. Meiry, Dept. of Aeronautics and Astronautics, M.I.T.*
Some Oculomotor Studies. *G. H. Bowman III, D. G. Fleming, G. W. Vossius, H. S. Davis, J. G. Fraser, Case Inst. of Tech. and Western Reserve Medical School*
The Human Operator as a Piecewise Linear Control System. *H. H. Sun, Drexel Inst. of Tech.*
Electromagnetic Analysis of Modes in Retinal Cones. *G. Biernson, A. V. Snyder, Sylvania Electronics Systems*

Radiological Instrumentation

Chairman: J. Hale
The Tetrascanner: A New Device for Detecting Brain Tumors. *G. C. Riggle, F. O. Anderson, H. D. Chalifoux, Biomedical Engg. Inst. Branch, N.I.H.*
Digital Radioisotopic Scan Recording Unit. *B. Kawin, R. Whiting, VA Hospital and Digitronics*
A Biomedical Cyclotron. *A. A. Fleischer, Cyclotron Corp.*
Miniature Thermoluminescent Dosimetry for Applications in Medicine and Biology. *S. J.*

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*Indicates papers solicited by A. Noordergraaf

Malsky, B. Roswit, C. G. Amato, C. B. Reid, C. Spreckels, B. Reid, Bronx VA Hospital and Manhattan Coll.

Peak Pulse Measuring Instrument for Use with Ionization Chamber Dosimeters. *N. C. Hoitink, E. M. Sheen, Pacific Northwest Lab., Battelle Memorial Inst.*

Heat Transfer (special session)

Chairman: J. D. Hardy

Skin and Subcutaneous Temperature Changes During Exposure to Intense Thermal Radiation.† *J. A. J. Stolwijk, J. D. Hardy, J. B. Pierce Foundation Lab.*

Chronic Deficits in Temperature Regulation Produced in Cats by Preoptic Lesions and the Injection of y-OH-Sodium Butyrate into the Preoptic Region.† *R. D. Squires, F. H. Jacobson, Aerospace Medical Res. Dept. U.S. Naval Air Dev. Center*

Heat Production in Fresh Water Turtles.† *D. C. Jackson, K. Schmidt-Nielsen, Dept. of Zoology, Duke Univ.*

Radiometric Measurement of the Temperature of Human Skin.† *W. C. Kaufman, J. C. Pittman, Aerospace Medical Res. Lab., Wright-Patterson AFB*

The Average Body Temperature Computer. *P. Sprawls, Jr., E. C. Peirce II, W. B. Miller, Emory Univ. School of Medicine*

Digital Computer Simulation of Finger Cooling in Man. *J. J. Powers, R. F. Goldman, Military Ergonomics Lab., U.S. Army Res. Inst. of Environmental Medicine*

Electric and Thermodynamic Properties of Biological Systems

Chairman: H. P. Schwan

Electrode Polarization Impedance: Limits of Linearity. *H. P. Schwan, J. G. Maczuk, Moore School of Elec. Engg., Univ. of Pa.*

A Microwave Null Method for the Measurement of Complex Dielectric Constant of Liquid Samples. *B. E. Pennock, H. P. Schwan, Moore School of Elec. Engg., Univ. of Pa.*

Potassium and Sodium Uptake in Vascular Smooth Muscle. *G. Karreman, A. W. Jones, Bockus Res. Inst., Univ. of Pa.*

Comparison of Vibration Potentials and Electrical Properties Between Bovine Serum Albumin and an Associated Colloid, Sodium Lauryl Sulfate in Water. *R. B. Beard, Biomedical Engg., Drexel Inst. of Tech.; S. Takashima, Moore School of Elec. Engg., Univ. of Pa.*

The Use of Pulsed Nuclear Magnetic Resonance Techniques for Studying Biological Systems. *T. C. Pilkington, L. T. Bumgardner, K. D. Straub, Duke Univ.*

Models of Mesomorphic Liquid Phases. *P. D. Edmonds, D. A. Orr, Moore School of Elec. Engg., Univ. of Pa.*

2:00 p.m. Sessions

Hemodynamics—II

Chairman: D. A. McDonald

Vascular Dimensions from Artery to Vein in the Living Animal.* *M. P. Wiedeman, Dept. of Physiol., Temple Univ.*

The Static Elastic Behavior of Excised Arteries. *E. C. Tickner, Itek Corp.*

Input Impedance and Wave Transmissions in a Randomly Branching Assembly of Elastic Tubes.* *M. G. Taylor, Dept. of Physiol., Univ. of Sydney*

A Delay Line Model of the Human Pulmonary Circulation.* *G. H. Pollack, A. Noordergraaf, Moore School of Elec. Engg., Univ. of Pa.*

Derivation of Oscillatory Arterial Blood Flow by Analog Solution of the Navier-Stokes Equation. *I. T. Gabe, M. R. C. Cardiovas. Res. Group, Postgraduate Medical School, London*

Comparison of an Electrical Model of the Human Systemic Arterial Tree with Measurements in Humans.* *N. Westerhof, U. Gessner, Georgetown Univ. Medical School and Johns Hopkins Medical School*

Some Aspects of the Theory of Models of the Arterial and Venous System.* *M. Rodenbeck, Inst. fur Biophysik, Karl-Marx-Universitat, Leipzig*

Wave Propagation in a Viscous Liquid Contained in a Stretched Elastic Tube.* *H. B. Atabeck, H. S. Lew, Dept. of Space Science and Applied Physics, Catholic Univ. of Amer.*

A Nonlinear, Nonuniform, Distributed Parameter Representation of the Aorta. *W. Welkowitz, M. Ferdman, S. Fich, Dept. of Elec. Engg., Rutgers Univ.*

Sensory Processing & Control—I

Chairman: J. H. Milsum

Neural Dynamics of Vestibular Transduction. *M. G. Jones, J. H. Milsum, McGill Univ.*

Spontaneous Neural Activity in a Pacemaker Ganglion. *J. Connor, Northwestern Univ.*

Energy Analysis of Evoked Response Data. *M. F. Eisenberg, Univ. of Fla.*

A Study of Carotid Sinus Control of Sympathetic Discharge. *E. Geller, P. Kezdi, J. E. Jacobs, Cox Coronary Heart Inst. and Northwestern Univ.*

Precision Measurements of "Simultaneous" EEG Discharges by Computer Methods. *R. Cohn, H. Leader, U.S. Naval Hospital and U.S. Pub. Health Serv.*

Electrophysiological Correlates in Human Stereotactic Surgery. *A. Sances, Jr., S. J. Larson, Marquette Univ. and Wood VA Hospital*

Space-Angles in Opthalmologic Surgery. *T. A. Wells, E. H. Harris, J. H. Allen, Tulane Univ.*

Automatic Ray Tracing of the Optical System of the Eye. *G. C. Cheng, Natl. Biomedical Res. Foundation*

Artificial Internal Organs

Chairman: L. W. Bluemle, Jr.

Hemolysis Rates for Blood Flow in Pipes. *K. A. Yarborough, L. F. Mockros, Northwestern Univ.*

Mathematical Analysis and Optimization of a Compact Low-Cost Pumpless System for Hemodialysis (DIALUNG). *W. G. Esmond, M. Strauch, H. Clark, Univ. of Md.*

Design of an Automatic Central Dialysate System for Chronic Hemodialysis. *E. A. Pecker, H. M. Hanish, Bio. Systems*

The Design of an Artificial Kidney Center. *H. D. Metz, Biomedical Engg. and Instr. Branch, Div. of Res. Services, Natl. Inst. of Health, Pub. Health Serv.*

Biventricular Cardiac Assistance. *T. Kolobow, G. G. Vurek, P. Blume, R. L. Bowman, Lab. of Tech. Dev., Natl. Heart Inst.*

Ventricular Compression for Cardiac Support. *S. Furman, A. Denize, R. A. Wallace, T. Stern, Montefiore Hospital*

Pneumatic Cycling System for Surgically Implanted Myocardian Augmentation Devices. *V. W. Bolie, T. C. Kirstein, Autonetics Res. and Engg. Div.*

The Mechanics of a Collapsing Tube Heart Pump. *M. Weissman, L. Mockros, Biomedical Engg. Center*

Hydraulic Control of an Artificial Heart. *A. Rogers, K. R. Williams, L. B. Morris, Univ. of Pa.*

A Control System for an Artificial Heart. *C. S. Swift, N. R. Cholvin, H. H. Erickson, Coll. of Engg. and Veterinary Medicine, Iowa State Univ. of Science and Tech.*

Instrumentation—I

Chairman: R. L. Bowman

Direct Measurement of Operative Temperature by a Globe Thermometer with a High-Temperature Source of Radiant Heat. *A. P. Gagge, John B. Pierce Foundation Lab.*

A Low-Light-Level Microspectrophotometer. *R. J. Zdrojkowski, R. D. Forsberg, Carnegie Inst. of Tech.*

Automatic Thermospectrophotometer. *T. D. Hutson, Lawrence Radiation Lab., Univ. of Calif.*

Micro-Manipulator Design. *W. R. Daniel, W. R. Baker, Jr., Vanderbilt Univ.*

Microhydraulic Stimulator. *D. G. Kilpatrick, consultant, Bala-Cynwyd, Pa.*

A Rapid Response Continuous Flow Blood pH Measuring Unit. *R. Gelfand, M. Reivich, C. J. Lambertsen, Dept. of Pharmacology, Univ. of Pa.*

A Method for the Study of the Mechanical Properties of Tendon. *D. Ellis, F. A. Melichar, N. J. Rapport, Univ. of Mich. Medical Center*

Isometric Hand Pressure Device. *J. L. Cockrell, B. G. Douglas, J. C. Moore, W. J. Nelson, Univ. of Mich. Medical Center*

Jaw Motion Plotter. *L. I. Suckle, J. M. Benjamin, Jr., Bionic Instr.*

Photoelectric Recording of the Motion of the Human Tympanic Membrane. *J. G. Jako, K. R. Jenner, Harvard Univ. Dept. of Otolaryngology and Donner Elec.*

Ultrasound in Diagnosis (special session)

Chairmen: J. M. Reid and C. R. Joyner

On the Origin of the "Midline" Echo in Sonoencephalography. *C. C. Grossman, Lab. of Electroencephalography and Diagnostic Ultrasound, Presbyterian Univ. Hospital*

Intracranial Pulsations as Measured by Ultrasound. *W. M. McKinney, W. S. Avant, F. L. Thurstone, B. Pou, Depts. of Neurology and Biomedical Engg., Bowman Gray School of Medicine*

Recent Results with an Ultrasonic Immersion Brain Scanner. *D. M. Makow, D. L. McRae, Natl. Res. Council, Div. of Applied Physics, and Montreal Neurological Inst.*

Compound C Scanning of Biologic Tissue Using Focused Ultrasound. *F. L. Thurstone, Bowman Gray School of Medicine*

The Performance Characteristics of an Ultrasound Microscope. *J. E. Jacobs, V. R. Ulbrich, Bio-Medical Engg. Center, Tech. Inst., Northwestern Univ.*

Applications of Transcutaneous Doppler Flowmeters. *R. F. Rushmer, D. W. Baker, H. F. Stegall, E. A. McCutcheon, Cardiovascular Instr. Program, Univ. of Wash.*

Doppler Ultrasonic Monitoring of the Fetal Heart. *J. S. Hitt, F. L. DaParma, Carnegie Inst. of Tech. and Mercy Hospital, Pittsburgh*

Sonic and Ultrasonic Recordings in Cardiac Diagnosis. *B. Kingsley, B. L. Segal, A. J. Kaspar, Hahnemann Medical Coll. and Hospital*

Acoustic Properties of the Mitral Valve. *J. M. Reid, C. R. Joyner, Moore School, Univ. of Pa.*

8:00 p.m. Research in Biomedical Engineering Training (special session)

Chairman: J. E. Jacobs

Analysis of Firing Patterns in Medullary Respiratory Neurons. *T. L. Parrot, D. G. Fleming, Case Inst. of Tech.*

A Nonlinear Analytical Arterial Model for Pulsatic Flow. *D. C. Wiggert, Dept. of Civil Engg., Univ. of Mich.*

A Transfer Function for the Baroreceptors of the Carotid Sinus. *J. W. Spickler, Northwestern Univ.; Paul Kezdi, Cox Coronary Heart Inst.*

Nonlinear Analysis: Higher Order Kernels of Pupil System. *Allen Sandberg, Lawrence Stark, Presbyterian-St. Luke's Hospital and Univ. of Ill. Coll. of Engg.*

Interdisciplinary Research in a Biomedical Engineering Program. *H. H. Sun, Biomedical Engg., Drexel Inst. of Tech.*

Research in the Biomedical Engineering Program at the University of Pennsylvania. *H. P. Schwan, D. B. Geselowitz, Moore School of Elec. Engg., Univ. of Pa.*

Undergraduate Bioengineering Education?

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†Indicates papers solicited by J. D. Hardy

*Indicates papers solicited by A. Noordergraaf

R. M. Arthur, Bioengineering Committee, Rose Polytech. Inst.

THURSDAY, NOVEMBER 11
10:00 a.m. Sessions

Hemodynamics—III

Chairman: A. Noordergraaf

Mathematical Models of Muscle Contraction.* *J. F. Buoncristiani, F. S. Grodins, Northwestern Univ.*

A Physical Approach to Cardiovascular Function.* *J. Beneken, Inst. of Medical Physics, T.N.O., Utrecht, Holland*

Analog Simulation of Left Heart and Arterial Dynamics. *D. E. Dick, V. C. Rideout, Dept. of Elec. Engg., Univ. of Wis.*

Analysis of Certain Hemodynamic Effects of an Artificial Ventricle. *R. T. Jones, A. R. Kantrowitz, Avco-Everett Res. Lab.*

The Evaluation of Right Ventricular Function Based on Hemodynamic Variables.* *J. Melbin, School of Veterinary Medicine; Electro-Medical Labs.; and Moore School of Elec. Engg., Univ. of Pa.*

The Vascular Waterfall.* *S. Permutt, Johns Hopkins Univ.*

Sensory Processing and Control—II

Chairman: H. H. Sun

A Neuron-Glial Cell Model Deduced from Neurological and Psychological Considerations. *R. J. Swallow, Purdue Univ.*

On the Measure of Absolute Refractoriness and Action Current in Nerve Cells. *F. A. Roberge, Dept. of Physiol., Univ. of Montreal*

Mathematical Description of Electroretinograms Obtained During Anoxia. *S. Buckser, B. W. Brown, Carnegie Inst. of Tech. and Biological Sciences Computation Center, Univ. of Chicago*

Interpretation of Rheoencephalographic Waveforms. *M. M. Drossman, K. Lifshitz, Rockland State Hospital and Polytech. Inst. of Brooklyn*

Simulation on the Formation of Sensory Cells Distribution. *M. Kubo, S. Watanabe, Central Res. Lab., Tokyo Shibaura Elec. Co.*

A Synaptic Equivalent with Controlled Weighting Factors. *R. A. Gruenke, J. R. Mundie, Jr., Biodynamics and Bionics Div., Aerospace Medical Res. Labs., Wright-Patterson AFB*

Respiration

Chairman: R. E. Forster

Respiratory Response to Sinusoidal Variations of Inspired CO_2 in Resting Man. *P. J. Stoll, Dept. of Elec. Engg., Dept. of Physiol. and Biophysics, Univ. of Wash.*

Evaluation of the Respiratory Flow-Volume Loop Technic. *D. W. Dery, E. Hendler, Aerospace Crew Equipment Lab., Naval Air Engg. Center*

Dynamic Airway Resistance Measurement by Plethysmography. *E. A. Wilkes, E. H. Chester, C. B. Payne, Jr., Case Inst. of Tech., Western Reserve Univ., and Cleveland VA Hospital*

A Simulation of Respiratory Mechanical Dynamics. *R. W. Jodat, J. D. Horgan, R. L. Lange, Coll. of Engg. and School of Medicine, Marquette Univ.*

An Analog Computer Program and Associated Circuitry for Ventrilatory Calculations. *H. T. Milhorn, Jr., Univ. of Miss. Medical Center*

Scaling of Respiratory Variables in Mammals. *W. R. Stahl, Oreg. Regional Primate Res. Center*

Electrocardiography—I

Chairman: R. Plonsey

Quadrupole Properties of a Normal Human Electrocardiogram. *D. B. Geselowitz, S. A. Briller, H. L. Gelernter, J. C. Swihart, M. A. K. Angell, Univ. of Pa. and IBM*

EKG Boundary Potentials in Conductive Models of the Human Torso. *L. Frederio, J. Grayzel, Elec. Res. Labs. and Columbia Univ.*

Computer Simulation of the Human Electrocardiogram and Vectorcardiogram. *C. R. Collier, M. E. Barber, Loma Linda Univ.*

Mathematical Model of the Total Body ECG with a Realistic External Torso Boundary. *R. H. Selvester, Ranchos Los Amigos Hospital and Loma Linda Univ.*

Correlation Between Body Surface Potential Distribution and Ventricular Excitation. *R. Barr, T. C. Pilkington, J. P. Boineau, M. S. Spach, Duke Univ. Medical Center*

Theoretical Basis for a New Vector Lead System. *C. V. Nelson, Maine Medical Center*

The Representation of the Electrocardiogram in the Phase Plane. *E. K. Franke, J. R. Braunstein, Univ. of Cincinnati*

Telemetry and Implanted Materials

Chairman: O. L. Franklin

Silicone Rubber Insulation for Subdermally Implanted Electronic Devices. *J. L. Boone, Dow Corning Center for Aid to Medical Res.*

The Interface Between Aluminum Bonded to Dental Enamel with Ultrasonic Energy. *R. Hoffman, L. Gross, Waldemar Medical Res. Foundation*

Carrier and Subcarrier Oscillators for Implanted Transmitters. *R. Rader, K. Griswold, Univ. of So. Calif. School of Medicine*

A Micropower Transmitter for Temperature Measurements. *T. B. Fryer, NASA Ames Res. Center*

An Implant Telemetry System for the Measurement of Internal Strain. *W. M. Ko, C. J. Slabinski, E. T. Yon, Case Inst. of Tech.*

An Electronic Method for Telemetering Cough. *H. Salomon, M. Shapiro, VA Hospital*

Measurement of Intra-arterial Pressure and Other Physiologic Variables in the Ambulatory Human with VHF Telemetry. *G. A. Bradfute, Jr., J. L. Wright, R. Burns, Cardio-Pulmonary Lab., Baptist Memorial Hospital*

2:00 p.m. Sessions

Hemodynamics—IV

Chairman: E. O. Attinger

Autoregulation in Circulation.* *A. C. Guyton, J. R. Walker, O. Carrier, J. M. Ross, Univ. of Miss. School of Medicine*

Computer Simulation of the Blood Pressure Control of Heart Period.* *P. G. Katona, Res. Lab. of Elec., M.I.T.; G. O. Barnett, Lab. of Computer Science, Mass. General Hospital; W. D. Jackson, Amer. Heart Assoc.*

System Analysis of Cardiovascular Functions, Their Regulation and Control by the Nervous, Endocrine, and Renal Systems.* *F. M. Attinger, G. M. Fischer, A. Fronek, A. W. Jones, G. Karreman, J. G. Llaurado, L. H. Peterson, G. D. Webster, C. N. Weygandt, J. Zabara, Bockus Res. Inst. and Moore School of Elec. Engg., Univ. of Pa.*

Carotid Sinus Baroreceptors and Ventricular Function.* *M. N. Levy, P. Martin, H. Zieske, St. Vincent Charity Hospital and Case Inst. of Tech.*

On the Regulatory Function of Unidirectional Rate Sensitivity in the Cardiovascular System.* *M. Clynes, Rockland State Hospital*

Signal Analysis of Externally Measured Carotid Artery Pressures. *D. R. Carlson, Kirtland AFB; D. E. Rathbone, F. W. Kroetz, Univ. of Pittsburgh*

A Method for the Determination of the Physical Characteristics of the Human Arterial System.* *R. Altman, U. Gressner, P. C. Luchsinger, VA Hospital, Georgetown Univ. School of Medicine, and Johns Hopkins Medical School*

ULF-BCG Discrimination of Coronary Heart Disease.* *S. A. Talbot, Johns Hopkins Medical School*

Probabilistic Models of the Spike Activity of Single Neurons (special session)

Chairman: T. F. Weiss

A Stochastic Model of the Repetitive Activity of Neurons.‡ *C. D. Geisler, J. M. Goldberg, Univ. of Wis. and Univ. of Chicago*

A Model for Retinal Ganglion Cell Firing.‡ *L. A. Bickling, Johns Hopkins Univ.*

A Markov Process Model for Neuron Behavior in the Interspike Interval.‡ *W. H. Calvin, C. F. Stevens, Univ. of Wash. School of Medicine*

Automatic Reduction and Analysis of Intercellular Neural-Electric Responses.‡ *F. F. Hiltz, Johns Hopkins Univ.*

Statistical Properties of Spontaneously Occurring Synaptic Potentials in Cat Spinal Motoneuron.‡ *T. G. Smith, Jr., M.I.T.*

Markov-Chain Models of Neuronal Activity.‡ *G. P. Moore, U.C.L.A.; D. H. Perkel, Rand Corp.; J. P. Segundo, U.C.L.A.*

Correlation Analysis of Impulse Trains of Neurons of the Cochlear Nucleus.‡ *L. J. Viernstein, R. G. Grossman, Johns Hopkins Univ. and Univ. of Texas*

A Statistical Analysis of the Firing Pattern of Primary Auditory Neurons.‡ *P. R. Gray, Res. Lab. of Elec., M.I.T.*

Some Parameters of Spontaneous Neural Activity. *W. B. Adams, E. J. Kletsky, Lab. of Sensory Communication, Syracuse Univ.*

Control of the Heart and Other Muscles

Chairman: R. E. Davies

The Theoretical Determination of the Intercellular Bridge Resistance Between Smooth Muscle Cells. *F. Koide, Dept. of Physiol., Univ. of Iowa*

Smooth Muscle Contraction. *J. Persichetti, Drexel Inst. of Tech.*

An Electrokinematic Theory of Muscle Contraction. *N. B. Ingels, Jr., N. P. Thompson, Palo Alto Medical Res. Foundation and Stanford Univ.*

Investigation of the Mechanism of Contratile Motion. *W. R. Baker, Jr., H. B. Johnston, Jr., J. C. Buckett, Bio-Medical Engg. Lab., Vanderbilt School of Engg.*

Digital Simulation for Biomedical System Studies. *R. D. Brennan, R. N. Linebarger, IBM*

A Comparison of Two Models of the Human Heart Rate Control System. *R. C. Dorf, J. L. Unmack, Dept. of Elec. Engg., Univ. of Santa Clara*

An Equivalent Circuit for Pacemaker Electrodes Implanted in the Human Epicardium. *D. Jaron, D. B. Geselowitz, S. A. Briller, Univ. of Pa.*

Closed Chest Ventricular Defibrillation Using Undirectional Triangular and Trapezoidal Waveforms. *G. A. Rahmoeller, J. C. Schuder, Dept. of Surgery, Univ. of Mo.; H. Stoeckle, Dept. of Pediatrics, Univ. of Mo.*

Quantized Spectrogram Portrayal and Pattern Matching Techniques in Heart Sound Analysis. *L. G. Kersta, Bell Tel. Labs.; M. L. Schwartz, N.J. Coll. of Medicine and Dentistry*

Measuring the Viscoelastic Properties of the Intact Human Finger. *D. H. Thomas, Drexel Inst. of Tech.*

Electrocardiography—II

Chairman: S. A. Briller

Computer Program for Automatic Electrocardiographic Diagnosis. *J. R. Whiteman, J. B. Calatayud, P. A. Gorman, R. J. Dobrow, C. A. Caceres, Div. of Chronic Diseases, Pub. Health Serv., and George Wash. Univ. Hospital*

EKG Arrhythmia Detection and Classification Using a Digital Computer. *J. T. Lynch, G. O. Barnetth, Mass. General Hospital, M.I.T., and Amer. Heart Assoc.*

Computer Analysis of the Pediatric Vectorcardiogram. *M. R. Behrer, Wash. Univ.*

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* Indicates papers solicited by A. Noordergraaf

‡ Indicates papers solicited by T. F. Weiss