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THE FUNCTION OF BASIC ELEMENTS IN DIGITAL SYSTEMS

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SUMMARY

It is shown that electronic digital calculating machinery, and systems which represent information in digital form, may in principle be constructed from an assemblage of three basic elements. These are a bistable element for the storage of a digit, a gate for controlling the flow of digits, and a diode for controlling the direction of flow of digits. The properties and use of an element which consists of a bistable element and two gates are described, and it is then shown that the functions of this element may be realized in the form of a practical vacuum tube based upon beam-deflection principles. This tube does not lend itself to the construction of a practical large-scale store, but rather to extensive use in the control and arithmetic sections of a digital machine.

(1) INTRODUCTION

The principles underlying the operation of automatic digital calculating machinery and devices which handle information in digital form were firmly established 100 years ago when Charles Babbage detailed the design for a machine to perform automatic computation. At that time manufacturing techniques were inadequate, and as a consequence the practical realization of his machine was delayed until the mass-production methods of the present century had been established.

The past decade has seen the successful construction and operation of both the electro-mechanical and electronic forms of automatic digital calculating machinery. The electronic machines, which are significant because of their very high speed of operation, have been made possible largely by the availability of conventional triodes (and pentodes, etc.) and the techniques developed primarily for use in the communication industry. The use of the triode in this manner depends not upon its linear amplifying characteristics but rather upon the non-linearities present at the extremities of its normal operating range. This suggests that the conventional triode may not necessarily be the best tube for this application, and that it may be possible to develop a tube which is more directly suited to the storage and switching requirements of high-speed digital machinery.

The idea of building special tubes for use in electronic digital calculating machinery is not new. In this field significant advances have been made in the development of numeric storage tubes. Both Haeff[1] and Rajchman[2] have constructed tubes for storing many hundreds of binary digits by means of electric charges retained in small cells upon an insulating surface. The demonstration by Williams[3] of the use of a conventional cathode-ray tube for digital-storage purposes has fostered the development of tubes free from screen imperfections. Pulse counting in computers has led to the development of tubes for performing this function. The Hollway[4] decimal counter tube, which depends for its operation upon the location of an electron beam in one or other of ten stable positions, is an example. Another approach has led to the development of special tubes for performing certain complicated computing functions. In the Computron[5] an attempt has been made to devise a tube with several hundred electron beams, for computing continuously the product of two binary numbers. Dr. Katz at Toronto has developed a group of special tubes which are of simple and conventional construction. He has shown that by adopting a particular form of construction, a variety of characteristics can be obtained by slight modifications of the electrode shapes. In 1946 Sharpless[6] suggested a course of development based on the single-beam bistable tube, observing that the use of beam deflection rather than grid control of the target current would eliminate the need for potential-dividing circuits when connecting the output of one tube to the input of another. Jonker[7,8] has more recently outlined the electrical and mechanical requirements of switching tubes for use in telephony and possibly in calculating machines. He has emphasized the value of ribbon-like electron beams in this application, and also the use of a simple and conventional form of construction. As opposed to previous efforts the present work has aimed at reducing the quantity and variety of components in digital machinery by endeavouring to devise a general-purpose tube to perform the basic storage and switching functions in such machinery.

The functions of the simplest basic elements may be determined by considering the necessary and sufficient combinations of two binary numbers in a digital system. These combinations are the logical ones of conjunction and disjunction, the former corresponding to digit-by-digit multiplication and the latter to logical summation. From basic elements performing these functions, together with a third element for storing a binary digit, devices can be constructed in a simple manner for performing the operations of addition, multiplication, counting, etc. Using the terminology of digital machinery, these elements are termed a "gate" for performing the process of conjunction, a pair of "diodes" for disjunction, and a "bistable" element for the storage of a digit.

In principle the bistable element may be one or other of two kinds: either a static device in which the value of the digit is determined by the direct potential of its output, or a dynamic device whose state is indicated by either the presence or absence of a continuous succession of output pulses. Since the output signals from these elements are always applied to gate or diode elements where the logical operations are performed, it is common to use the static device in preference to the dynamic one because of the practical difficulty which is found in matching the output pulses (in both voltage and time) from two bistable elements of dynamic form.

If these elements are to be realized in practical form it is only necessary to consider the bistable and gate elements, since the diode is currently available in simple form. The observation that the output of a bistable element of static form is always connected to the input of a gate suggests a composite element consisting of a bistable element permanently connected to a gate. Symmetry suggests, as a further step, the use of two gates permanently connected to the opposite outputs of a bistable element such that one gate is open to the flow of information and the other closed when the digit stored is unity, and vice versa

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when it is zero. Although the symmetrical arrangement is not essential for the composite element, there are several devices, such as shift registers, counters, encoders, etc., where two gates are required for each bistable element. In these cases the inclusion of the second gate in the composite element does add to the element's complexity. As opposed to this, the total number of components in the device is reduced, and as seen later, the addition of the second gate does not appreciably complicate the construction of the vacuum tube designed to perform these functions. An element consisting of a bistable element and two gates is referred to here as a "binary gating" element.

To perform the function of the binary-gating element a binary-gating tube has been built. This depends for its operation upon the independent deflection of three ribbon-like electron beams and the collection of their current in a target assembly. Deflection control of the target current rather than grid control, as used in triodes, permits the output target of one tube to be connected directly to the input deflector of another without the use of potential-dividing circuits. The use of three ribbon-like electron beams rather than a single circular beam leads to a desirable electrode arrangement consisting of three simple cells each of similar construction. The beams are produced in a cylindrical form of the Pierce-type electron gun, which has the advantages of simplicity and relative ease of design. In the output part of the tube the possibility of using secondary emitting targets which are electrically floating has been considered. The main difficulty encountered was that of obtaining a high secondary-emission ratio over a long period of time. Problems also arise in the use of such tubes in supplying the secondary-emission current when connecting the output of one tube to the input of another. Consequently the use of secondary emission was abandoned, and the beam currents were used directly by suppressing the secondary emission at the targets in the normal manner.

(2) THE BINARY-GATING ELEMENT AND ITS APPLICATIONS

The application of the binary-gating element and the diodes to the construction of a digital system is indicated by considering in detail their use in a typical portion of an arithmetic unit of an electronic digital calculating machine. The example chosen is that of a shift register with an associated binary counter, as is used in serial binary machines for the temporary storage of numbers. Such a device has not been constructed from binary-gating tubes; it is considered here simply to indicate the manner in which the tubes could be used in a practical system.

The symbol used for representing the binary-gating element is shown in Fig. 1. Terminal 1 is connected to the input of the

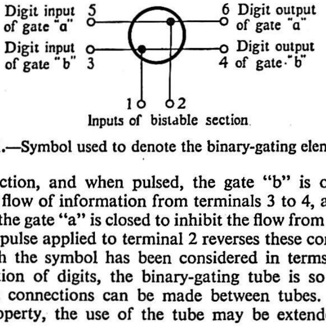

Fig. 1.—Symbol used to denote the binary-gating element.

bistable section, and when pulsed, the gate "b" is opened to permit the flow of information from terminals 3 to 4, and at the same time the gate "a" is closed to inhibit the flow from terminals 5 to 6. A pulse applied to terminal 2 reverses these conditions.

Although the symbol has been considered in terms of pulse representation of digits, the binary-gating tube is so designed that direct connections can be made between tubes. Because of this property, the use of the tube may be extended to the application where the binary-digit representation is by means of two different voltage levels, rather than by pulses.

Continuously-generated timing pulses, termed "clock pulses" p_c, are separated by intervals of time, termed "clock periods" of duration T. By the use of extra timing pulses having the same repetition frequency as the clock pulses but separated from them by some fraction of a clock period, binary-gating elements may be used as delay elements. These additional pulses are referred to here as "quarter pulses" p_a, "shift pulses" p_s, and "three-quarter pulses" p_b, all of which are shown in Fig. 2. They occur at one-quarter, one-half and three-quarters of a clock period, respectively, after the clock pulses.

Digits are transmitted by means of two lines, known as the "D-bus" and "1/D-bus." Digit 1 is represented by a pulse on the D-bus and no pulse on the 1/D-bus, digit 0 being represented by the reverse conditions. The double bus is not essential, but is used in this case because it tends to simplify the circuits.

For an example of the use of the binary-gating element, consider a shift register with a capacity for 40 binary digits, together with an associated counter for generating the pulses to control the flow of digit pulses to and from the register. As indicated in Fig. 2, a number entering the register upon the input bus (consisting of both the D-bus and the 1/D-bus) is preceded by a "write pulse" upon the "write-pulse bus" by an interval of one clock period. An outgoing number upon the same digit bus is preceded one clock period earlier by a "read pulse" upon the "read-pulse bus." These transfers are made possible by the continuous application of the p_c, p_a, p_s and p_b pulses, respectively.

To accept a number from the digit bus, the shift register is sequenced as follows: At a clock-pulse time the first digit is established in the storage element A0, as shown in Fig. 2. The next quarter pulse transfers the content of A0 to S0, the content of A1 to S1, and so on up to A40 and S40. The following pulse of the p_1 group, which is generated in the associated binary counter, transfers the content of S0 to A1, the content of S1 to A2, and so on up to S39 and A40. After 40 of these operations the first digit appears in S40, the second in S39, etc., and the fortieth in S1.

Reading from the register which is initiated by a read pulse requires the 40 pulses of the p_2 group to be applied to the element S40, in addition to those pulses which are required during the writing process. These pulses transfer the contents of S40 to the digit bus at clock-pulse times.

As shown in Fig. 2, the p_1 pulse group is counted by means of the binary counter, which is initiated by either a read pulse or a write pulse. The 40 pulses of the p_2 group which are required only during the reading process are obtained by using each of the p_1 pulses to gate out the following clock pulse from the continuously-generated clock-pulse train.

Each of the six stages of the binary counter consists of a simple ring-of-two counter from which every second input pulse is gated through to the following stage. Counting is initiated by either a read pulse or a write pulse, which first sets the counter to zero and then admits shift pulses to the input of the counter by opening the input gate. When 40 pulses have been counted, a set of six "coincidence" gates permits the passage of a clock pulse, which closes the input gate to the counter and thus terminates the transfer operation of the register. In the example chosen it is seen that the number leaving the register during the reading process re-enters the register via the element A0. In this way the number is retained in the register. During the writing process, however, the incoming number replaces the old one.

The unit described consists of a shift register, a binary counter and some associated circuits. The binary-gating element may

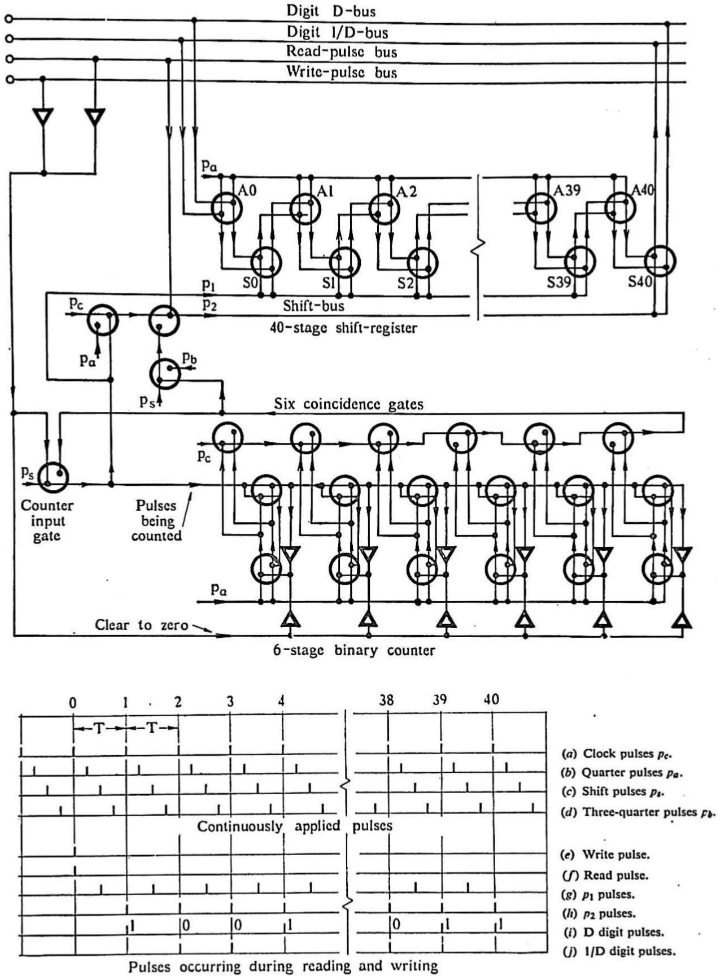

Fig. 2.—A 40-stage shift register and associated binary counter, assembled from binary-gating elements.

similarly be used in the construction of binary adders, multipliers, decoders, ring counters, etc. There is no reason to suspect that the applications are limited to these cases—in fact, these examples confirm the building-block nature of the binary-gating element.

(3) BINARY-GATING TUBE

(3.1) Electrical Principles

The bistable section of the binary-gating tube is based on the principle suggested by Sharpless[6] and used recently by Hollway[4] in counter tubes. As indicated in Fig. 3, the bistable section consists of an electron gun, two pairs of deflector plates, and a pair of symmetrically located targets. Each target is connected to a load resistor and to the opposite deflector of the second pair. Such an arrangement may possess two electrical stable states, which are distinguished by the position of the electron beam. The beam may strike either target, and in doing so be held there by the deflection forces resulting from the feedback connections between targets and deflectors. The state of the device is indicated electrically by the target potentials, and it is from these targets that connections are made to the gate sections of the tube. The device may be set to a required state by momen-

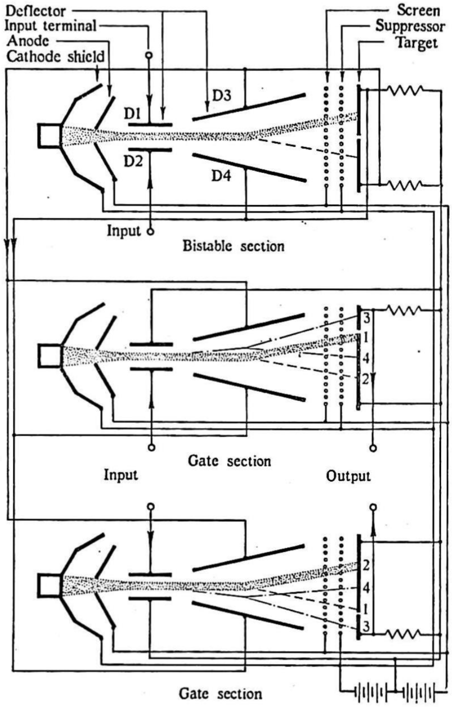

Fig. 3.—Electrode connections between sections of the binary-gating tube.

tarily applying a potential difference to the first pair of deflectors to overpower the deflection force of the second pair, thus forcing the beam into its new location.

The electrode arrangement of the gate sections of the tube differs from that of the bistable section in the positioning of the targets, which are offset from the central axis, and also in the omission of the connections between the targets and the second pair of deflectors. Connections are made between targets of the bistable section and the second pair of deflectors of the gate section, so that in the absence of a potential difference between the first pair of deflector plates of the gate section, their electron-beam location is similar to that of the beam in the bistable section. These locations are indicated in the diagram by target positions 1 and 2, respectively, target position 1 being associated with the "gate open" condition and target position 2 with the "gate closed" condition. Information appearing as a voltage pulse upon the input deflector of a gate section momentarily causes the beam to move either from target location 1 to 3 or from location 2 to 4 depending upon the state of the bistable section. In the former case, which corresponds to the gate-open condition, the beam strikes the output target, resulting in an output signal across the load resistor. In the latter case the beam deflection is insufficient to move the beam on to the output target, and no signal is produced at the output.

The binary-gating tube has been designed to operate with the anode and screen grid connected to a 400-volt supply. Equally satisfactory performance is observed when this voltage lies in the range 300–500 volts. The deflectors and targets are preferably operated at about half the anode voltage, i.e. 200 volts. Target currents observed with the anode at 400 volts are approximately 0·2 mA. The pulses applied to the trigger deflectors of the bistable section and to the input deflectors of the gate sections are 25 volts in amplitude, although in a well-aligned tube this value may lie in the range 15–35 volts. From a consideration of the beam current and trigger-pulse amplitude, together with the requirement that the output of one tube must be connected directly to the input of another, it follows that the target load resistance required is 125 kilohms. In the bistable section of the tube the relatively small external stray capacitance present at the targets enables the sensitivity of the deflectors which cross-connect to the targets to be made only half that of the trigger deflectors, without a loss of overall switching speed. The load resistances used in the bistable section are consequently 250 kilohms.

(3.2) Construction

As indicated in Fig. 4, the binary-gating tube is similar in general appearance and form of construction to the more conventional tubes. The plane-shaped electrodes are mounted between mica discs to provide mechanical support and electrical insulation. Significant features of the tube are the electron gun, the deflection system and the target assembly.

In the electron gun three ribbon-like electron beams are formed, each originating from a separate portion of the common indirectly-heated cathode, and emanating from one of three apertures in the anode of the gun. Beam formation takes place in the region between the cathode shield and the anode, where electrons from the cathode are confined to a wedge-shaped region. Upon leaving the aperture the electrons move in a beam through the deflection system to a line focus at the targets.

Between the electron gun and the targets the path of the beam electrons is controlled by two pairs of deflectors. The first pairs of deflectors associated with each beam are electrically separate from one another and are mechanically supported by glass beads. The common connections required between the second pairs of deflectors enable the construction to be simplified by using two long flat plates to form a pair of deflectors common to all three beams. In addition to controlling the general direction of the electron paths, the deflection system is maintained at a lower potential than that of the anode and screen grid to assist in the focusing of the beam. This also provides for suppression of the secondary electrons produced at both the anode aperture and the screen grid.

The target assembly consists of several flat plates supported on glass beads. Secondary emission from the target surfaces is suppressed by a closely spaced suppressor grid placed between the screen grid and the targets and held at cathode potential. The screen grid, placed between the suppressor grid and the deflector system, maintains the electron velocities in this region and prevents the target potentials from influencing the electron paths.

The complete assembly is connected to a 12-pin button base and enclosed in a cylindrical glass envelope to form a tube approximately 28 mm in diameter and 65 mm in length.

(3.3) Electron Optical Design

The use of the Pierce-type electron gun, in cases where it may be applied, enables a first-order approximation of the electrode geometry to be made by computational methods, thus confining trial-and-error experimental techniques to final adjustment of

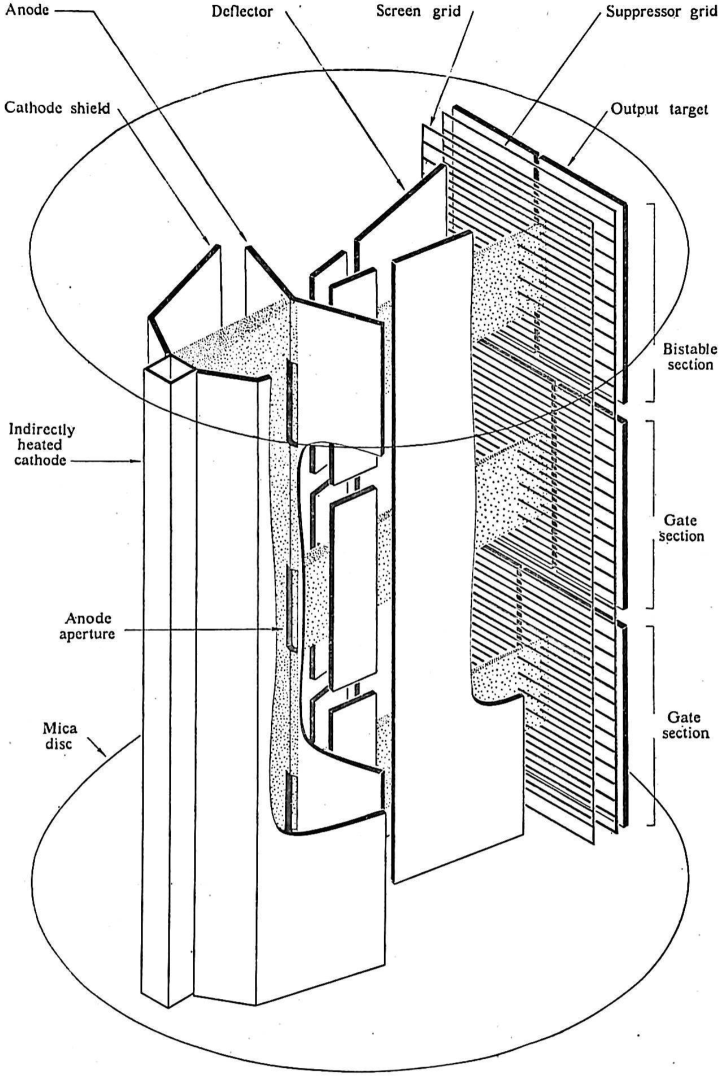

Fig. 4.—Electrode configuration of the binary-gating tube.

the second-order effects. The choice of the Pierce gun depends upon the predominance of space-charge over thermal-velocity effects in determining electron paths. In the binary-gating tube, conditions are intermediate between these two cases, space charge predominating within the gun and thermal velocities in the beam beyond the gun. The gun to be described is designed initially on the basis of space charge within both the gun and the beam, due consideration being given to the lens action of the anode aperture. Finally the width of the focus under these conditions is estimated by considering the beam spreading due to thermal effects.

Considering space charge only, Pierce[9] computed the approximate shapes of the cathode shield and anode necessary to confine the electrons in the gun to a wedge-shaped region. These curved electrodes are difficult to make with accuracy, so for use in the binary-gating tube the simplified shapes of Fig. 4 have been obtained. These have been computed using a conduction-sheet analogue device, the necessary shapes being obtained by trial to give a close approximation to the Langmuir[10] diode-distribution relation along the boundary between the space-charge and the space-charge-free regions of the gun.

This potential relation is given by

$$V = k_1(r\beta^2)^{2/3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where V = Field potential at radius r.
r = Radial position measured from the centre of curvature of the cathode.
$\beta = u - 2u^2/5 + 11u^3/120 - 47u^4/3\,300 + \ldots$
$u = \ln(r/r_c)$
r_c = Radius of curvature of the cathode.
k_1 = Constant.

Considering the lens action of the anode aperture, but neglecting both space-charge and thermal-velocity effects in the region beyond the anode, the electrons are directed to a cross-over point which is further removed from the anode than the "cathode-centre," as shown in Fig. 5. The focal length of the

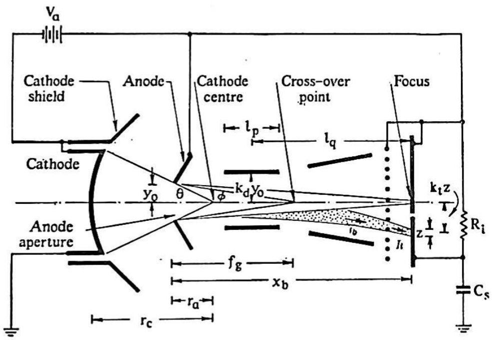

Fig. 5.—Symbols used in analysis.

divergent lens at the anode aperture is computed from the Davisson and Calbick[11] relation,

$$f_s = -2V_a/E_a \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where f_s = Anode-aperture focal length.
V_a = Field potential at the anode aperture.
E_a = Change in gradient through the aperture.

For the present analysis E_a is given the value of the derivative of the Langmuir potential relation at $r = r_a$. From the lens formula the focal length of the gun, f_g, is given by

$$\frac{1}{f_g} = \frac{1}{f_s} + \frac{1}{r_a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Thus electrons leaving the anode aperture move towards the cross-over point and not the cathode centre.

Disregarding the effects of thermal velocities in the beam between the anode and the output targets, the effect of space charge is shown by Thompson and Headrick[12] to cause the beam to spread, and the focus to recede to a position further from the anode than the cross-over point. The binary-gating tube is designed for the limiting focusing condition, in which the focus occurs in a distance of twice that of the cross-over point from the anode aperture, and the paths of the electrons at the focus are tangential to the axis. The beam perveance for this case is given by

$$\frac{I_b}{l_c V_a^{3/2}} = \frac{41\cdot 8 \times 10^{-6} y_0}{x_b^2} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where, I_b = Total beam current.
l_c = Length of cathode.
y_0 = Half the anode-aperture width.
x_b = Beam length measured from the anode aperture.

The limiting focusing condition is obtained when the following two conditions are fulfilled:

(*a*) The gun perveance, as computed by the Langmuir[10] cylindrical-diode current relation, is equal to the beam perveance required by the Thompson and Headrick beam space-charge-spreading relation for the limiting focusing condition:

$$\frac{I_b}{l_c V_a^{3/2}} = \frac{14\cdot 66 \times 10^{-6}\theta}{r_a \beta^2 \pi} = \frac{41\cdot 8 \times 10^{-6} r_a \theta}{x_b^2}$$

where $\theta = y_0/r_a$

Therefore $r_a^2\beta^2 = 0\cdot 111 x_b^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$

(*b*) The paths of electrons leaving the anode aperture are directed towards a cross-over point located midway between the anode aperture and the required focus point:

$$f_g = x_b/2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

By trial solution of eqns. (5) and (6), the necessary gun proportions are

$$r_c = 0\cdot 59\, x_b \quad . \quad . \quad . \quad . \quad . \quad . \quad (7a)$$

$$r_a = 0\cdot 21\, x_b \quad . \quad . \quad . \quad . \quad . \quad . \quad (7b)$$

In practice, it is found that the focus may be improved, and the current picked up by the deflectors reduced, if a limiting aperture is included whose width is one-third of the anode aperture, and which is placed at a distance of three times the anode-aperture width from the anode. For clarity this aperture is not shown in Fig. 4. However, its effect must be taken into account when computing the beam current, which in this case is reduced to one-third of its original value. In the binary-gating tube described

$$x_b = 13\,\text{mm}$$

From eqns. (7*a*) and (7*b*)

$$r_c = 7\cdot 7\,\text{mm}$$
$$r_a = 2\cdot 7\,\text{mm}$$

Allowing for the effect of the limiting aperture

$$y_0 = 0\cdot 075\,\text{mm}$$
$$l_c = 4\,\text{mm}$$
$$V_a = 400\ \text{volts.}$$

Therefore, from eqn. (4),

$$I_b = 0\cdot 59\ \text{mA.}$$

By experiment the screen grid was found to reduce the beam current at the target to 0·20 mA.

The important assumption in the space-charge-spreading theory is that the electron beam at the anode aperture is both homogeneous and homocentric; these being conditions present in the Pierce-type electron gun when thermal velocities are disregarded. Langmuir[13] and Pierce[14] have shown that the effect of thermal velocities is to limit the current densities which can be obtained in electron beams, and to destroy the fine-line focus which would otherwise be possible in ribbon-like beams in an aberrationless electron optical system.

In the absence of space charge in the beam the focus occurs at the cross-over point, as shown in Fig. 5. The equation for the effects of thermal velocities in ribbon beams shows that the maximum current density which can be obtained at the focus point is given approximately by

$$J_{max} = J_0 \frac{2}{\sqrt{\pi}} (eV/kT)^{\frac{1}{2}} \sin \phi \quad . \quad . \quad . \quad . \quad (8)$$

where, J_0 = Cathode current density.
V = Beam potential.
ϕ = Beam convergence angle at the cross-over point for electrons leaving the anode with zero velocity.

The ratio of the beam width at the cross-over point to that at the cathode is given by J_{max}/J_0. When $V = 400$ volts and the width of the cathode is 0·054in, the beam width at the cross-over point is 0·024in, as compared with 0·018in at the anode aperture. Assuming the beam to continue spreading at the same rate, the expected focus width at the target would be 0·030in. The formula shows that the use of a limiting aperture cannot be expected to reduce the spreading due to thermal velocities to any appreciable extent. It can be expected to intercept and remove the electrons of high thermal energy and thus reduce the stray current entering the deflector electrodes.

The equation for the effect of thermal velocities shows that the maximum current density which can be obtained in a beam is increased as the angle of convergence of the electron paths is increased. Thus the beam focus can be improved by using a condensing lens. In the binary-gating tube, such a focusing effect is obtained by operating the deflection system at a lower potential than the anode and the screen grid, the latter two electrodes being electrically connected. The operation of the tube in this manner does not prevent the output of one tube being connected directly to the input of another, since the presence of the screen grid enables the output targets of the tube to be connected through their appropriate load resistors to the same supply as the deflectors. In fact, with the tube described the best operating conditions were found when the target and deflectors were operated at about half the potential of the anode and screen, as indicated in Fig. 3. The focusing effect of this lens may be computed by using one or other of the various numerical methods, such as are given by Klemperer and Wright[15] or Gans,[16] based upon the differential equation of motion of the paraxial electrons. Alternately, as has been done in the design of this tube, the potential of the deflection system necessary to give the best line focus may be obtained by experiment. It was found that the line-focus width could be reduced from 0·030in to 0·010in by lowering the deflector potentials to one-half that of the anode.

Secondary electrons produced at the target are suppressed in the binary-gating tube by means of a suppressor grid placed between the screen grid and the targets. The method used for estimating the dimensions of these grids is similar to that used in the design of pentodes, and presented in a convenient form by Spangenberg.[17]

Pierce[18] had given an expression for the limiting trans-conductance of beam-deflection amplifier tubes in terms of thermal velocities and the capacitance between the deflector plates by combining the expression for the maximum current density with that for the deflection sensitivity. For use in the design of the binary-gating tube, an expression is derived for the time-constant associated with the change of potential of a target when the beam is suddenly switched on to it, in terms of the width of the focus at the target, the beam deflection, the total stray capacitance, the anode potential, and the ratio of the deflector-plate separation to the beam width at the anode. The thermal velocities are not considered directly in this derivation, because space-charge and focusing effects in the deflection system cannot be neglected in this case. However, their effect is implied in the term for the beam width at the focus. The variation of the capacitance between the deflector plates as a function of their separation is not taken into account, since their capacitance is comparable with that of the stray capacitance to earth of the wiring when the tube is used in computer circuits.

In the circuit shown in Fig. 5, the following symbols are used:

$2y_0$ = Beam width at limiting aperture.
$2y_0k_d$ = Separation of the deflector plates.
l_c = Length of the cathode (beam thickness).
x_b = Length of the beam.
z = Beam width at target.
V_a = Anode potential.
I_b = Beam current.
I_t = Current entering the target.
R_1 = Load resistance.
C_s = Stray capacitance at the target.
V_t = Input, or output, signal (the signals are of equal amplitude to enable direct connection to be made between tubes).

The target response to an input signal which causes the beam to be suddenly switched on to it is given by

$$v_0 = I_t R_1 [1 - \exp(-t/T)] \quad . \quad . \quad . \quad . \quad (9)$$

where $$T = C_s R_1 = C_s V_t / I_t \quad . \quad . \quad . \quad . \quad . \quad (9a)$$

In the deflection system

$$V_t = 4V_a \frac{k_d y_0}{l_p} \frac{k_t z}{l_q} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where, l_p = Length of the deflector plates.
l_q = Distance from the centre of the deflector plates to the target.

From eqn. (4),

$$I_t = k_s I_b = 41 \cdot 8 \times 10^{-6} V_a^{3/2} \frac{k_s y_0 l_c}{x_b^2} \quad . \quad . \quad (11)$$

where k_s = Fraction of the beam current passing through the screen grid and striking the target.

By substitution in eqn. (9*a*),

$$T = 9 \cdot 6 \times 10^4 \frac{1}{V_a^{\frac{1}{2}}} \frac{k_d}{k_s} \frac{k_t z x_b^2}{l_p l_q l_c} C_s \quad . \quad . \quad . \quad (12)$$

In the binary-gating tube described

C_s = 15 $\mu\mu$F (approx.)
l_p = 2·25mm
l_q = 10·5mm
k_d = 6·3
$k_t z$ = 1·0mm
k_s = 0·34
l_c = 4·0mm
V_a = 400 volts
x_b = 13mm

Substituting these values in eqn. (12), $T = 2{\cdot}4$ microsec. This agrees with the time-constants associated with the waveforms in Fig. 6 and with the observed maximum speed of operation of 150 000 changes of state per second.

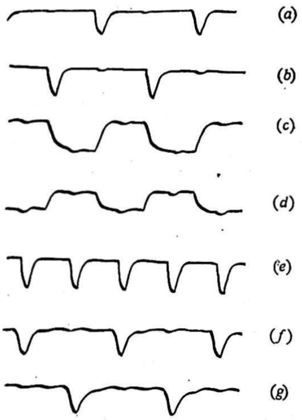

Fig. 6.—Oscillograms showing the performance of the binary-gating tube at a frequency of 50 000 pulses/sec.

(a) Pulses applied to trigger deflector D1.
(b) Pulses applied to trigger deflector D2.
(c) Waveform at bistable deflector D3.
(d) Waveform at bistable deflector D4.
(e) Input pulses applied to gates "a" and "b."
(f) Output pulses from gate "b."
(g) Output pulses from gate "a."

(4) CONCLUSION

Approaching the design of digital systems from the viewpoint of basic functions has led to the establishment of three basic elements and the practical realization of two of them in the form of a beam-deflection vacuum tube. Experience may show that the binary-gating tube does not represent the best possible compromise between complexity of the tube and that of the overall system. A simpler element which can perform either bistable or gate functions by a simple change of external connections may lead to a more economical overall arrangement. Whatever tube is finally chosen for the purpose, it does appear that its use would simplify the design, construction and maintenance of digital machinery by reducing the number and variety of its components.

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