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MEASUREMENTS SECTION

A STORAGE SYSTEM FOR USE WITH BINARY-DIGITAL COMPUTING MACHINES

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SUMMARY

The requirement for digital computing machines of large storage capacity has led to the development of a storage system in which the digits are represented by a charge pattern on the screen of a cathode-ray tube. Initial tests have been confined to commercial tubes. Short-term memory of the order of 0·2 sec is provided by the insulating properties of the screen material. Long-term memory is obtained by regenerating the charge pattern at a frequency greater than 5 c/s. The regeneration makes accurate stabilization of the position of the charge pattern on the c.r. tube unnecessary.

The properties required of a storage system, and its operation as part of a machine, are stated. If such a machine were operated in the series mode, an instruction would be set up and obeyed in 600 μsec.

(1) INTRODUCTION

Proposals for the construction of electronic digital computing machines have resulted in a demand for a new type of storage system. In order to establish a background against which the particular storage system described in the present paper may be set, the introductory Section of the paper includes a description of the system of numbers to be used in proposed computing machines, the electronic representation of this system, and a statement of the properties required by a storage system.

(1.1) The Binary System of Numbers

The problem of electronic digital computing from the engineering standpoint, lies primarily in the construction of suitable electronic devices having the same number of states as the number of possible values of a digit, so that a one-to-one correspondence may be established between each state of the device and each value of the digit. The number of values which a digit may take depends, of course, on the system of numbers used in the machine, and it follows that it is advantageous to choose a system which can be represented electrically with ease and economy. For these reasons the binary system of numbers has become popular in recent plans for electronic digital computing machines,[1,2] although in the past the decimal system has been used.[3,4]

Systems of numbers may be derived from the common series:

$$a_{n-1}b^{n-1} + \ldots + \ldots + a_1b^1 + a_0b^0$$

which represents all integers with n significant figures. The decimal system, for example, is obtained if $b = 10$, and the a's are allowed any one of the values between, and including, 0 and 9. In the binary system $b = 2$ and a is either 0 or 1. The decimal number 19, say, is then $1 \times 2^4 + 0 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 1 \times 2^0$ in the binary scale, which can be written 10011 with the least significant figure placed on the right.

The decimal, or binary, point is on the immediate right of the term a_0b^0. The series can be continued to the right as follows:

$$a_{-1}b^{-1} + a_{-2}b^{-2} + \ldots + a_{-m}b^{-m}$$

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(1.2) Electronic Representation of the Binary System

In the binary system only two values are possible for a, so that any two-state electronic device may be used to represent a binary digit. Examples of such devices are a variety of flip-flop circuits, the difference in level of two d.c. or a.c. voltages, the presence or absence of a video or r.f. pulse, and the device described in the paper, namely the presence or absence of a stored charge on the inner surface of a c.r.t. screen. As a digit is moved to different parts of the machine during computation, its representation will change, so that at one time or another during a computation it will have adopted several of these possible forms.

If a piece of information (a number, say) is represented by k digits, the electronic quantities, corresponding to the digits, may exist either sequentially on one channel, one of the k time periods being assigned to each digit, or simultaneously on k channels, one channel being assigned to each digit. The two methods of operation, which are called series[2] and parallel,[1] respectively, are shown at (*a*) and (*b*) in Fig. 1, the binary

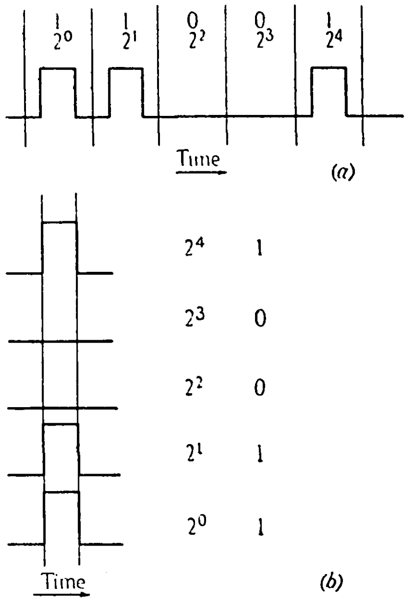

Fig. 1.—Series and parallel representation.
(*a*) Series: pulse train on a single channel.
(*b*) Parallel: pulse on five channels.

equivalent of the number 19 being used as an example. In the Figure video pulses are used for digital representation, and at Fig. 1(*a*) the least significant figure is placed on the left, so that time can be shown increasing from left to right in the conventional manner.

Information may be represented "dynamically" by pulses, which only exist transiently, or "statically" by d.c. coupled flip-flop circuits, which retain the information until they are purposely reset to a standard condition. Dynamic information may be converted into static information by, for example, applying the pulses shown at (*b*) to five d.c. coupled flip-flop circuits. The set of flip-flop circuits is called a "staticisor."

(1.3) Required Properties of a Storage System

It should be stated at once that a computing machine cannot "think." It follows that the first step in setting up a problem on a machine is to sub-divide it into a sequence of simple arithmetic or logical operations externally (i.e. outside the machine), and construct a "table of instructions." Each instruction in the table will, in general, require that an elementary operation be performed on, or by, a number, i.e. a number will be moved from one "address" of the machine to another. To every address a digit combination will be assigned, so that an instruction consists of two digit combinations, and is indistinguishable from a number in appearance. Instructions and numbers, which are collectively termed "words," are therefore similar, the only difference between them being their function in the machine.

Since all the words applicable to a problem cannot be introduced into the machine simultaneously, they must be "remembered" during the loading period, and, until used, during the solution. Further, temporary "memory" of some type must be provided during each elementary computing operation. The storage system provides this memory property of the machine.

The general opinion of mathematicians is that it will be necessary to store approximately $3 \cdot 2 \times 10^5$ binary digits, in the form of 10^4 words, with 32 digits per word.

If the two-valve flip-flop circuit were used, $6 \cdot 4 \times 10^5$ thermionic valves would be required, which is clearly impracticable from the points of view of size, cost and probable reliability of the equipment. Even in smaller machines the use of flip-flop circuits would defeat, to some extent, the purpose of the change from decimal to binary representation, since decimal representation by ring counters in a machine of similar capacity would require only three times more valves; and against this would have to be set the expense of the conversion from the decimal to the binary system, and vice versa when a binary machine is used.

Recently developed two-state devices, which are far less complex than existing two- or ten-state devices, are the main justification for the change from decimal to binary representation. Further, they make digital computing machines with large storage capacity a practical proposition.

Sufficient attention has been given to the memory property to indicate that it is of primary importance, but in order to make practical use of a store it must also be possible to insert, extract or erase the remembered information. The insertion of information into a store has been called "writing." The extraction of information from a store, "reading," does not imply that the information is erased from a store, since it may be required at a later time. "Erasing," of course, implies that information is erased from a store, but in its preferable form it is really a superseding process in that a word may be written into an occupied address, deleting the word already there. This property increases the effective capacity of a store, since new information, such as partial answers, may be written over information which has been used, without an intermediate erasure process.

To summarize, a store must have the following properties:

(*a*) It must be possible to write a word quickly into any address, such writing superseding any word already present at that address.

(*b*) The words at all addresses not being written in must be remembered indefinitely, changes occurring only as the result of a definite writing process; errors of 1 digit per million would be fatal.

(*c*) It must be possible to read the word in any address quickly without erasing it, or any other word.

(*d*) It must be possible to write into or read from any address with absolute certainty. Reading from or writing into an adjacent address in error, even if it occurred only once in a million times, would be a serious disadvantage.

(*e*) The store must be capable of holding a very large number of words (about 10^4) each comprising a number of digits, which are either 0's or 1's.

For (*a*) and (*c*) the significance of "quickly" is related to the time-scale upon which the machine as a whole is to work. The longest operation of frequent occurrence is multiplication. If this process occupies, say, 5 millisec writing and reading should occupy less than, say, 1 millisec, otherwise the computation will be seriously retarded.

The paper describes an attempt to meet these requirements using charge storage on a cathode-ray-tube (c.r.t.) screen as the memory mechanism.

(2) PHYSICAL BASIS OF THE STORAGE SYSTEM

Before describing the mechanism of digit storage, the arrangement of digits on the storage surface will first be mentioned. The digits are represented by charge distributions which exist on small areas of a c.r.t. screen, the charge distributions being arranged in the form of a two-dimensional array. This array is produced by a television type of raster, in which the digits of a line, and the lines of the raster, are scanned sequentially, each digit corresponding with a "picture element." Typical displays are shown in Fig. 2, which illustrates the appearance of the c.r.t.

(*a*)

(*b*)

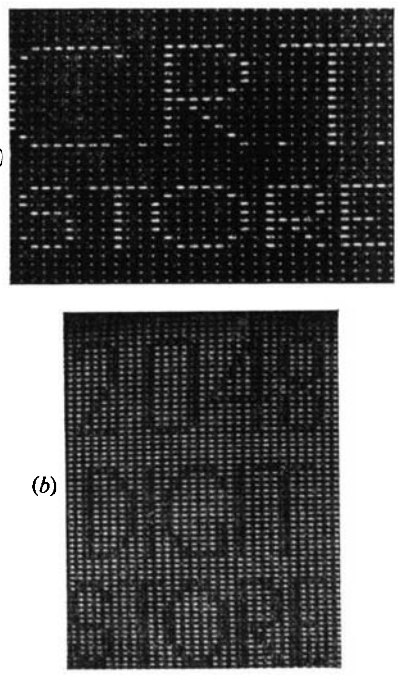

Fig. 2.—C.R.T. displays.

(*a*) 1 024 digits.
(*b*) 2 048 digits.

face when storage is in progress. In Fig. 2(*a*) there are 32 lines each of 32 digits. Each digit may have one of two forms as indicated by the pattern shown stored. A "signal" or "pick-up" plate, consisting of a sheet of metal foil, or gauze, external to the c.r. tube is closely attached to the face of the tube (see Fig. 3). Each area of the screen is therefore capacitance coupled into a

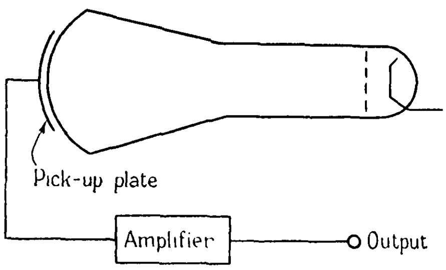

Fig. 3.—Detection of signals.

common channel, as in the iconoscope. This method of detecting changes of charge on an insulating surface has also been used to determine the secondary emission ratio of insulators using pulse technique.[5]

Having formed a general picture of the representation of digits by a two-dimensional array of suitably charged areas, attention will now be confined to the small area of the screen corresponding with a single digit. The potential distributions existing on this area with different types of electron bombardment, and the resulting video signals that are obtained from the pick-up plate are described below. References to literature[6,7] on the subject of charge storage have been included.

(2.1) Equipment

The voltage level of the video signals is increased by connecting the pick-up plate to the input of a suitable amplifier, as shown in Fig. 3. The equivalent input circuit of the amplifier is shown in Fig. 4(*a*) where i_s represents the signal current due to electrons

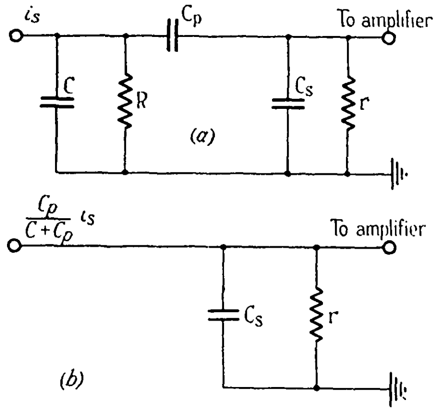

Fig. 4.—Amplifier input circuit.

arriving at and leaving the screen surface; C_p, the capacitance of the bombarded area of the screen to the pick-up plate; C, the capacitance of the bombarded area other than that to the pick-up plate; C_s, the remaining stray capacitances to earth; r, the input resistance of the amplifier; and R, the ohmic resistance due to the fact that the screen material is not a perfect insulator. The leakage time constant $(C_p + C)R$ is known to be of the order of 0·2 sec, while very approximate values for $(C_p + C)$ and R are 0·002 $\mu\mu$F and 10^8 megohms respectively. The time constant $C_s r$ is less than 0·1 μsec and r is approximately 1 000 ohms. Since $R \gg r$, the signal voltage developed across r is substantially unaffected by R, which is therefore neglected. The pick-up plate current appropriate to i_s and flowing through C_p is very nearly $C_p i_s/(C + C_p)$, so that the input circuit may be reduced to that shown in Fig. 4(*b*), the final signal voltage being $C_p r i_s/(C + C_p)$. The amplifier, which is fully described in Appendix 9.1 has a bandwidth of 2 Mc/s, and may be regarded as a resistance of 100 MΩ. The voltage output from the amplifier is, then, 1 volt per hundredth of a microamp of current flowing to, or from, the pick-up plate. There is no phase reversal in the amplifier, and conventional current flowing from the pick-up plate to the amplifier gives a positive output voltage.

It should be noted that this equipment can only detect rates of change of surface charge on the c.r.t. screen, so that the following descriptions of potential distribution on the screen are qualitative. The absolute value of these distributions is not of primary importance to the final storage system.

(2.2) Potential Distribution with Steady Single Spot

In a c.r. tube which has its deflector plates, internal conductive coating, and first and third anodes all connected to earth potential, and its grid, cathode and focus electrodes connected in a normal manner with respect to a negative potential (say − 2 000 volts), the inner surface of the screen will also be at earth potential, because it is in contact by leakage resistance with the internal conductive coating. This assumes that no beam current has been present for some time. Now in the types of commercial c.r. tube investigated (CV1097 and CV1131), the relation between secondary emission ratio of the screen material and primary electron velocity is of the form shown in Fig. 5.[8]

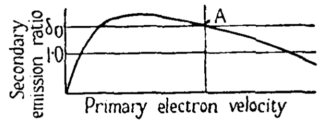

Fig. 5.—Secondary emission ratio as a function of primary electron velocity.

At points of operation such as A, the secondary emission ratio δ_0 is greater than unity. This is true for all primary velocities in the range 1 000 volts to 3 000 volts at least. It follows that if, operating under such conditions, the electron beam is switched on and falls steadily on a single spot on the c.r.t. screen, the number of secondary electrons leaving the spot and moving towards the electrode assembly, will exceed the number of primary electrons arriving at the spot. The resulting net loss of negative charge causes the potential of the bombarded spot to become positive, and its potential is then higher than that of any electrode in the tube. Later secondary electrons will therefore be ejected into a retarding electric field, and those which have emission velocities below that corresponding with the potential of the spot will be returned to the screen. The electrons with low emission velocities will, in fact, return to the spot; those with higher velocities, repelled by other electrons, will have time to acquire an additional component of velocity parallel to the screen surface and will return to the immediate vicinity of the spot. Experiments indicate that, for times of bombardment less than 400 μsec, the screen is substantially unaffected at distances greater than a spot diameter from the centre of the spot. If the effective secondary current is defined as that caused by secondary electrons which leave the spot, and are not returned to it by the retarding field, the effect of the retarding field will be to reduce the effective secondary emission ratio δ. The potential of the spot will, in fact, rise to a value E_0, thought to be about three volts,[6] such that the retarding field causes the effective secondary emission ratio to be unity. E_0 can be interpreted in terms of the velocity distribution of the secondary electrons,[9] typically indicated in Fig. 6 as that point to the right of which the number of secondary electrons per unit time equals the primary current I_p. The potential of the spot will now remain constant at E_0, but the longer the spot is bombarded the larger is the affected area around it. The potential distribution on the screen is summarized in

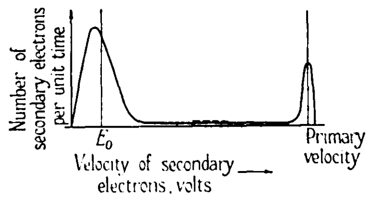

Fig. 6.—Velocity distribution of secondary electrons.

Fig. 7 in which increasing positive potential is plotted in the direction of the arrow, so that, using the analogy of gravitational field, electrons may be said to "fall" towards regions of positive

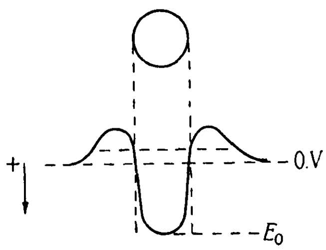

Fig. 7.—Potential distribution with a single spot—a "well."

potential. The depression in the distribution has been termed a "well."

The time taken to establish the potential E_0 depends on the capacitance per unit area of the screen, the current density of the beam, the secondary emission ratio and the velocity distribution of the secondary electrons. It follows that, with a given c.r. tube, the time taken is inversely proportional to the current density. Defocusing at constant beam-current, to double the spot diameter, will increase the time scale by four, whilst doubling the beam current, with constant spot size will halve the time scale. The spot capacitance appears to be charged exponentially towards E_0 as shown in Fig. 8(a), and the electron beam may be regarded

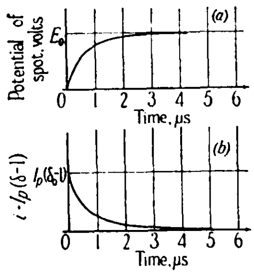

Fig. 8.—Charging of a bombarded spot to equilibrium potential.

as an ohmic resistance to the first order of approximation, the time constant formed by the spot capacitance and beam resistance being of the order of 1 μsec or less. The net current i flowing to the spot is therefore of the form shown in Fig. 8(b), rising to an initial value $I_p(\delta_0 - 1)$ corresponding with the secondary emission ratio δ_0, and falling approximately in an exponential manner to zero as the effective secondary emission ratio, δ, approaches unity. The area under the curve is the charge required to raise the spot capacitance through E_0 volts, and is therefore proportional to spot area. Since the capacitance of the spot is almost entirely that to the pick-up plate, this current i will also flow from the pick-up plate to supply the required bound negative charge. The pick-up plate measures the rate of change of charge over the whole screen surface, and this means that the electrons which return to the screen around the spot will cause a slight reduction in the plate current. A further reduction, due to another effect, will now be described.

(2.3) Effect of Interrupting the Beam on a Single Spot

With the spot held stationary as before, let the beam current be switched on and off by applying a square waveform of frequency 1 kc/s to the control grid of the c.r. tube. When the beam is switched on for the first time, the potential distribution shown in Fig. 7 will be established on the screen surface; but, subsequently at instants of switching on the beam, substantially no change will have occurred in this distribution, because the leakage time-constant of the screen $(C_p + C)R$ is large compared with a cycle of the grid modulating waveform. It follows that only a small change in surface charge is required at these instants to maintain the potential distribution, and consequently the output voltage of the amplifier in Fig. 3 due to this change, is negligible. However, when the beam is switched on, a cloud of electrons in the secondary current, and in the beam itself, is suddenly introduced in the vicinity of the pick-up plate. This is equivalent to bringing a negative charge near to the pick-up plate, and a transient current flows to the plate to supply the required induced positive charge. The electron cloud is introduced extremely rapidly if the grid modulating square wave is sharp, and the shape and time scale of the resulting amplifier output pulse, which is negative going, will be defined entirely by the transient response of the amplifier. When the beam is switched off by the square wave, the electron cloud is suddenly removed and an equal and opposite positive pulse appears at the

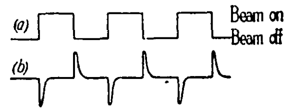

Fig. 9.—Electron cloud pulses.
(a) Grid modulating waveform.
(b) Amplifier output.

amplifier output, as shown in Fig. 9. The amplitude of these pulses increases with the beam current. The pulse waveforms are completely independent of spot size.

(2.4) Interrupted Double Spot

Two spots, as shown at 1 and 2 in Fig. 10(a), may be obtained on the tube screen by applying to a deflector plate a square

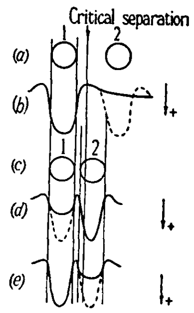

Fig. 10.—Interrupted double-spot potential distributions.

waveform having half the frequency of the grid modulating waveform, and phased relative to it as shown in Figs. 11(a) and 11(b).

If the spot is initially at 1, the potential distribution will be as previously described and is shown by the full line in Fig. 10(b). The beam is now switched off, and then switched on again in position 2, causing this spot to move rapidly positive and generating the well shown dotted.

If the separation between the spot centres is greater than a critical value (about 1·33 spot diameters), no other effect will

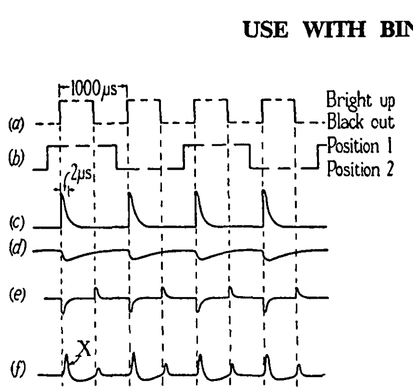

Fig. 11.—Interrupted double-spot waveforms.

(a) Grid modulating waveform.
(b) Shift waveform.
(c) Output pulse due to i_e.
(d) Output pulse due to i_r.
(e) Output pulse due to i_c.
(f) Amplifier output voltage.

occur, and at subsequent instants when the beam is switched on in the positions 1, 2, 1 and so on, this double well distribution will be maintained by insignificant changes in surface charge, making good the small leakage, as was the single well distribution described in the previous Section. Consequently the amplifier output waveform will again be as shown in Fig. 9(*b*).

If, however, the separation is less than the critical value, as shown in Fig. 10(*c*), some of the secondary electrons emitted during the excavation of well 2 will be attracted to well 1 and begin to "refill" it as at Fig. 10(*d*). The extent to which well 1 is refilled depends on the separation between the spots, and the time for which well 2 is bombarded, but it is probably never completely refilled with the times of bombardment used in practice, since the fuller it gets the less likely are secondaries from well 2 to reach it. The partial refilling of well 1 causes a potential distribution in position 1 corresponding to an effective secondary emission ratio which is greater than unity, since for unity ratio a well must be excavated to the depth E_0. Therefore when the beam is switched off, moved back to position 1, and switched on again, well 1 is rapidly re-excavated to full depth, whilst well 2 is partially refilled, producing the distribution shown at Fig. 10(*e*). This process of excavating one well and partially filling the other can be repeated indefinitely, and, if the system is symmetrical, the charge ejected from one well will equal in magnitude that deposited in the other, since the charge ejected was deposited during the previous half-cycle of operation. In fact, if the precise electrons emitted in excavating one well went immediately to the refilling of the other, no signal due to changes in surface charge would be obtained. However, the excavation process is much more rapid than the refilling process, as would be expected from the fact that whereas all emitted secondaries emerge with velocities away from the well being excavated, less than half of them have a component of velocity in the direction of the well being refilled, and many of these have velocities too great to be attracted to the well, or to any part of the screen. The amplifier output pulse, at the instant of switching on the beam, under these conditions will therefore be the sum of three pulses, namely that due to excavating a partially filled well to full depth, that due to partially filling the adjacent well, and the negative pulse induced by the introduction of the electron cloud. These effects will be considered separately.

The excavation of a partially filled well to full depth establishes an additional positive charge on the screen surface, which binds an equal and opposite negative charge on the pick-up plate. This negative charge is produced by a current i_e flowing from the pick-up plate into the amplifier input circuit, and a positive pulse is obtained at the amplifier output. The current i_e is similar to the current i of Section 2.2, but its initial value corresponds to an effective secondary emission ratio less than δ_0, since the excavated well was only partially filled. This current is also slightly modified by electrons returning to the screen around the well. With a perfect amplifier the output pulse, which is indicated at Fig. 11(*c*), would be a replica of i_e.

The partial refilling of the adjacent well reduces the positive surface charge in that position, and releases an equal and opposite bound charge from the pick-up plate. Hence a current i_r flows to the pick-up plate and a negative pulse is obtained at the output of the amplifier. The areas under the i_e and i_r waveforms are equal, because the charges involved are equal, but i_r has a longer time scale and a smaller amplitude. The i_r waveform is shown in Fig. 11(*d*), and its shape changes with beam current and spot size in the same manner as i or i_e (see Section 2.2).

The induced current i_c which flows because of the presence of the electron cloud has been described previously, and produces the output waveform shown again at Fig. 11(*e*).

The net output voltage of the amplifier is the sum of the three waveforms (*c*), (*d*) and (*e*), Fig. 11, and is typically as shown at (*f*), though many variations are possible by adjusting brilliance and focus. The net pulse at the instant of switching on the beam can, in fact, be made negative if the brilliance is sufficiently increased, but it is not proposed to run the c.r. tube in this condition.

(2.5) Separation of Double-Spot

It follows from the previous section, that both the amplitude and sign of the pulse obtained when the beam is switched on, with fixed beam current and focus, depend upon the separation of the spots. This pulse is that marked X in Fig. 11(*f*), and its amplitude change as a function of the separation between spot centres is summarized in Fig. 12. The pulse shown in Fig. 11(*e*)

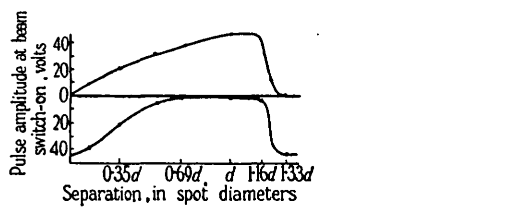

Fig. 12.—Output pulse at beam switch-on as a function of double-spot separation.

occurs about 0·2 μsec before those shown at (*c*) and (*d*), because the current pulse in the pick-up plate, which produces the output waveform (*e*), is much larger and narrower than the current pulses which produce waveforms (*c*) and (*d*), and the output of the amplifier therefore responds to it with less delay time. Hence, the pulse X is never quite zero at any value of spot separation, but may be a small negative pulse followed by a small positive pulse. For this reason the positive and negative amplitudes are plotted separately. In plotting Fig. 11 only the amplitude of the pulses immediately following the instant of beam switch-on is considered. The negative overshoot of the pulse X due to partially refilling the adjacent well is ignored, as is the positive pulse contributed by waveform (*e*) when the beam is switched off.

Referring to Fig. 12, if the separation is zero, the conditions are identical with those for a single spot and the pulse is negative, as shown in Fig. 13(*a*). The pulses in the latter figure are tracings taken during the experiment from the face of a tube monitoring the amplifier output. As the separation is gradually increased, the negative pulse decreases in amplitude and is almost zero with a separation between centres of 0·69*d*, *d* being the diameter of the spot. During this time, the positive pulse amplitude is increasing, the waveform being as indicated in Fig. 13(*b*). The positive

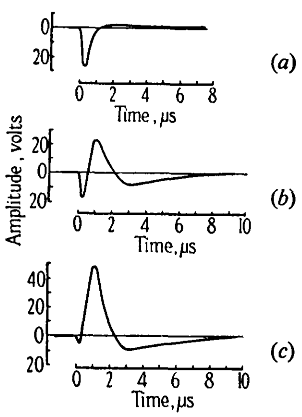

Fig. 13.—Output pulse at beam switch-on.
(a) Separation = zero or greater than $1 \cdot 33d$ (critical).
(b) Separation = $0 \cdot 35d$.
(c) Separation = d to $1 \cdot 16d$.

pulse continues to increase up to a separation d, i.e. no overlap between the spots, and then passes through a flat maximum between d and $1 \cdot 16d$. The pulse during this stage is shown in Fig. 13(c). The amplitude of the positive pulse falls off quite sharply towards zero with increased separation beyond this point, while the negative pulse amplitude increases rapidly from zero until at $1 \cdot 33d$ the output pulse is entirely negative again as at Fig. 13(a). Separations greater than $1 \cdot 33d$, which has been called critical, give no further change.

Six curves, of which Fig. 12 is typical, were taken for various fixed values of beam current and focus. The negative pulse, the amplitude of which gives a measure of beam current, was varied in amplitude from 16 volts to 42 volts; and the spot diameter was varied from 1 mm to $2\frac{1}{2}$ mm. For all the curves, the critical separation was within the limits $1 \cdot 28d$ to $1 \cdot 38d$, with the mean value $1 \cdot 33d$. The diameter of the spot was deduced from the amount of shift required to move the spots from coincidence to just touching. The difficulty of setting up the latter condition visually may involve errors up to about $\pm 5\%$.

The critical distance has, then, no absolute value. In the case of two spots of equal area, it is equal to kd, where $k = 1 \cdot 33$ for the particular screen material investigated. (The separation experiment was performed with a CV1097 type of tube.) The fact that the critical distance increases linearly with spot diameter, indicates, as might be expected, that increasing linear dimensions has no effect. For the increased separation is compensated by the increased attraction on secondary electrons by the adjacent well, due to the increased spot area.

The constant k is determined by the screen material, and will depend on the velocity distribution of the secondary electrons, for this determines the depth E_0 of a well, and therefore influences the attractive force due to the adjacent well. The secondary emission ratio, like the beam current, influences only the times taken to excavate one well and fill the adjacent well.

(3) APPLICATION TO DIGIT STORAGE

From the phenomena described above, the following statements may be made:

(a) Either of two states of charge may be left at will at a given spot on the c.r.t. face. These states are

(i) a well of full depth, by bombarding the storage spot, ceasing the bombardment and not bombarding any other spot in the vicinity, or

(ii) a partially filled well, by bombarding first a storage spot, and then another spot in the vicinity before ceasing bombardment.

(b) Charge distributions will be maintained for a time—a few tenths of a second—depending on surface leakage.

(c) Renewed bombardment [within the few tenths of a second noted under (b)] of the storage spot will give, at the instant of recommencing bombardment, a negative signal from the amplifier in case (a) (i), or a positive signal in case (a) (ii).

(d) Bombardment of spots displaced by more than $1 \cdot 33$ spot diameters from a given spot has no influence on the potential distribution at that spot.

Item (a) above indicates a mechanism of writing a digit on a storage spot, and item (c) a mechanism of reading it. From (b) it is clear that the inherent storage time is inadequate. This can be overcome by arranging that each stored digit is read and re-written well within the inherent storage time, thus giving a new start to the stored charge with all the leakage compensated. This "regeneration" process completely eliminates the commonly quoted objection to digit storage by charge distribution, that leakage will lead to "spreading" and mutual interference between digits, it also has other advantages described later.

Item (d) is important in that it sets a limit to the closeness with which individual storage spots can be packed on the storage surface and hence influences the digit holding capacity of the store; this factor is discussed next.

(3.1) Estimated Separation and Arrangement of Storage Elements

Since each storage unit of the type outlined requires a c.r. tube, amplifier and regenerating mechanism, it is important economically to store as many digits as possible in each unit. It has been shown that bombardment of the screen at a distance of more than $1 \cdot 33d$ from a storage spot has no influence on that spot. It follows that the single storage spot considered so far can be surrounded by other storage spots, provided that the separation between spot centres is greater than $1 \cdot 33d$. For present purposes a separation of $2d$ will be assumed (see Section 5.3). Furthermore, each storage spot must also have reserved an adjacent spot which can be bombarded to perform the "filling" process. The form and magnitude of this additional area depends on the detailed arrangement of the system, but in a simple case it may be considered as a second spot spaced d from the storage spot. The whole storage element is then contained in a rectangle $d \times 2d$. Associated with each such element is a "separation area" to provide clearance from other elements. The boundary of this separation area must, for safety, be at least $\frac{1}{2}d$ away from the boundary of the storage element proper. The whole rectangle occupied by each digit is therefore $2d \times 3d$ and it follows that an estimated area of $6d^2$ is required per digit, or $0 \cdot 06$ cm^2 if $d = 1$ mm.

The screen of a c.r. tube is circular and a circular array of digits would give optimum use of the available area. This is difficult to arrange and in any case assumes complete absence of plate shadow. Accordingly a rectangular array has been chosen. A 6-in tube, which has an available area of 8 cm × 12 cm, should therefore have accommodation for 1 600 digits with the estimated allocation of $0 \cdot 06$ cm^2 per digit. Greater numbers should become possible by improvement of focus, or by increase of tube screen area with given focus.

Bearing in mind that each digit is to be regenerated at frequent intervals, necessitating continuous scan of the whole array, the method of setting out the array is to set up the digits in a series of spaced horizontal lines as in television rasters, as mentioned earlier [see Fig. 2(a)]. With this arrangement the basic requirement is regenerative storage of a number of digits on a single horizontal line, the array being developed from the line by shifting the line perpendicular to its length through $2d$ after each horizontal sweep.

Many systems derived from the properties stated in Section 3, may be used to regenerate the stored information. Five such original systems have been tested, and although, for reasons given later, it has been decided that one of these is outstanding at present, a brief outline is given of the alternatives, because, with further development, this decision will be reconsidered. The first four of these systems operate on the pulse obtained from the amplifier when the electron beam is switched on to a spot, and all use the principle that the sign of this pulse is positive or negative depending on whether an adjacent spot within the critical distance has or has not been bombarded since the storage spot was last bombarded. The fifth system operates on a slightly different principle explained later.

(3.2) System 1—Dot-Dash Display

Fig. 14(*h*) is a segment of a horizontal time-base waveform in which short periods of constant voltage alternate with longer

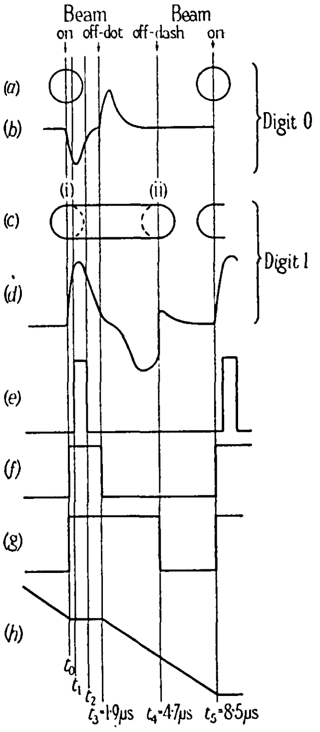

Fig. 14.—Dot-dash waveforms.

(*a*) Dot display.
(*b*) Dot waveform.
(*c*) Dash display.
(*d*) Dash waveform.
(*e*) Strobe.
(*f*) Dot brilliance waveform.
(*g*) Dash brilliance waveform.
(*h*) Time-base waveform.

periods of constant rate of change. If a repetitive waveform of this kind, containing, say, 32 such segments is used to deflect a c.r.t. spot, which is intensified only during the periods of constant voltage, by applying waveform of Fig. 14(*f*) to the control grid of the tube, then a row of 32 dots will appear on the screen. Two of these are shown at Fig. 14(*a*). If the separation of the dots is in excess of $1 \cdot 33d$, each can be used independently as a storage spot, the beam being used to operate on each one in turn. The corresponding amplifier output waveform shown at Fig. 14(*b*) goes negative at the instant of switching on the beam, as stated in Section 3[*a*(i)], since there has been no bombardment of spots in the vicinity between successive bombardments of the storage spot. If the intensifying waveform is changed to Fig. 14(*g*) the dots on the c.r. tube will change into short lines or "dashes" [see Fig. 14(*c*)]. The initial dots are spaced by about $3d$ so that the dashes may be accommodated. The amplifier output waveform is now as shown at Fig. 14(*d*). The precise nature of this waveform will be explained later, and it is necessary here to note only that the initial pulse when the beam is switched on is positive. This is in accordance with note (*a*)(ii) of Section 3, because now there has been bombardment of spots in the vicinity of the storage spot since the latter was last bombarded. This bombardment took place during the previous sweep as the spot moved away from position (i) towards position (ii) [Fig. 14(*c*)]. Dots and dashes thus correspond with states (*a*)(i) and (*a*)(ii) of Section 3 respectively and give rise to characteristic signals as defined under (*c*) in that Section. Either dot or dash may be written in at will by using either waveform (*f*) or (*g*) of Fig. 14 as an intensifying waveform. On a subsequent sweep dots will be "read" as negative output pulses and dashes as positive output pulses, irrelevant parts of the amplifier output waveform being discarded by using the "gating" waveform or strobe shown at Fig. 14(*e*).

In order to make the system regenerative it is necessary to cause dots to be re-written wherever dots are read, and dashes to be re-written wherever dashes are read. That this procedure is possible may be seen from the fact that whether a dot or a dash is to be written the intensifying waveform is the same in the time interval t_0 to t_3, whereas the amplifier output waveform has indicated which should be written well before t_3, during the strobing interval t_1 to t_2. Hence if the intensifying signal to the c.r.t. grid is fed through a gate circuit which is controlled by the strobed amplifier output in such a way that the intensification is turned off at t_3 if the control signal is negative (or zero), but is maintained until t_4 if the control signal is positive, the system will be regenerative in that it will immediately re-write everything it reads. This arrangement is shown in outline in Fig. 15. Details of a suitable gate circuit operated by the positive control signal appear in Appendix 9.2.

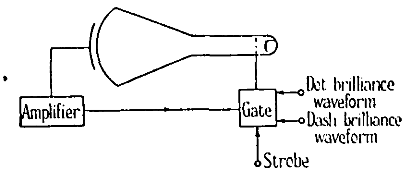

Fig. 15.—A regenerative storage system.

In practice it has been found possible to replace the special time-base waveform, Fig. 14(*h*), by a simple linear time-base, provided the duration ratio of waveforms (*g*) and (*f*) is not less than about $2 \cdot 4$ to 1, and provided also that the sweep speed is such that not more than $0 \cdot 7$ of a spot diameter is traversed during the short intensification period of $1 \cdot 9\ \mu$sec. The dots then appear as very short lines instead of true dots.

The waveform of Fig. 14(*d*) is of considerable interest and will now be analysed in some detail.

Let a horizontal line on the c.r.t. screen be produced by applying the waveform (*a*) of Fig. 16 and its paraphased form to the X plates of the tube, the grid modulating waveform being phased as at Fig. 16(*b*). Electron cloud pulses shown at Fig. 16(*c*) will of course provide a part of the amplifier output. The remainder of the output, shown at Fig. 16(*d*), is due to the following causes. When the beam is switched on initially, the positive well which is formed, is partially filled as the spot moves away from the beginning of the line. This happens in all positions previously occupied by the spot, as the spot leaves them behind, and moving trail of positive charge is formed beneath and behind the spot as indicated in Fig. 17(*b*). When the spot reaches the end of the line, the beam is switched off, the trail of

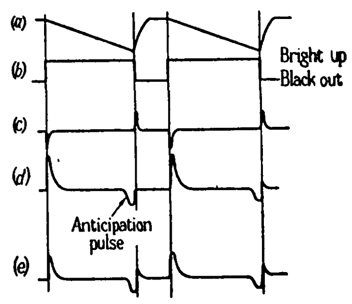

Fig. 16.—Amplifier output-pulse with a line display.

(a) Time-base waveform.
(b) Grid modulating waveform.
(c) Electron cloud pulses.
(d) Pulses due to charge on c.r.t. screen.
(e) Net amplifier output-pulses.

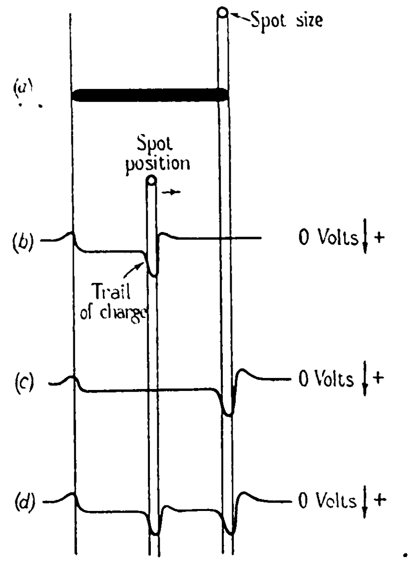

Fig. 17.—Potential distributions with a line display.

(a) Line display.
(b) Initial potential distribution: beam on.
(c) Potential distribution: beam off.
(d) Subsequent potential distribution: beam on.

charge is left on the screen, and the potential distribution is then as indicated at Fig. 17(c). Now, when the beam is switched on again at the beginning of the line, a trail of charge has to be recreated, and this causes the initial positive pulse of Fig. 16(d). Once the trail of charge is created, there is no net change of charge on the c.r.t. screen until the remanent charge at the end of the line is approached. During this period the amplifier output is zero, and the potential distribution is of the form shown in Fig. 17(d). As the spot approaches within the critical distance of the remanent charge, low-velocity secondary electrons with component velocities along the line begin to destroy the remanent charge. Since, when the beam is switched off the potential distribution must again be as in Fig. 17(c), a quantity of surface charge, equal in magnitude to the created trail of charge, is destroyed during this period. Hence a negative pulse, equal in area to the initial positive pulse, appears in the amplifier output voltage, as shown in Fig. 16(d). This negative pulse, which anticipates the cause to which it is due, namely, the switching off of the beam, has been called the "anticipation" pulse. The net output of the amplifier is the sum of the waveforms (c) and (d) of Fig. 16 and is shown at (e). If the length of the line is decreased, the waveform of Fig. 16(e) becomes the waveform of Fig. 14(d). The theoretical minimum length of the line for maximum amplitude of the initial positive pulse is such that the trail of charge is completely established before secondary electrons begin to destroy the remanent charge at the end of the line. The currents flowing from and to the pick-up plate to produce the positive and anticipation pulses, respectively, are then entirely separated in time. In practice, it is found that little loss in amplitude of the pulse occurs if the length of a dash is made such that the separation between centres of the initial and final spots, which form the lateral boundaries of the dash, is not less than $1 \cdot 7d$. With this value the positive and anticipation pulses are beginning to coalesce as shown in Fig. 18.

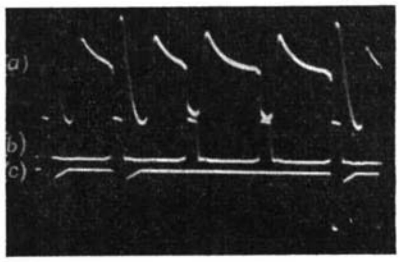

Fig. 18.—Strobing of signals.

(a) Signals.
(b) Strobe.
(c) Strobed output.

By way of example, the display, and amplifier and strobed outputs appropriate to the decimal number 19, are shown in Fig. 19 (b, c and d). In a two-state device either state may be defined as representing a "0," the other state representing a "1." In the present paper the digit will be said to be "0" when the potential distribution on the c.r.t. screen is the same as it would be if the amplifier gave zero output and the gate circuit acted appropriately.

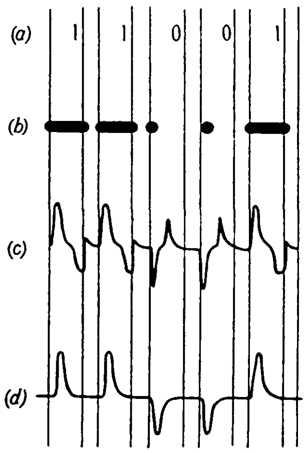

Fig. 19.—Electronic binary representation of decimal number 19.

(a) Binary. (c) Amplifier output.
(b) C.R.T. display. (d) Strobed output.

(3.3) System 2: Dash-Dot Display

This system is identical with system 1, except that the negative pulse at beam switch-on operates a suitable gate circuit instead of the positive pulse. The positive pulse now corresponds to the digit "0" and the display is a dash as shown in Fig. 20(c). The negative pulse shortens the dash to a dot, and corresponds to the digit "1."

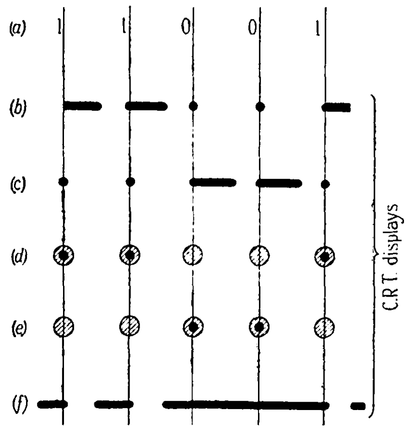

Fig. 20.—Storage-system displays.
(a) Binary. (b) Dot-dash. (c) Dash-dot. (d) Defocus-focus. (e) Focus-defocus. (f) Anticipation.

(3.4) System 3: Defocus-Focus Display

An alternative method of achieving the choice between a positive or negative indication at beam switch-on is to apply the waveform of Fig. 21(*b*) to the focus electrode A_2 of the c.r. tube.

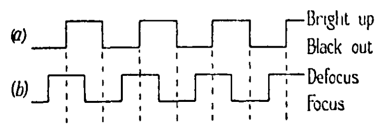

Fig. 21.—C.R.T. electrode waveforms for defocus-focus display.
(a) Grid modulating waveform.
(b) A.2 waveform.

If waveform of Fig. 21(*b*) is phased relative to the grid modulating waveform as shown, the result will be a defocused spot which suddenly becomes focused, as shown in Fig. 22(*a*).

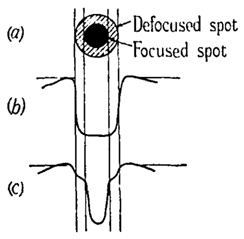

Fig. 22.—Potential distributions with focus-defocus display.
(a) Display. (b) Well 1. (c) Well 2.

When the beam is switched on for the first time, well 1 shown at Fig. 22(*b*) will, of course, be excavated by the defocused spot. However, when the spot is focused, the shaded area at Fig. 22(*a*) will be partially filled by secondary electrons, producing the potential distribution well 2 shown at Fig. 22(*c*). At subsequent instants of beam switch-on it will always be necessary to convert well 2 into well 1, and a net positive pulse will be obtained at the amplifier output. If the c.r.t. beam is switched off before it is focused, the focused spot will never be present, and the potential distribution is always well 1. Once this distribution is established, the output from the amplifier at beam switch-on will be the negative pulse due only to the introduction of the electron cloud near to the pick-up plate. The sign of the output pulse at beam switch-on is therefore positive or negative, depending on whether the spot is allowed to focus or not.

If the system is operated on the positive pulse, the gate circuit of Section 3.2 is used. The only modification is to make the time-base pause from $t = t_0$ to $t = t_4$ (Fig. 14). Horizontal separation of the digits is achieved by allowing the time-base to run down linearly from $t = t_4$ to $t = t_5$, when the beam current is always off. The spot is defocused from $t = t_0$ to $t = t_3$ and focused (or blacked out) from $t = t_3$ to $t = t_4$.

The display appropriate to the decimal number 19 is shown in Fig. 20(*d*).

(3.5) System 4: Focus-Defocus Display

If the system in the previous section is operated by the negative pulse at beam switch-on, in conjunction with the gate circuit required in Section 3.3, the display will be as shown in Fig. 20(*e*).

(3.6) System 5: Anticipation

Whenever the beam current is switched-off, a remanent charge is left on the screen, and with a moving spot, an anticipation pulse is obtained during the next time-base sweep. This gives a warning that at some "later" instant during the previous sweep, the beam was switched off. If the possible instants of switching off the beam are predetermined by a square wave applied to a gate circuit, which allows the beam to be switched off once only after an anticipation pulse has been received, then the system is regenerative. For, once established, a remanent charge will cause the beam to be switched off at the same instant of each successive sweep, and the charge will be reinstated each time. The display is indicated in Fig. 20(*f*).

(4) A COMPLETE STORAGE UNIT

Attention will now be confined to system 1, which is summarized in Figs. 14–17 and 19. The remaining systems, which operate satisfactorily on a single line of digits, have been rejected; systems 3, 4 and 5, because of the difficulty of maintaining similar conditions of focus over the whole c.r.t. screen, when many lines of digits are used; and system 2 because operation on the negative amplifier output is not as satisfactory as operation on the positive pulse.

Horizontal spacing between the digits on the tube screen is achieved by using a linear X-time-base waveform, generated as described in Appendix 9.4. Vertical spacing is achieved by using a specialized Y shift generator described in outline below, and in more detail in Appendix 9.5. Each horizontal line contains 32 digits (i.e. one word), occupies a distance of 10 cm on the c.r.t. screen, and lasts for 272 μsec. The blackout period is 34 μsec. The raster has 32 lines, and at present occupies a vertical distance of 8 cm. A 10 cm by 8 cm rectangle on the tube face therefore contains 1 024 digits or 32 words, Fig. 2 (see Section 5.3).

The type of Y-shift generation used is intimately connected with the writing, reading and timing properties of the storage. For not only is it necessary to scan the raster lines sequentially with the object of regenerating the stored information; but it is also essential to arrange that any line may be written in or read off as soon as possible after the machine has given that instruction, without waiting for that line to be scanned in the regeneration sequence. A suitable circuit is now outlined.

(4.1) Y-Shift Generator

Fig. 23 is a schematic diagram of a Y-shift generator, which produces 32 equal-step changes of potential followed by a rapid flyback. Along the top of this figure is a five-stage scale-of-two counter, each stage being triggered from the previous one; the first stage is triggered by the X time base blackout waveform. The counter output waveforms are as shown in Fig. 24(*b*–*f*). If these waveforms are added in the form $1 \times (b) + 2 \times (c) + 4$

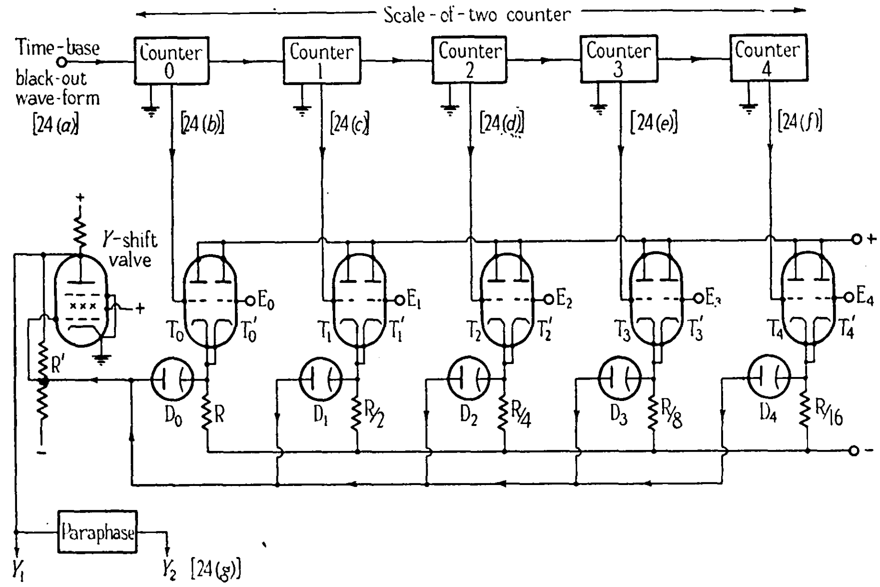

Fig. 23.—Simple Y-shift generator.

The numbers in brackets thus [24(a)] refer to the corresponding numbers of waveforms in Fig. 24.

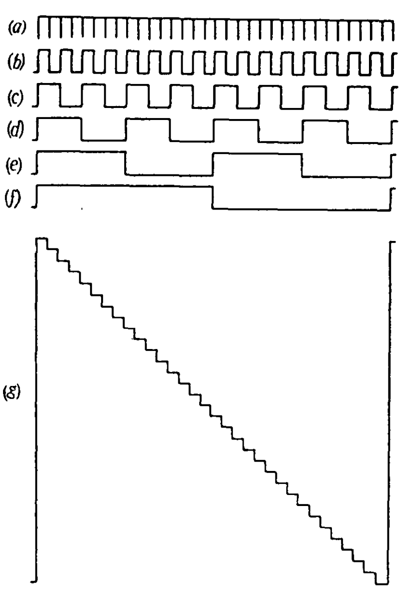

Fig. 24.—Waveforms of simple Y-shift generator.

(a) Blackout waveform.
(b) Counter 0.
(c) Counter 1.
(d) Counter 2.
(e) Counter 3.
(f) Counter 4.
(g) Y-shift (paraphase).

$\times$ (d) + 8 $\times$ (e) + 16 $\times$ (f), the desired waveform, Fig. 24(g) results. With this waveform and its paraphased version applied to the Y-plates of the c.r. tube the single line display of Section 3.1 becomes a 32-line raster. Addition in the appropriate ratios is performed by the circuit shown in Fig. 23, the operation of which is described in Appendix 9.5. It should be noted, however, that the counter waveforms, Fig. 24, (b)–(f), are used to switch careful "weighted" component shifts in and out of circuit, so that the amplitude of the counter waveforms is relatively unimportant.

A scan of this type is entirely adequate for the purpose of regenerating stored information, provided that the vertical separation of lines is adequate and the interval between scans of a given line is sufficiently short compared with the inherent memory time of the screen. It would, however, be possible to read off or write in a given line only when its turn came in the scan cycle. This disability can be eliminated by allocating alternate sweeps of the time base to "scan" and "action" phases of the system. During scan phases, the raster lines are scanned sequentially with the sole object of regenerating the stored information. During action phases any line in the raster may be chosen at will, and information read off or written in that line. With this arrangement the lines of the raster are not scanned sequentially but in the order 0*, n, 1, n, 2, n . . . 31, n,

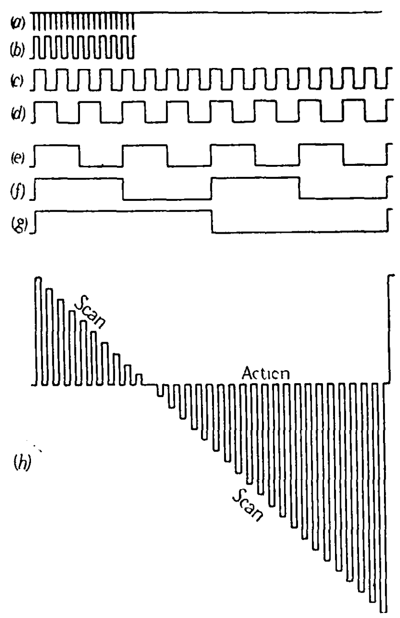

Fig. 25.—Waveforms of improved Y-shift generator.

(a) Blackout.
(b) Halver.
(c) Counter 0.
(d) Counter 1.
(e) Counter 2.
(f) Counter 3.
(g) Counter 4.
(h) Y-shift (paraphased).

0, n, 1 . . . where n is any chosen line not usually constant but varying as the computation proceeds. It is, however, shown constant in the waveform of Fig. 25(h), which illustrates the new

* The first line of the raster is called line 0 for convenience.

form of the Y-shift waveform. To produce this waveform, the blackout waveform of Fig. 25(*a*) feeds a halver, which is a scale-of-two counter yielding the waveform of Fig. 25(*b*). This waveform then operates the counter chain of Fig. 23 which delivers the waveforms of Fig. 25(*c–g*). The halver waveform also performs electronic switching operations such that during the scan phase of the halver, waveforms of Fig. 25(*c–g*) are added, appropriately "weighted," as before, but during the action phase they are superseded by five control voltages, which, operating through the same "weighting" circuits as the counter waveforms, take over control of the line scanned. Technical details of a suitable circuit will be found in Appendix 9.5. Here we need only note the importance of using a common "weighting" circuit so that line *n* during action phases exactly coincides with line *n* during scan phases.

Though it might appear at first sight that this action/scan sequence will halve the speed of calculation, in fact such is not the case, because since it applies only to the store, computation can proceed unhindered, and further, some time must be set aside for changing the five potentials selecting the action line. These potentials must not be changed whilst they are controlling the shift, or diagonal traces will be generated, but they can conveniently be changed during the scan phase.

In a machine the five control voltages would be derived from a staticisor operated by a sequential five-pulse code. In the experimental store they are in fact derived from a staticisor, but the operating pulses are coincident pulses on five separate lines and may be made positive or negative on each line by setting five switches appropriately. The pulses are obtained from the halver waveform and occur at the end of each action phase, so that the staticisor can only change its state during scan phases when it is not controlling the Y-shift.

An amplified discussion will be found in Appendix 9.5.

It should be noted at this point that although the Y-raster generator, X-time-base generator, and the circuits generating such waveforms as the strobe for the amplifier output, are essential to the operation of a single storage unit, these circuits are common to all further units. It is only necessary to repeat the c.r. tube, amplifier and gate circuit, since all the c.r. tubes and gate circuits will be operated in parallel to a common time scale. For this reason, a c.r. tube and its associated amplifier and gate circuit will be called a "storage unit."

(4.2) Experimental Input Unit

Information will eventually be introduced into the store via an input unit, which may take many forms. An experimental method of input, far too laborious to be used in practice and designed with the sole object of testing the storage unit, is as follows.

The beam is switched on 32 times during one X-time-base sweep, and with an empty store a negative pulse is obtained from the amplifier each time, the display being 32 lines of 32 dots. If a negative pulse of dash width is inserted into the gate circuit, in such a manner as to give the same effect as a positive pulse output from the amplifier (see "write" input in Fig. 32) and timed coincident with one of the instants at which the beam is switched on, then a dash appears at the corresponding point of the display and a "1" is inserted into the store. If, further, the pulse is generated during action phases only then the dash will appear only on the action line. The circuit supplying the pulses is arranged in such a manner that pressing one of 32 keys, arranged in the form of a typewriter, causes a pulse to be generated at the corresponding instant of switching on the beam. A "1" is inserted in position k of line 1, by operating the switches controlling the Y-shift staticisor so that line 1 is the action line, and then pressing key k of the typewriter. Once inserted the digit (k, 1) is regenerated, and remembered by the store indefinitely.

A "1" may be erased from the store by interrupting the regenerative loop during the time that the "1" would normally be regenerated. This is conveniently done by switching the action line into the appropriate position and applying a negative pulse to the suppressor grid of V_1 in the gate circuit (see Fig. 32). Thus, although the control grid of this valve receives the positive pulse from the amplifier, appropriate to a dash, no anode current will flow in the valve, and the display will be converted into a dot.

It follows that the typewriter unit may either write or erase a "1," and that a single pole, double-throw switch may be used to select either of these alternatives.

If the input to the gate circuit from the amplifier is connected to earth potential for a period longer than a raster period, then the store will be filled (dashes everywhere), for pulses will be applied to the control grid of V_1 during every strobe period. If, on the other hand, the output of the amplifier is disconnected from the gate circuit for a period longer than the raster period, the store will be emptied.

(5) EXPERIMENTAL RESULTS AND OPERATING DATA

It is now possible to fill or empty the store, and, by means of three control systems, namely, the insert-erase switch, the typewriter and the Y-shift staticisor, to change the state of digit (k, 1). Specific patterns, such as the one shown in Fig. 2(*a*), may therefore be written into the store, in order to test the memory of the storage unit. The pick-up plate prevents direct photography, and a monitor c.r. tube wired in parallel with the storage c.r. tube was photographed. During the initial tests many memory periods of between one and two hours were recorded.

By adding a sixth unit to the Y-shift generator a 64-line raster was produced, and the storage capacity doubled (2 048 digits). The scan frequency was then about 25 c/s. The pattern shown in Fig. 2(*b*) was written into the store, and was "remembered" for four hours before the equipment was switched off. It is interesting to note that in this time approximately $7{\cdot}5 \times 10^8$ opportunities occurred for a change in the pattern to take place, due to possible spurious pulses occurring during strobe periods. The existence of this multitude of opportunities for change may be regarded as a disadvantage of frequent regeneration. There is, however, a very great corresponding advantage. In any system where the position of a storage element is defined in terms of two multi-valued deflecting potentials (or currents), subsequent recovery of the stored information depends on accurate correspondence between geometrical position and deflecting potentials and also on accurate reproduction of the deflecting potentials themselves. Both these requirements are much more easily met when the interval between storage and recovery is very short, since long-period drifts in supply voltages, or tube sensitivity, result only in a drift of the pattern as a whole without damage to it, provided the drift between regenerations is small compared with the spot size.

The factors influencing the operating conditions used to obtain these results will now be described. It will be seen that a compromise has been made between many conflicting factors.

(5.1) Primary Electron Velocity

From Section 2.2 it follows that the third-anode voltage of the c.r. tube should be such that the primary electron velocity corresponds with a screen secondary emission ratio greater than unity. With the screens used in commercial c.r. tubes a further limitation is imposed, and this is now discussed.

The signal output from the amplifier normally produced by scanning a line on the c.r.t. screen is shown in Fig. 16(*e*). However, if the line is moved to some positions on the screen the output is as shown in Fig. 26. Disturbances of the type shown at X are caused by imperfections of the screen. It is found that

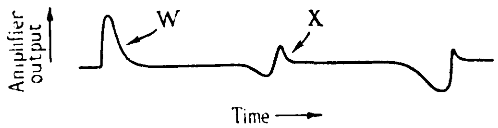

Fig. 26.—Screen imperfection signal.

the amplitude of these screen imperfection signals increases from zero to a maximum, and then decreases to zero again, as the line is moved across the c.r.t. screen through approximately one spot diameter, in the direction perpendicular to its length. The linear dimensions of the imperfections are therefore very much smaller than one spot diameter. Any explanation of the imperfection signals must take account of this fact. The imperfections themselves are probably of the following types.

First, the screen may contain small particles of carbon, which have a secondary emission ratio less than unity for all primary electron velocities. (A possible source of these particles is the internal conductive coating of the c.r. tube.) When such a particle is subjected to electron bombardment, it will receive more electrons from the primary beam than it loses by secondary emission. The particle will therefore accumulate negative charge, and it will continue to do so until its potential is approximately cathode potential. Secondly, as can be seen by the naked eye, the screen material is perforated at several points. The operative screen material at these points is glass, which, as indicated in Fig. 27, has a much lower inversion point B (about

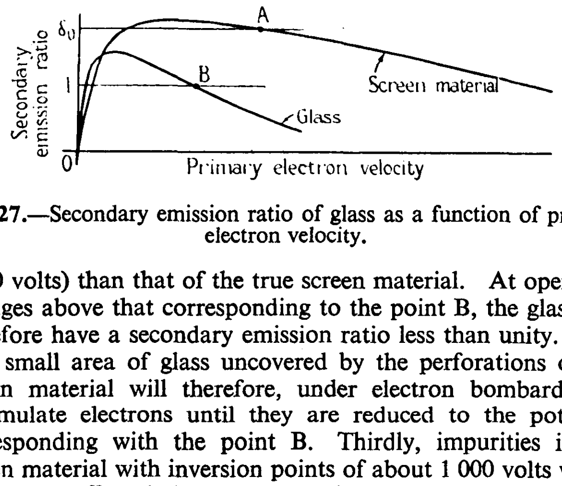

Fig. 27.—Secondary emission ratio of glass as a function of primary electron velocity.

1 000 volts) than that of the true screen material. At operating voltages above that corresponding to the point B, the glass will therefore have a secondary emission ratio less than unity. The very small area of glass uncovered by the perforations of the screen material will therefore, under electron bombardment, accumulate electrons until they are reduced to the potential corresponding with the point B. Thirdly, impurities in the screen material with inversion points of about 1 000 volts would produce an effect similar to that ascribed to glass.

In all the above cases, small regions of the screen under electron bombardment will be at potentials which are very negative with respect to the remainder of the screen if a high accelerating voltage is used. Now the operation of the storage system is based on the fact that the potential distribution formed at a region P depends on whether an adjacent region within the critical distance has, or has not, been bombarded, since P was last bombarded. If such an adjacent region has been bombarded, the potential distribution at P is changed by secondary electrons arriving at P from the bombarded point. If, however, a screen imperfection exists between P and the adjacent region, some of the secondary electrons will be prevented from reaching P by the potential barrier produced by the imperfection. P will, in fact, always tend to operate as a point which has not had bombardment in its vicinity. In the dot-dash system the effect is, therefore, that if the accelerating voltage is high and the imperfection occupies an area of the screen sufficiently large when compared with the spot area, then it is impossible to write a "1" into the store at P.

The screen imperfection signal X in Fig. 26 consists of an anticipation pulse followed immediately by the positive pulse due to re-establishing the trail of charge (see Section 3.2). This will be understood if it is remembered that, as the spot passes through the imperfection, some of the secondary electrons, which would normally return to the part of the screen behind the spot are prohibited from doing so by the created potential barrier. A remanent charge must therefore exist in front of the imperfection and this produces an anticipation pulse during the following scan. The trail of charge is partially destroyed when the anticipation pulse is created, but it is reformed when the imperfection has been passed by the spot and this reformation produces the positive pulse. It is found that if the ratio of the peak to peak amplitude of the screen imperfection signal to the amplitude of the positive signal obtained when the beam is switched on (see W in Fig. 26), is plotted as a function of the accelerating voltage applied to the primary electrons, then the result is as shown in Fig. 28.[10] As might be expected from the previous discussion,

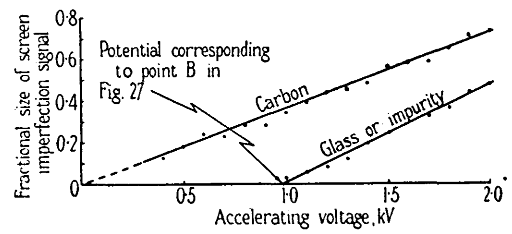

Fig. 28.—Variation of screen imperfection signals with accelerating voltage.

the imperfection signals due to glass or impurities vanish when the accelerating voltage is reduced to the value corresponding with the point B in Fig. 27, because at this voltage there is no potential barrier. The amplitude of the signals due to carbon decreases linearly as the accelerating voltage is decreased, and tends to zero as the accelerating voltage approaches zero. These results were obtained with a CV1131 type of c.r. tube, which had a soft glass envelope, and the particular imperfection signals plotted were the largest which occurred at any point of the screen. No c.r. tube has yet been found with more than one carbon type of imperfection. The number of glass or impurity imperfections with ratios greater than 0·1 (but less than 0·2) is about twenty at 1 400 volts.

With these results in mind it was decided to operate the storage c.r. tube at the comparatively low accelerating voltage of 1 400 volts. The tube was not specially selected, except that it had a hard glass* envelope, and there was a carbon imperfection in the screen. This c.r. tube, which stored the information for Fig. 2, has been used for a period of three months, and no difficulties have arisen due to screen imperfections.

(5.2) Effect of Spot Size (Focus)

The storage capacity of a single c.r. tube is determined primarily by the accuracy of focus, and its uniformity over the used area of the tube screen, it being necessary to choose less than optimum focus at the centre if bad defocusing at the corners is to be avoided. For maximum capacity, the tube should be operated at the highest possible accelerating voltage. With present screens, the imperfections limit this voltage to 1 400, and it is apparent that an attempt should be made to produce a more

* Inversion point approximately at 1 200 volts.

perfect screen, with the consequent increase in storage capacity. This is being attempted.

Although, for constant beam density, the amplitude of the positive signals obtained when the beam is turned on will decrease as the focus is improved, no difficulty is anticipated, because, as shown in Fig. 18, excellent signal/noise ratio is obtained with the present spot size (about 1 mm diameter). Loss of signal current may therefore be compensated by increased amplifier gain.

As shown in Fig. 2(*b*), 2 048 digits have been stored, the area occupied on the storage tube being 154 cm² (11 cm × 14 cm). In Fig. 2(*a*), the area occupied by 1 024 digits is 64 cm² (10 cm × 6·4 cm). The deterioration in the uniformity of focus over the larger area can be seen by the fact that for satisfactory operation—negligible interference between digit areas—the area occupied by 2 048 digits is more than twice that occupied by 1 024 digits.

(5.3) Action Line Limitation of Storage Capacity

The conception of critical distance between two adjacent spots cannot in fact be applied without reservation as it was in Section 3.1, to determine the separation required between any two charged areas of a raster for negligible mutual interference. For the net electric field at a spot under electron bombardment is no longer due to a single adjacent charged area, but to all the remaining charged areas of the raster. It follows that the required separation is greater than the critical distance previously defined, and this is particularly true for the areas comprising the edges of the raster, where the net lateral electric fields are greatest.

The method adopted to determine the required separation experimentally is to adjust the focus, and separation between areas, until the relevant positive signals obtained at any point of the raster, are not decreased by more than 5% by mutual interference, when adjacent dots are converted to dashes. It is found to be sufficient to examine areas in the corners and centre of the raster only.

Since a small amount of mutual interference between adjacent charged areas is allowed to occur, the time of bombardment of the areas becomes important, particularly when this time is only of the order of 1 μsec. (The time of bombardment of the areas is determined by the velocity with which the spot travels across the c.r.t. screen. This velocity is discussed in the next Section.) It may be seen, for instance, from Fig. 13 that, in the double-spot experiment, bombardment times less than 2 μsec produce but little filling of the adjacent well. If, then, some areas of the raster are scanned more frequently than others, more mutual interference will occur in these regions. This will happen when the store is part of a computing machine and it is necessary to read or write into the store frequently during one raster period, for under these circumstances certain lines of the raster will be scanned more often than other lines. With a 32-line raster, and the method of raster generation described in Section 4 and Appendix 9.5, it is never possible to scan a particular line more than 33 times as often as the adjacent lines. For in one raster-period this line would be scanned once during a scan period, and 32 times during action periods at most.

To determine the extra degree of separation between digit areas required to nullify this effect, the following procedure was adopted. It was arranged for the c.r. tube to be normally blacked out by halver waveform during action periods. A circuit triggered by the waveform of the last counter in the Y-shift generator, and re-triggered by halver waveform prohibited this black-out for one action period during each raster period. The action line was therefore scanned only twice as often as the remaining lines. This arrangement was used to write the information shown in Fig. 2 into the store, and provides a close approximation to having no action line whatever. The control of black-out by halver waveform was removed and the action line scanned during every action period. The extra vertical separation was then determined. It was found that when this was done the area occupied by the raster had to be increased by 20% (10 cm × 8 cm) for a 32-line raster. This is a very stringent test, because it is inconceivable that it will be necessary in practice to read or write into one particular line during 32 consecutive action periods. An increase of 20% in the area of the 64-line raster (11 cm × 17 cm) allowed any particular line to be scanned eight times only during one raster period, mainly because rapid deterioration in uniformity of focus occurred with this large raster area.

(5.4) Lateral Velocity of the Electron Beam

The time period assigned to each digit, which at present is 8·5 μsec, determines the final speed at which the computing machine will operate. This time period, which should therefore be made as small as possible, depends upon the maximum rate at which the electron beam can be allowed to move across the c.r.t. screen. It is apparent that the faster the electron beam moves, the less will be the amplitude of the positive pulse obtained when the beam is switched on at the beginning of a dash. For the amplitude of this pulse is determined by the amount of refilling of the well which occurred during the previous sweep, and the depth to which the well is excavated during the present sweep. Since, as was explained in Section 2.4, refilling requires more time than excavation, the speed of operation is limited primarily by the refilling process. Less refilling will occur as the speed is increased, because the electron beam bombards adjacent spots for less time, and the amplitude of the positive pulse therefore decreases.

An estimate of the speed at which some decrease in amplitude may be expected, can be derived from the double-spot experiment. From Fig. 12, the limits of separation between which maximum refilling of the adjacent well occurs, are seen to be d and $1 \cdot 16d$. From Fig. 13(*c*), refilling of the adjacent well is seen to be almost complete in 4 μsec at the operative value of beam current. If, therefore, the diameter of the spot is 1 mm and the spot travels at speeds greater than 0·04 mm/μsec some loss of positive pulse amplitude is expected.

As the speed is increased, the pulse obtained when the beam is switched on at the beginning of a dash changes from a positive pulse to a negative pulse via stages similar to those shown in Fig. 13 (*c*, *b*, and *a*). Fig. 29[10] in which both positive and negative amplitudes are plotted, indicates the change in the amplitude of the pulse as a function of the reciprocal of the speed with which the electron beam moves across the c.r.t. screen. The point A corresponds with the speed estimated above. If the speed is increased by a factor of ten, approximately, the point B is obtained. This is the operating point used at present and it corresponds with 8·5 μsec and 3·1-mm digit separation. If the speed is increased by a further factor of ten (4 mm/μsec), the positive pulse ceases to exist, and the output pulse is the negative pulse due to the electron cloud effect. It is, of course, impossible to operate the storage system at this last speed because the pulse obtained when the beam is switched on will always be negative independent of whether a dot or a dash is being read. However, it may prove possible to operate the system at some point between B and C, the speed corresponding with C being twice the present speed.

It should be noted that Fig. 29 holds for particular values of brilliance and focus only, the values chosen being the ones normally used in operation.

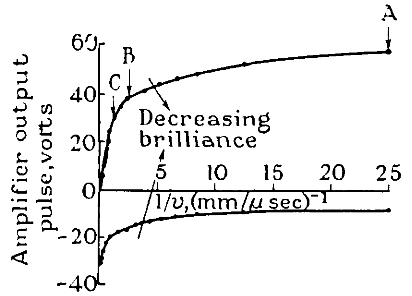

Fig. 29.—Variation with sweep velocity of pulse produced when the beam is switched on at the beginning of a dash.

(5.5) Recapitulation

Recapitulating, it must be possible to distinguish between two types of signal, which correspond to two types of stored charge distribution. The area occupied by the digit areas, and the time assigned to each digit are made as small as possible consistent with the maintenance of this distinction.

In the dot-dash system the choice is between a positive or a negative signal when the c.r.t. beam is switched on, and the amplitude of these signals depends upon factors discussed above and in Section 2.

The line of immediate future development is clear. Improvement of focus can be attacked from the normal standpoints. Final results will depend on the production of a more perfect screen, and the resultant increase in accelerating voltage. If this proves difficult, screens of the present quality, but free from carbon, deposited on some insulator (such as mica) with a higher inversion point than glass, may be successful. Higher storage capacity per c.r. tube will then be possible. When the maximum storage per tube has been obtained the required storage capacity can be built up by using the appropriate number of tubes. All tubes would be scanned synchronously, but the action line would be intensified only on the appropriate tube so that the co-ordinates of an individual stored digit becomes k, l, t, where t is the tube number.

(6) ALTERNATIVE SCANNING SYSTEMS

The scanning system so far described is most suitable for series machines in which one complete word is stored on each line. Machines designed for the parallel mode of operation require all the digits of a word to be simultaneously available on different wires. Working on a basis of 32 digits per word, 32 c.r. tubes might be used, one digit of each word occupying one space on each tube. With this arrangement, the digits occupying the 32nd space in each line would not be available for 272 μsec. This time can be reduced by splitting the scan into 8 columns of

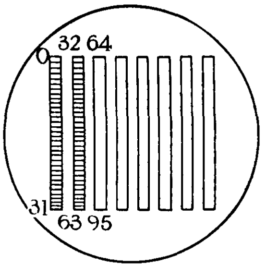

Fig. 30.—Alternative scanning arrangement.

short lines, each containing 4 digits, as shown in Fig. 30, arrangements being made to read any digit in any line at any time. This would reduce the time to obtain any digit to 34 μsec.

Alternatively, the time sweep may be abolished and replaced by a deflection signal generator which is arranged to sweep the spot discontinuously from space to space on the c.r.t face by means of appropriate X and Y voltages. Provided the deflection generator could be switched to any desired co-ordinates rapidly any digit could be recovered at any time. The appropriate co-ordinates could probably be generated with the required accuracy in about 20 μsec.

(7) CONCLUSION AND ACKNOWLEDGMENTS

It has been demonstrated that large numbers of digits can be stored on the screen of an ordinary commercial c.r. tube and that the development of special tubes for this purpose is worth pursuing and should lead to an increased storage capacity per c.r. tube.

The authors wish to acknowledge their indebtedness to the Chief Superintendent, T.R.E., for facilities provided during the research, and to Prof. M. H. A. Newman, F.R.S., and Mr. A. M. Turing, O.B.E., for much helpful discussion of the mathematical requirements of digital computer stores.

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(9) APPENDICES

(9.1) The Amplifier

Each stage of the amplifier is separately screened, and the heater and h.t. supplies are fed to each stage through suitably filtered leads to prevent h.f. oscillations. These arrangements are omitted from the circuit shown in Fig. 31.

The first three stages, which are identical, are fed back, by a resistor of 500 kΩ connected between the anode of V_3, and the grid of V_1. The feedback reduces the effect of microphony voltages in V_1 to negligible proportions, and defines the output voltage of V_3 as $0{\cdot}5i_s$ volts, if i_s is the signal current in microamperes provided by the pick-up plate. The fourth stage is controlled by its screen-grid voltage to give manual gain-control. The anode load of the fifth stage is very much greater than the input impedance of the sixth stage. Consequently, almost all the pulse current, delivered by V5, flows in the 33-kΩ feedback resistor of stage 6. Stage 6 is d.c. fedback, as shown, to provide outputs with approximate d.c. levels of either + 5 volts or − 15 volts.

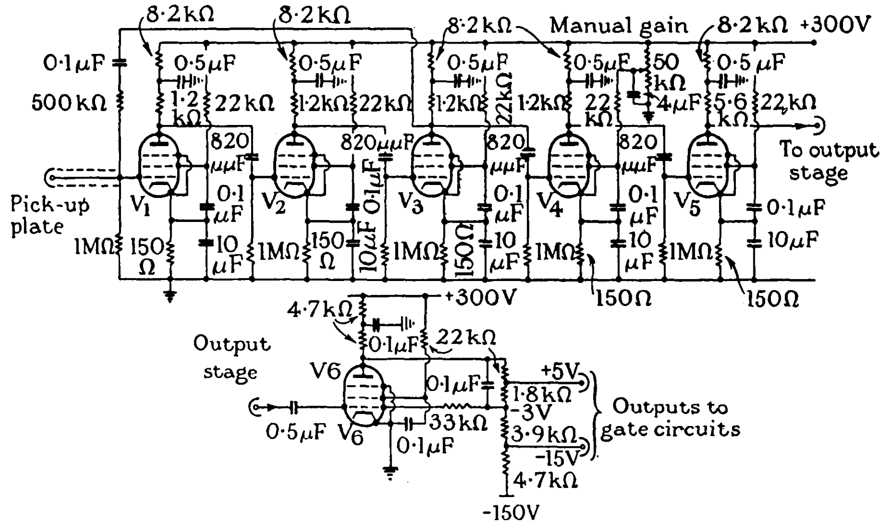

Fig. 31.—The amplifier circuit.
V_1–V_5 = CV1091. V_6 = CV173.

The voltage output of the amplifier is $100i_s$ when the manual gain is set so that the voltage gain of the last three stages is 200. The double-spot experiments were performed with this setting.

(9.2) Gate Circuit

References will be made to Fig. 32.

The effect of this circuit is to provide the grid of the c.r. tube with narrow positive pulses, to give a standard display of dots corresponding to the digit "0"; these pulses are made wider, producing a dash corresponding to the digit "1" if, and only if, the circuit receives a positive pulse from the amplifier at specified instants, the instants at which the beam is switched on.

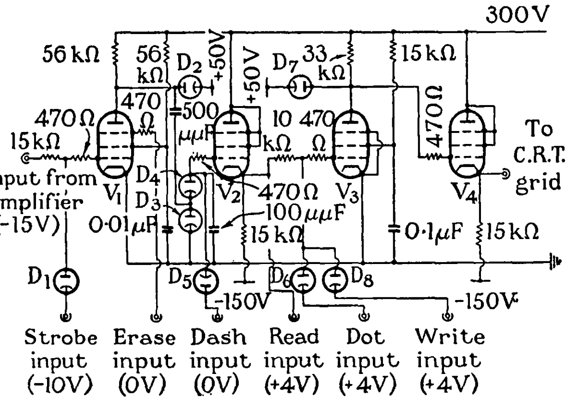

Fig. 32.—The gate circuit.
V_1–V_4 = CV1091.

The standard display is provided by narrow negative dot pulses [Fig. 33(*d*)] applied to the cathode of the diode D6, the cathode being biased positive with respect to its anode. These pulses cut off the control grid of V_3, and the anode of V_3, which was bottomed, rises quickly in voltage until caught by the diode D7 at about + 50 volts. The resultant anode waveform shown dotted at Fig. 33(*f*) is cathode followed by V_4, and applied to the c.r.t. grid via a d.c. restoring circuit, which defines the highest voltage reached by that grid, as the voltage set up on the brilliance control of the c.r. tube. Black-out of the X-time-base recovery sweeps is provided by the fact that the dot pulses are inhibited at their source during the black-out period. This is also true of the dash and strobe pulses.

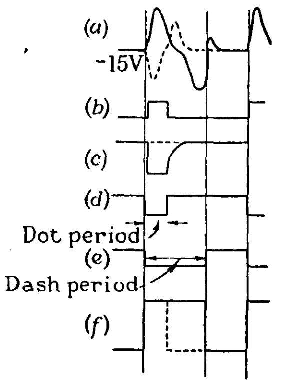

Fig. 33.—Waveforms appropriate to gate circuit.
(*a*) Amplifier output. (*b*) Strobe. (*c*) V_1 anode. (*d*) Dot waveform. (*e*) Dash waveform. (*f*) Output to c.r.t. grid.

The valves V_1 and V_2, and their associated diodes, are the true gate circuit. The amplifier output, Fig. 33(*a*), biased to − 15 volts, is fed to the grid of V_1 only during the strobe period. At all other times this is prevented by conduction of D_1. The strobe waveform is shown at Fig. 33(*b*), the strobe period being a short period immediately after the beam is switched on. There is normally no anode current in V_1, and the anode voltage is defined as + 50 volts by the diode D_2. The anode waveform Fig. 33(*c*) has a negative pulse for every positive pulse delivered by the amplifier during a strobe period. The negative pulses are cathode followed by V_2 via the diode D_4, and applied to the control grid of V_3. The upper voltage limit of the control grid of V_2 is defined as 0 volts by conduction of D_4 and D_3, and its lower limit is defined as − 15 volts, by conduction of D_5. The cathode of V_2 will therefore swing in voltage between the approximate limits + 3 volts and − 12 volts, which are sufficient to cause full anode current, or no anode current, respectively, in V_3. The condenser taken from the control grid of V_2 to earth prevents the grid changing its voltage unless it is driven. The grid will therefore remain at − 15 volts for a period, the dash period, determined by the waveform of Fig. 33(*e*) applied to the anode of D_5. It will then be driven to 0 volts and will remain there until it receives another negative pulse from the anode of V_1. Fig. 18 shows the practical equivalents of the idealized waveforms of Fig. 33 (*a*, *b* and *c*).

The action of the circuit is summarized as follows. If the display at a certain spot on the c.r. tube was previously a dot, a negative pulse will be delivered by the amplifier during the strobe period, when the spot is bombarded again. Since the control grid of V_1 is normally cut-off, the negative pulse has no effect, and the gate circuit is inoperative. A dot is therefore produced again by the dot waveform, D_6 and V_3. The corresponding waveforms are shown by the dotted lines in Fig. 33. If the display was previously a dash, a positive pulse from the amplifier gives rise to anode current in V_1. The resulting negative pulse at the anode of V_1, takes the grid of V_2 to $-$ 15 volts where it remains until driven back to 0 volts by the dash waveform acting through D_5. The grid of V_3 is therefore cut off initially by the dot waveform and held off for a dash period by the cathode of V_2, reproducing the dash display.

A convenient "read" output for the storage unit is derived from the cathode of V_2, and it takes the form of a negative pulse of dash width for each stored "1." External information, represented in this manner, can be written into the storage unit by applying it to the cathode of D_8. Each negative pulse extends a dot into a dash. When writing new information over old information, it is also necessary to convert a dash into a dot. This is achieved by applying a negative waveform to the suppressor grid of V_1, which cuts off the anode current in V_1 during the writing period, breaks the regenerative loop, and allows completely new information to be inserted via D_8.

(9.3) The Clock Circuit

The clock circuit, which produces the 8·5-μsec digit cycle, comprises an *LC* oscillator, squarer, and cathode follower. The strobe and dot and dash waveforms are produced from this square wave and fed to the gate circuits from low impedance sources.

Two phantastron circuits in series, dividing four and nine respectively, are triggered by the clock waveform. The outputs of the phantastrons are used to produce a square waveform, which is positive for 4 clock periods, and negative for 32 clock periods. This is the X-time-base black-out waveform, and it is used to control the X-time-base circuit and Y-shift generator.

The circuits used are well known, and require no detailed description.

(9.4) X Time-Base Circuit

This circuit is a Miller time-base followed by an anode-follower circuit to provide the paraphase. A linear sweep is produced starting at a potential defined by a diode.

The alternative sweep for dot-dash storage, shown in Fig. 14(*h*)

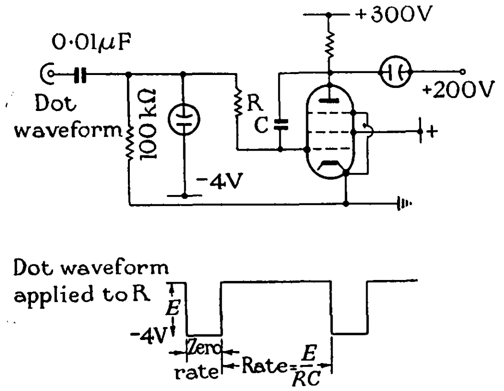

Fig. 34.—Generation of time base with pause during dot period.

pauses during the dot period. This is achieved by returning the time-base grid leak to the dot waveform and d.c. restoring the waveform with an inverted diode to a potential equal to the mean grid-potential during the sweep (Fig. 34). During the dot period no current flows in R and the rate of sweep is therefore zero. If E is the amplitude of the dot waveform the rate of sweep at all other times is E/RC.

The sweep required for focus-defocus storage pauses during the dash period, and is achieved as above by using the dash waveform instead of the dot waveform.

(9.5) Y-Shift Generator

References will be made to Fig. 23, which is a schematic diagram of the simple Y-shift generator. Along the top of this figure is the five-stage scale-of-two counter, each stage being triggered from the previous one: the first stage is triggered by the X time-base black-out waveform. Each counter n (n = 0, 1, 2, 3 or 4) is associated with a triode Tn which has a resistance $R/2^n$ in its cathode lead, and the cathode of the triode is connected via a diode Dn to the grid of a pentode called the Y-shift valve. The output of the Y-shift valve and its paraphased version* are applied to the Y-plates of the c.r. tube. The circuit is completed by triodes T'_n whose cathodes are also connected to the resistors $R/2^n$. For the moment it will be assumed that the currents in these triodes are cut off by negative voltages E_n. The outputs of the counters 0 to 4 are as shown in Fig. 24 (*b–f*), and if these are added together in the proportions 1, 2, 4, 8, 16 (i.e. 2^{n-1}) respectively, then the resultant output is the step waveform, Fig. 24(*g*). This step waveform is therefore the output voltage of the paraphase of the Y-shift valve, since each time a triode T_n is cut off by the negative going half-cycle of the waveform of counter n, a current proportional to $2^n/R$ flows into R through D_n. The Y-shift valve operates as a fed-back adding circuit,† adding contributions from $R/2^n$ whenever D_n conducts. R′ is chosen to give suitable Y-shift.

It follows from the above discussion that if the grids of the triodes T_n have negative voltages applied to them, which are sufficient to cut off the valve currents, then the line of the raster scanned by the time-base can be chosen at will by applying suitable voltages E_n to the triodes T'_n. For E_n can be chosen so that D_n either does or does not conduct (2^5 possibilities), and if D_n conducts a contribution 2^n is made to the line number. If, for example, with the convention that the first line in the raster is called line 0, it is desired to scan line 21, then E_1 and E_3 are made positive and E_0, E_2 and E_4 are made negative. Only the diodes D_0, D_2 and D_4 conduct and a Y-shift of 21 ($2^0 + 2^2 + 2^4$) units is produced. It will be observed that the line chosen by operating the triodes T'_n and the corresponding line of the raster produced by the triodes T_n are accurately the same, since they both depend on the resistors $R/2^n$ and not on the triodes involved, provided the triodes are actuated by sufficiently large potentials.

The requirement for prompt execution of an instruction by reading or writing leads to the division of the raster operation into the two phases called "scan" and "action," control being exercised by waveforms applied to the grids of the triodes T_n and T_n.

The modifications necessary to make the circuit of Fig. 23 conform to this requirement are shown in Fig. 35. Here the black-out waveform triggers a halver circuit, which, in turn, triggers the five-stage scale-of-two counter, the waveforms involved being as shown in Fig. 25 (*a–g*). The halver circuit is itself a scale-of-two counter. The halver waveform is added to each of the counter waveforms, and the resulting waveforms, Fig. 36, (*a–e*), are applied to the grids of the triodes T_n, after being

* Paraphase is by see-saw or anode-follower circuit.[11]
† Reference 11, Section 9.2.

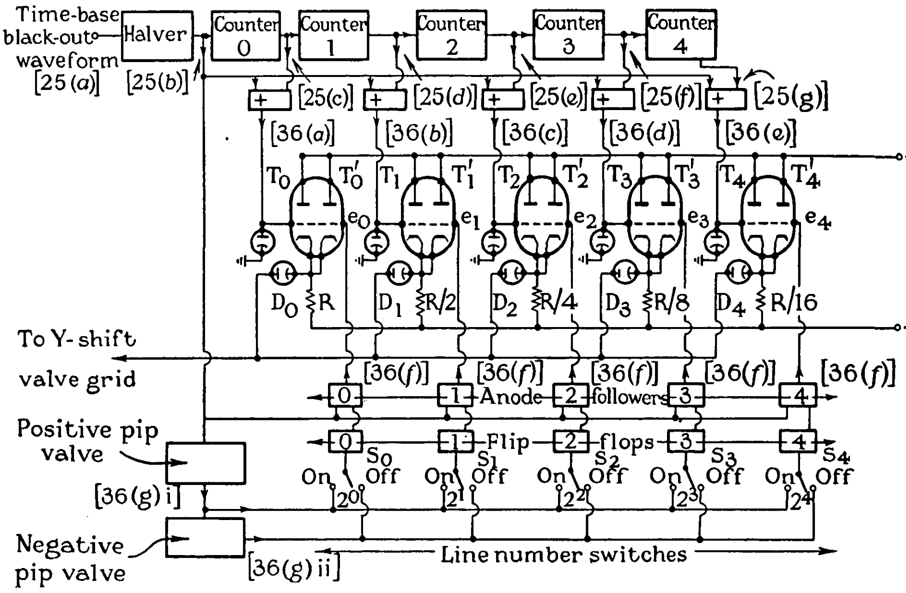

Fig. 35.—Improved Y-shift generator.

The numbers in brackets thus [25(*a*)] refer to the waveforms shown in the correspondingly numbered Figures.

d.c. restored to earth potential. In other words, the greatest voltage achieved by any of the waveforms, Fig. 36, (*a–e*), is zero volts. Further, the waveforms have sufficient amplitude to prevent current flowing in the triodes T_n except during those half cycles of the halver waveform during which they are at zero volts. Now, if it is assumed for the moment that the potentials e_n applied to the triodes T'_n are sufficiently negative to prevent current flowing in T'_n, it will be seen that during the first scan period (Fig. 36) current flows in all the triodes T_n, so that the diodes D_n do not conduct, the Y shift is zero and the electron beam of the c.r. tube scans line 0. But during the first action period no current flows in any T_n, so all D_n conduct, the Y shift is at its maximum value and line 31 is selected. During the second scan period only D_0 conducts, so that unit shift occurs and line 1 is scanned. During the following action period all the diodes D_n conduct again, so that line 31 is again selected. It will be clear from such considerations that the whole raster of 32 lines will be scanned sequentially, line 31 being the action line between scans of adjacent lines. The Y-shift waveform will be as shown at Fig. 25(*h*) except that here line 10 is being selected. In order to select line 10, say, appropriate positive (T'_n conducting) and negative (T'_n non-conducting) voltages, e_n, should be applied

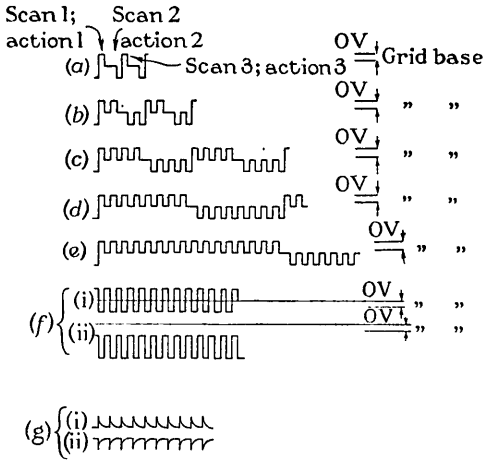

Fig. 36

(*a*) Halver + counter 0. (*b*) Halver + counter 1. (*c*) Halver + counter 2. (*d*) Halver + counter 3. (*e*) Halver + counter 4. (*f*) Halver, phase 2 (H_n). (*g*) Staticisor trigger pips.

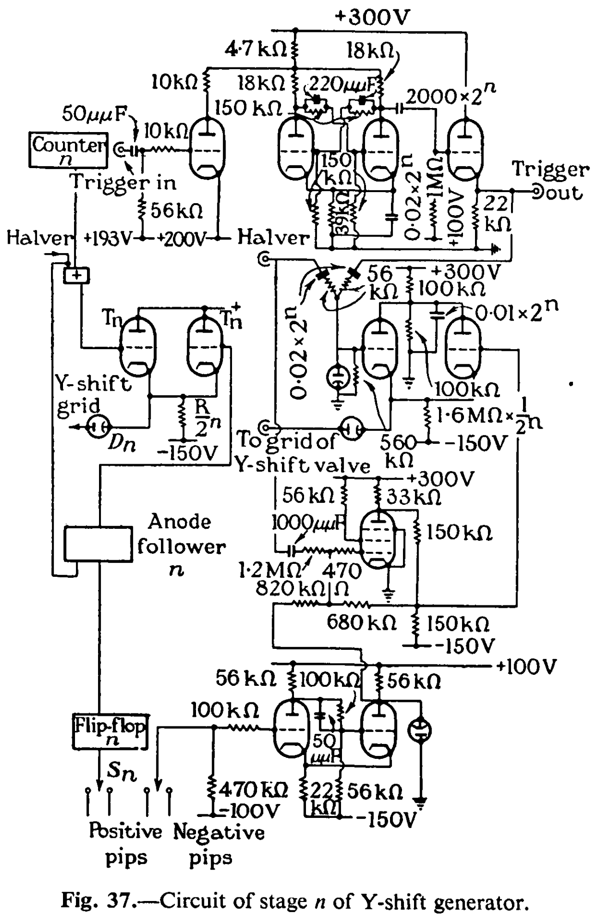

Fig. 37.—Circuit of stage *n* of Y-shift generator.

to the grids of T'_n during the action periods only, since these voltages must not interfere with the scan, i.e. with the voltages applied to the grids of T_n. To select line 10 requires a shift of 10 units during the action periods only, so that during those periods e_0, e_2 and e_4 must be positive and e_1 and e_3 negative. Hence if the waveform (i) of Fig. 36(*f*) is used for e_0, e_2 and e_4 and waveform (ii) of Fig. 36(*f*) for e_1 and e_3, line 10 will be selected. Here the opposite phase of the halver to the one previously considered is used, and is arranged alternately to switch on and cut off current in T'_n at (i), or is biased well beyond cut-off at (ii), Fig. 36(*f*). One cycle of the shift waveform under these conditions is shown at Fig. 25(*h*).

In order to change the action line, the d.c. levels of the waveforms e_n must be changed from 0 volts to beyond cut-off of T'_n or vice versa. These voltages must not be changed during an action period, because, if they are, a diagonal line will be traced across the screen by the electron beam, and stored information will be wiped out. They may, however, be changed at any time during a scan period, since they only affect T'_n which plays no part in the operation during a scan period. It is convenient to arrange that a change in voltage can only occur at the beginning of the scan period immediately following the throw of a switch. To achieve this, either the positive or the negative pips shown in Fig. 36(*g*), which occur only at the beginning of scan periods, are applied to the input grids of five flip-flops by means of five switches. This arrangement is shown at the bottom of Fig. 35. When a switch is thrown, the corresponding flip-flop cannot change its state until it receives a pip. This ensures that change of state can never occur during an action period. The positive or negative voltages produced by the flip-flops are added to the halver waveform by anode followers to produce the waveforms of Fig. 36(*f*).

Stage *n* of the schematic diagram of the Y-shaft generator shown in Fig. 35 is reproduced in schematic form on the left of Fig. 37. Details are shown in corresponding positions on the right of the figure.

DISCUSSION BEFORE THE MEASUREMENTS AND RADIO SECTIONS, 2ND NOVEMBER, 1948

Dr. A. M. Uttley: Prof. Williams started this work a few months before he left the T.R.E., and I should like to refer to developments carried out at the Establishment since his departure. It is stated in the paper that there were five different ways of using the principle of the dug and partially-filled well, and I believe I am right in saying that before the work went from T.R.E. to Manchester the anticipatory-pulse method of storage was being used. The dot-and-dash method was later adopted in Manchester. At the T.R.E., we built a store based on the same principle as the author's, but having certain differences. In May, 1948, we completed a serial store containing 1 024 digits. The positive- and negative-going waveforms can be seen quite clearly. I believe, however, that it is wrong to represent 0 by the absence of a pulse. We are hoping to do our computing work with a positive pulse for 1 and a negative pulse for 0. Many relay computers use both a 0 relay and a 1 relay, rather than an unoperated relay to mean 0. Checking of all digits then becomes possible. To this end of a three-state computer, we have modified the gating circuits, so that the positive-going wave detected at the moment of switching on of the beams causes one trigger circuit to go over, and a negative-going wave triggers another circuit; the combined output of these two trigger circuits gives a positive 4-microsec pulse for 1, and a negative-going pulse for 0.

This has not converted storage into a complete three-state system. We have to switch on the beam to find whether there is a 1 or a 0 there, and there are only the two states, the excavated or the partially-excavated well. For three-state computing, therefore, this is only a temporary measure. We hope and believe that truly three-state storage will one day be achieved. Needless to say, our routing, adding and trigger circuits are all three-state.

Another way in which our work is differing from that of the authors, and deliberately so, is that we are hoping to complete a parallel arithmetical machine rather than a serial machine. This results in an interesting change in the use of the cathode-ray tube. If one cathode-ray tube is used to store the least significant digit of 1 024 different numbers, and the next tube to store the next most significant digit of 1 024 different numbers, and so on, then, in order to read one number, all the cathode-ray tubes in parallel have to be switched to corresponding points of the same X-Y co-ordinates on all the tubes; it is then possible to take out simultaneously all the digits of a number. In between the actions of reading from, or writing into, the store, we interleave moments of regeneration. Digits are regenerated sequentially as in a television scan, but between these moments the store can be used at any point. It is possible to leap from point to point in a quite random manner; our experiments suggest that the time taken to move from one point to any other is likely to be about 10 microsec.

I am sure that it is generally realized that the authors are the first to have succeeded in making a practical storage system for electronic computers. Such variations as those I have mentioned only emphasize the fundamental achievement represented by their work.

Dr. F. Aughtie: How did the authors discover the storage property described in the paper; was the discovery quite accidental, or was it based on any theoretical reasoning? They have produced what seems to be the first successful electronic digital storage device.

The authors suggest that there are five methods of using the basic storage property, but it seems to me that the dot-dash and dash-dot methods are essentially the same, differing only in which of the characters is used to represent 1. This distinction is not a fundamental one, because, in a large machine, the respective representation of 1 and 0 may be different in different parts of the machine. The same comment applies to the two focusing methods, so that it seems to me that only three different methods are described in the paper.

Do the authors confirm that in Fig. 23 the input impedance of the amplifier is low compared with any of the resistances, *R*/16, etc.? If this interpretation is correct, they have used current and not the more common voltage summation. What was their reason for this choice?

Mr. W. P. Anderson: Devices depending for their operation on secondary emission have been used in the radio field for many years, but they have always had rather a bad reputation, mainly owing to the large and unpredictable variations in their characteristics which are liable to occur. It appears, however, that the storage tube described by the authors should escape these difficulties as, being an on/off device, its operation should be unaffected by large variations in the secondary emitting properties of the screen material.

This equipment is a good example of the value of a realistic engineering approach to a problem, undeterred by the complexity involved, when this complexity is due only to the extensive application of known techniques. In a comparatively short time it has been brought to the point where it can be used as a part