"Picture logic" for "Bacchus" a fourth-generation computer

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This paper examines the logical problems involved in designing a proposed "picture arithmetic" computer ("Bacchus") operating by transferring, inverting, shifting and superposing whole pictures of information, in parallel, simultaneously, without scanning. Each picture is controlled by a one-bit device of "third generation" hardware, and may contain up to 10^8 elements switched in as little as 10^{-8} seconds, and up to 10^4 pictures are possible. Associated problems such as input, output, and realization of this logic are considered in varying degrees of completeness. Serious heat problems will be met in the region 10^{17} to 10^{20} logical operations per second.

Introduction

It has recently become conventional to distinguish between "first-generation computers" and "second-generation computers." The term *second-generation computer* has come to mean transistorized core-store computers, mostly with some sort of time-sharing routine, and the earlier computers are of the "first generation." The second generation has reached its zenith with Atlas and Stretch, at about 10^6 operations/sec.

The third-generation computers which will go up to 10^8 operations/sec, will be transistorized with magnetic-film stores or superconducting stores. Few if any of these machines are even on the drawing board, and these machines are currently believed to be the ultimate machines beyond which no significant speed improvements are possible, although cost reduction can still occur.

We can, however, consider a new method of approach by which, instead of decreasing the characteristic switching time of two-state systems, we make the switching process more fruitful. We will see that we are led to limiting figures of switching a picture of 10^8 elements in 10^{-8} seconds, and that 10^4 such pictures may be considered.

We must at this stage examine our knowledge of picture operations in other contexts.

It is possible to transfer a picture either in parallel or serially. The difference in speed is the number of elements in the pictures, which may be as high as a factor of 10^8. In previous systems of cathode-ray tube storage for computers the picture was scanned at random, which is a serial process. On the other hand, in the Image Iconoscope type of television camera tube there is a stage of parallel signal multiplication in which an incident-light picture is transformed into an electron picture which is multiplied in number and electron-energy by a cascade process, and the amplified picture is eventually scanned. For our purpose the significant fact is that the picture can be amplified in parallel. Another device which operates in parallel on a picture is the Image Converter tube, which is used in high-speed photography involving time exposures of 10^{-8} seconds.

What is novel therefore is the unification of parallel picture operations and computer design. The logical problems to be discussed call for new types of picture device for which there has been no previous need. The fact that some picture operations are standard techniques suggest that there will be no fundamental obstacles to the development of the necessary new devices.

The fact that essentially a one-bit control unit can control an entire picture means that even if the number of pictures were as large as 10^4 most of them could be individually controlled, since 10^4 bits of third-generation hardware is only about 200 words of 50 bits, a very small size for a fast store. The program store would probably be much larger, and later versions of the computer might have a device for transferring instruction blocks from the picture store to the third-generation hardware, with sizable reductions in the hardware program store. The element size for instructions may be larger than that for numerical data.

The fact that one bit controls an entire picture suggests the possibility that by giving each picture a restricted set of operations and using a "functional destination organization" one could achieve the effect of 10^4 pictures of 10^8 elements all switching independently in 10^{-8} seconds. If we allow 100 bits for a floating-point mantissa and exponent this implies an active storage of 10^4 pictures of 10^6 words, which is 10^{10} words of 100 bits. As a comparison the British Museum Library is about 2×10^6 books. If we assume that each book is of 2×10^6 bits then the total storage of our proposed machine is one quarter of the total storage of this library.

Furthermore, if this degree of parallelism is achieved, one logical operation is performed on each of 10^4 pictures in 10^{-8} seconds, which is to be compared with perhaps 100 logical operations in 10^{-8} seconds as the ultimate with conventional techniques.

The maximum averaged rates are thus 10^{20} logical operations per second compared with 10^{10} per second. Problems of power supply would be most formidable.

It is therefore apparent that the theoretically possible new performance range opened up by Picture Logic is comparable with the new performance range opened up by the introduction of electronic switching in 1946, which raised the theoretically possible logical operation rate by a factor of order 10^9 compared with relay operation.

In the early days of development the picture might contain only 10^4 elements instead of the ultimate 10^8 elements. Even so, 10^4 elements switching in 10^{-7} seconds is still 10 times faster than the 10^{10} logical operations per second with the ultimate conventional technique, and would be much cheaper.

A picture of size 10 by 10 cm would need an element 1 mm square for 10^4 elements per picture, and 10 microns square for 10^8 elements per picture.

NOT, AND, operations

If we can arrange to perform the operations of Boolean algebra on our pictures we can construct a computer.

We will postulate that by suitable technological skills we have been able to obtain a series of picture devices which collectively possess the following four properties.

(*a*) We may transfer the picture in location A to some other picture location B, for which we write $B = A$.

(*b*) We may move a picture left or right as many elements as we wish, and also up or down as many elements as we please. We will write this as $A = (A)$ and specify the type of shift by a suitable legend.

(*c*) We may transfer to location C pictures from locations A and B, superposing these pictures. With a convention to be stated this will be shown to give $C = A$ AND B in the Boolean sense.

(*d*) We may replace a picture by its light-dark complement; this we write $A =$ NOT A.

We shall adopt here the convention that a light element which is a pulse = P = O, and a dark element which is no-pulse $= N = 1$. We see then that operation (*d*), $A =$ NOT A is the Boolean operation NOT A because all pulses are interchanged with no-pulses, giving all 0 and 1 interchanged.

The superposition in (*c*) gives us the AND operation in the Boolean sense since defining $C = (A$ superposed with $B)$ in C, we get the situation shown in Table 1.

Table 1

A	B	A	B	C	C
0	0	P	P	2P	0
0	1	P	N	P	0
1	0	N	P	P	0
1	1	N	N	N	1

We see that the superposition of two no-pulses gives us no-pulse, whilst the superposition of pulse and no-pulse gives a pulse.

There is a technical problem since the pulse superposed with pulse gives a brighter pulse than the other cases. We can suppose that

(*a*) the picture hardware corrects this, or

(*b*) it does not matter in view of the subsequent fate of the picture.

An example of (*b*) would be using the picture as NOT C, when the different no-pulse levels would be swamped by a superposition of a pulse.

We are now in a position to perform basic Boolean operations on each element of a picture, relating it to the correspondingly located elements of other pictures. This one-to-one correspondence gives an *implicit addressing* of the individual elements.

If we wish to exercise any degree of reasonable control over these operations we must find a procedure for dealing selectively with the various words according to some pre-determined criterion. This we shall deal with in the next Section.

Interleaving, Vector Recording, Jump operations

We wish to develop a jump operation for picture logic. We define this as follows.

We wish from a given picture D to select an array of elements, one from the corresponding position in each word, and using this "one-bit" which we call d, we form a picture C which contains those words of picture A for which the elements in d are 1, and those words in picture B for which the elements in d are 0.

It is convenient to discuss first a method by which we store words within a picture.

Let us take a specific numerical example as follows. We take a picture of size 8,192 elements by 8,192 elements, with words of 64 bits, so that there are about 10^6 words in this picture.

We then arrange our words in 8,192 rows of 128 words each, and if we denote the words in the first row as $A_0\ A_1 \ldots A_{127}$ and in the second row as $B_0\ B_1 \ldots B_{127}$ and so on, and denote the jth bit of each word X_k as X_k^j, then we use an interleaving recording system such that the bits in the typical first row, reading from left to right, are $A_0^0, A_1^0, A_2^0, \ldots, A_{127}^0, A_0^1, \ldots, A_{127}^1 \ldots, A_0^{63}, A_1^{63} \ldots A_{127}^{63}$.

In this way the first elements of every word in the entire picture are brought together into a continuous rectangular array which we call the "bit". In this instance

$$\begin{aligned} 1 \text{ bit} &= \text{array of } (128 \text{ elements}) \times (8192 \text{ elements}) \\ &= \text{array of } 1{,}048{,}576 \text{ elements.} \end{aligned}$$

We now define the operation of *vector recording* as that operation which given some bit d records it in every one of the 64 bit positions. This means that these elements of d for which $d = 1$ are recorded as a word of 64 ones, whilst those elements of d for which $d = 0$ are recorded as a word of 64 zeros.

We now see that writing $V(d)$ for the vector-recorded picture of d, we have our conditional operation given by

$$C = [A \text{ AND } V(d)] \text{ OR } [B \text{ AND } (\text{NOT } V(d))]$$

where as usual the inclusive OR operation is

$(A \text{ OR } B) = \text{NOT } [(\text{NOT } A) \text{ AND } (\text{NOT } B)]$

$(A \neq B) = [A \text{ AND } (\text{NOT } B)] \text{ OR } [(\text{NOT } A) \text{ AND } B]$.

It should be noted that

$\text{NOT } V(d) = V(\text{NOT } d)$.

The process by which vector recording may be affected typifies *the concept of a single logical operation to each picture location*, which is a "functional destination organization" as used in the English Electric Deuce.

We imagine for this process a string of seven locations, from each of which the picture proceeds to the next location, being right-shifted and superposed with the previous picture in a decreasing binary sequence.

Thus for 64 bits per word we have the situation shown in Table 2.

Table 2

Location	1	Positions in which bit d is recorded	0
	2		0, 32
	3		0, 16, 32, 48
	4		0, 8, 16, . . ., 56
	5		0, 4, 8, . . ., 60
	6		0, 2, 4, . . ., 62
	7		0, 1, 2, 3, . . ., 63

Now whilst some particular picture is in location 5, some other picture is being treated simultaneously in location 3, and in fact it is possible to have as many as seven different programs streaming through the unit simultaneously. Thus although it takes seven "beats" for a given picture to be vector recorded, the actual overall rate is one per beat.

This type of operation requires just a single program control device for each of these picture locations, and would appear to be both feasible and cheap.

A similar overlapping treatment of pictures from different sources may be carried out in almost any unit that is constructed, including arithmetic ones. The overall control of picture entry and exit from the various units is the function of an editing unit which also monitors input and output.

Matrix operations; Multiplication, Inversion, Transposition

It is reasonably evident that we have so far "developed" a very fast computer provided that there are large volumes of work to be handled. The problem which arises now is to consider ways in which this work potential may be applied to small and to medium-size calculations.

In a serial-operation computer of conventional type it is not significant to distinguish between two programs of equal length, one of which obtains results by a successive iteration process on a single number, and the other of which deals with essentially "picture" programs such as a matrix operation. In a Bacchus type machine, this difference is significant. In this Section we shall consider the tasks of matrix multiplication, inversion, and transposition, since matrix addition and subtraction are trivial. We will begin by considering a picture array of 8192×8192 elements with words of 64 bits. We have 8,192 rows of 128 words.

Let us consider the following simple example with matrix orders chosen small merely to facilitate the discussion.

We have a matrix A of order 5×128 and a matrix B of order 128×3. We wish to form the matrix C of order 5×3, $C = AB$.

In order to do this let us recall that basically the multiplication involves the "sum-multiplication" of every row of A by every column of B.

Let us write $A = \text{column } (A_1 A_2 A_3 A_4 A_5)$
$B = \text{row } (B_1 B_2 B_3)$

when A_j is of order 1×128
B_j is of order 128×1.

We now use a generalized vector-recording process, to write the matrix A down three times and the matrix B five times, as follows.

$A1, A1, A1.\ A2, A2, A2.\ A3, A3, A3.\ A4, A4, A4.\ A5, A5, A5.$
$B1, B2, B3.\ B1, B2, B3.\ B1, B2, B3.\ B1, B2, B3.\ B1, B2, B3.$

These are recorded in 15 corresponding consecutive rows of 128 words, in each picture.

We now picture-multiply the pictures A and B, giving the individual products in C, and then add the 128 products in each row of C by seven cycles.

1. Picture right shift 64 elements added to original picture.
2. Picture right shift 32 elements added to new original picture.

At the end of this time we obtain in 15 successive rows the ordered 15 elements of the matrix C, $C_{11}, C_{12} \ldots C_{53}$.

It would also be possible to choose a scheme to put the product in a row or even a rectangular array instead of a column.

The actual detailed procedure of matrix recording will depend in practice on the size of the picture, and number and sizes of matrices to be handled.

We could have applied exactly this procedure to give us a single column result for the multiplication of a matrix of order 64×128 by a matrix of order 128×64, to give a matrix of 64×64 with 4096 elements.

Thus in the time for one multiplication, seven additions, and a number of vector-recording operations we have dealt with a problem that in conventional technique would have required $64 \times 64 \times 128$ cycles, which is about 10^6 multiplications and 10^6 addition and control cycles.

Thus we see here an example of the equivalence of speed and capacity in handling matrices of medium size (although by conventional standards 128×64 is a large matrix).

Another situation which provides a useful example is the case of the inversion of a matrix.

This may be considered as the evaluation of $(n + 1)$ determinants of order n. If we write the matrix of the determinants as $A_0A_1 \ldots A_n$, where A_j is of order $n \times 1$, then by writing this entire matrix down n times and picking out sets of n columns we get every one of the $(n + 1)$ determinants, since we get, [denoting by D_j the determinant with column j missing]

$A_0A_1 \ldots A_{n-1} = D_n$
$A_nA_0A_1 \ldots A_{n-2} = D_{n-1}$
$A_{n-1}A_nA_0 \ldots A_{n-3} = D_{n-3}$
...
$A_1A_2 \ldots A_n = D_0$.

We can then evaluate these determinants simultaneously by pivotal condensation, the actual details of which will depend on the number and order of the determinants to be evaluated, as well as the picture size.

We can, as a simplified example, consider a stage in the pivotal condensation of a single determinant of order n in picture A.

We first vector-record the top row of the determinant in every row position on a separate picture B.

We now picture-divide A by B, giving us an array in which every element in the top row is unity. We now vector-record our chosen pivot column in every column position except its own, and subtract this picture from the previous picture, giving us a determinant with one unity and the remainder zeros in the top row of the modified determinant. The remaining details can be left to the reader.

The problem of transposition of a given matrix can best be solved by vector-recording processes in which the matrix of order $m \times n$ is converted to a single row of order mn, and then broken up into the appropriate transposed form by further vector recording.

A device which is of great value in this sort of work is to use a special "map-picture" which contains areas filled with binary 1 and other areas filled with binary 0. This enables the selected fields to be picked out of a picture by an AND operation with the "map-picture." The latter may be provided by the editing unit, by a special program routine, or by an input device.

At this stage we may consider a problem which is really closely related, namely the basic operation of multiplication of two pictures. So far it has been implicitly assumed that the amount of work available is sufficient to make the multiplication of units of 10^6 words an efficient process. We can now ask ourselves if we can apply any of our multiple recording techniques to sacrifice storage for speed.

We can certainly reduce the number of serial additions in the multiplication process as follows. We begin with our picture of 8192×8192 elements as before, with words of 64 bits, 128 standardized words per row. We now take a column of 128 full rows as our unit block for multiplication, and we get 16,384 words in this block, which is 128×128 words.

Let us call the blocks to be multiplied A and B, and denote the bits of each block as *rows* of bits $a_0a_1 \ldots a_{63}$ and $b_0b_1 \ldots b_{63}$.

We now form the *vertical* array $a_0a_1 \ldots a_{63}$ and vector-record it in all columns filling the A picture.

We then vector-record the matrix B at the top of its picture location; underneath it we record B right-shifted one bit, and underneath that B right-shifted two bits, and then three, four, . . . 63 right shifts.

In this configuration the AND operation on these two vector-recorded pictures will produce all the partial products in a format ready for summation in six summations by the usual block-sum process for 64 blocks.

We will not specify the process for addition and subtraction, as the possibilities for speed increases are not at present apparent, when compared with well-established serial logics.

Multiple programs may be run in the arithmetic unit by dividing it into rectangular fields, each with a 6-bit hardware counter, so that the phase of any addition procedure is available for each field, rendering it completely independent of other fields. Thus a second program may commence an addition while a first program has gone through only 23 carry cycles. It is necessary to allow 64 carry cycles for a 64-bit word since the longest carry word must be accommodated.

Input–Output

Photographic means are a fairly obvious choice for the principal input and output devices. There are two problems involved. In input the object is to obtain the highest input rate possible, requiring a fixed illumination of the film and a maximum density of recording of data. However, since input and output are to be interchangeable we need to consider the more difficult task of output.

Ideally we can think of output as an instantaneous motion of a film-frame into position, an exposure time of t seconds, and a repetition of this process at maximum speed.

Now the exposure time is inversely proportional to A, the speed in ASA of the film, and the output of information per frame is inversely proportional to d^2, where d is the smallest distance in microns for resolution by the film. Thus the data output rate is dependent on the product Ad^{-2}. We can conveniently define an output figure of merit $U = Ad^{-2}$ which is an arbitrary measure of the data-output rate in elements/sec.

The measure of the input speed is $S = 10^3d^{-2}$, and this is also a measure of the amount of storage space required for a given amount of data.

Table 3 gives values of A and d for Ilford Films (35 mm) as quoted in December 1960.

Table 3

FILM	A (ASA)	d (MICRONS)	U=OUTPUT	S = INPUT
HPS	800	30	0·889	1·111
HP3	400	25	0·640	1·600
FP3	125	20	0·313	2·500
PAN.F.	50	15	0·222	4·444
M.N.P.	6·25	11	0·0517	8·264

Table 4

SYSTEM	TRANSFER	E(ELECTRON VOLTS)	λ(cm)	V(CM/SEC)	d(CM)	n(ELEMENTS)
VISIBLE	SHARP	3·09	4×10^{-5}	3×10^{10}	5×10^{-5}	4×10^{10}
LIGHT	FUZZY	3·09	4×10^{-5}	3×10^{10}	2×10^{-2}	$2{\cdot}5 \times 10^{5}$
ELECTRONS	FUZZY	10	$3{\cdot}88 \times 10^{-8}$	$1{\cdot}88 \times 10^{8}$	$6{\cdot}23 \times 10^{-4}$	$0{\cdot}258 \times 10^{9}$
		100	$1{\cdot}23 \times 10^{-8}$	$5{\cdot}93 \times 10^{8}$	$3{\cdot}50 \times 10^{-4}$	$0{\cdot}817 \times 10^{9}$
		6000	$0{\cdot}158 \times 10^{-8}$	$46{\cdot}9 \times 10^{8}$	$1{\cdot}26 \times 10^{-4}$	$6{\cdot}33 \times 10^{9}$

$P = L = 10$ cm.

It is apparent that the film which is best for output, namely HPS, is the worst for input, for which purpose Micro-neg-pan (MNP) is the best. Note that for output the highest frame speed of HPS more than makes up for the loss due to its having the lowest film resolution.

A top quality photographic lens, such as a 50 mm focal length f 1.4 used in a 35 mm camera, will give about 85 lines per mm resolution, which is just about equal to that of MNP. However, we would use specially constructed lenses working at a fixed distance, fixed aperture, and possibly in monochromatic light, which should permit higher lens resolution, since there are special films with resolutions of 1 micron which have not been examined.

The high data-handling rate means that for many applications a direct print-out in common language using a character-matrix method would be essential. As regards the actual exposure time needed for output, if we regard the picture as being as bright as a domestic television set, we would guess at an exposure time of order 10^{-3} sec at f 1.4 for HPS, meaning a frame rate of about 1000 frames/sec output.

If we take each frame as having 30 lines per mm and a rectangle of side 36×24 mm we get 777,600 elements per frame, giving an output rate of about $7{\cdot}8 \times 10^{8}$ elements/sec which with normal binary recording and 100 bits per word gives $7{\cdot}8 \times 10^{6}$ words/sec which is much faster than a Xerographic printer.

It is usual to have faster input than output so that an input speed rather faster than this should be possible. Multiple input and output channels could be provided.

The part played by a fixed store in machines such as Atlas could be played in part at least by a single frame specially composed by photographing a large drawing with the elements marked in black ink where appropriate.

"Sharp" and "Fuzzy" transfers, picture capacity

In this Section we will distinguish two physically distinct processes by which a picture may be transferred. We will refer to them by the names sharp and fuzzy transfers. We will also consider the limiting factors that determine the maximum capacity of a picture, and give some thought to the process of realization of this logic.

The first process of transfer, and the most familiar one, is the sharp transfer in which a picture is transferred from one location to another by a lens system, all points of the picture illuminating all points of the lens, and wavefronts from many different sources in the picture overlapping in space and time.

With a lens of f-number f, and light of wavelength λ_s, a distant point source is imaged into a diffraction disk. The radius of the central maximum under such conditions is d_s where

$$d_s = 1{\cdot}220 \text{ f } \lambda_s.$$

The other process by which a picture may be transferred is the fuzzy transfer in which an array of separate sources is transferred by parallel non-overlapping discrete pencils.

With wavelength λ_f, and a distance L between source and destination, any point on the original picture is expanded to a linear dimension of order d_f where

$$d_f^2 = L\,\lambda_f \qquad \text{(see Fig. 1).}$$

We see therefore that in a picture of side p cm, the number of elements is n where the elements are of side A_s, A_f cm so that

$$A_s \gg d_s, \quad A_f \gg d_f$$
$$n_s = p^2 A_s^{-2} \ll p^2 \lambda_s^{-2}$$
$$n_f = p^2 A_f^{-2} \ll p^2 L^{-1} \lambda_f^{-1}.$$

For electrons a fuzzy transfer would probably need less power than a sharp transfer, and it is easier to amplify and shutter an electron picture.

The largest picture capacity is possible if, with p and L fixed, we choose both λ_f and λ_s to be small. Thus it pays to have sharp visible light transfers, but fuzzy electron amplifying transfers.

With $p = L = 10$ cm the values of d_s, d_f for various values of λ are given in Table 4.

Fig. 1 illustrates the disc of diffraction produced by a point O. The path difference between the central maximum of brightness and the first minimum is one wavelength.

It is immediately obvious from Table 4 that the resolution of a sharp transfer is far superior even to that of a fuzzy transfer of much smaller wavelength.

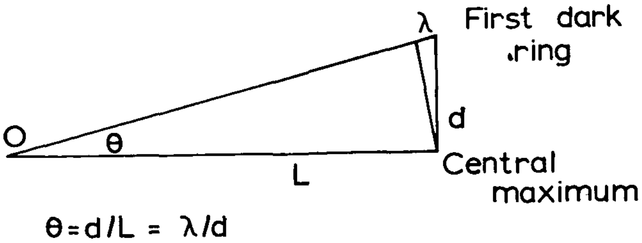

Fig. 1—Fuzzy transfer

There is not too much difficulty in getting 10^8 elements per picture with the sharp transfer, as this represents an element of about 20×20 diffusion lengths in size, which should be enough to give a reasonable definition, since the element size is 10^{-2} mm.

With the 6000 ev electrons, the picture of 10^8 elements would be about 10×10 diffusion-lengths which is, on a natural scale, only one quarter as good as the other case. It represents a limit of resolution which might just be obtainable, and would be attainable with higher voltages.

If each element consists of a pulse of average size N electrons, then for operation at 10^{20} elements per second for one year we need a reliability of 10^{-28} in distinguishing between ones and zeros. Thus if we take the standard deviation as $N^{1/2}$ we need to allow for ten times this deviation which means that

$$N \gg 10N^{1/2} \qquad N \gg 100.$$

In practice a pulse of 600 electrons will be a reasonable minimum figure. As a consequence of this, if the resolution in a picture at minimum acceptable brightness is increased, then the brightness must also be increased.

If the energy requirement of one element is that of 600 electrons falling through 1000 volts we get the energy of one element as 6×10^5 ev, which is just 10^{-13} Joules. (The comparable figure for the human brain is 10^{-10} Joules per element.)

If the rate of picture operation is N elements per second the power required is $P = 10^{-13}\ N$ watts, so that if $N = 10^{16}$ elements per second $P = 1$ KW, and for $N = 10^{20}$ elements per second $P = 10$ MW. As a consequence we infer that in the ultimate system with 10^8 elements switching in 10^{-8} seconds each picture will dissipate 1 KW, with enormous cooling difficulties. As long as the power dissipation is kept down to 1 watt per picture, which is equivalent to 10^{13} elements per second for each picture, we get 10 KW for 10^4 pictures, giving 10^{17} elements per second. Thus the technological problems of heat dissipation are unlikely to be serious until a factor of 10^7 of the total gain of 10^{10} has been achieved.

We now examine one problem of outstanding fundamental importance which has been ignored hitherto. This is the problem caused by the fact that emitted secondary electrons have a wide distribution in solid angle and energy. If an electron with a 3 volt lateral component receives a 300 volt forward impulse the ratio of energies is 100 and the ratio of velocities is 10, so that the angle of spread is an angular radius of 0·1 radians. By comparison the spread assumed for a 1 micron drift in 10 cm is 10^{-5} radians. In order to overcome this problem the picture store should be made by successive depositions of thin films on to an optically flat glass plate. In this way the spread of 1 micron can occur over a distance of perhaps 10 microns, which is also a spread of 0·1 radians. A 1 micron thin film is about 10,000 atoms thick, and films of this type are frequently required in the optical instruments industry.

All existing design data are drastically improved by this reduction of length from 10 cm to 10 microns, with the sole exception of the problem of heat dissipation. A heat dissipation of 1 watt per picture involves only 0·01 watts per cm^2, so it appears feasible. This serves also to reinforce the conclusions reached previously concerning heat dissipation. An alternative possibility might be to do the amplification by a single high-voltage stage. Thus we see that the capacity of a picture might just reach 10^8 elements in a picture of 100 cm^2.

A further problem which arises is the time necessary for transmission of the picture. For a distance of order 10 cm a light picture takes only 3×10^{-10} seconds, whilst the time for an electron picture is of order 10^{-8} to 10^{-7} seconds.

We thus see that a characteristic switching time of about 10^{-8} seconds is the limit of technique, and this value may be attained in practice with some difficulty. It may be noted that the time delay in the emission of secondary electrons is believed to be of order 10^{-13} seconds at most.

The present techniques with Image Converter tubes involve electrons with about 6000 ev energy, where a sharp light picture is converted into an enlarged electron picture. The resolution of the electron picture impinging on the viewing screen is said to be 25 lines/mm, compared with the figure of 100 lines/mm which we have concluded represents the limiting value. The corresponding figure for the photocathode is a maximum resolution of about 100 lines/mm, agreeing with our chosen value. Exposures of 10^{-8} seconds are possible.

Of course the requirements for this system and for a computer picture are vastly different, the main differences being the much higher overall operating speed, larger power requirements and much higher picture stability in the computer. If we wish to realize this picture logic it would seem probable that a good choice would involve external sharp light transfers and internal regenerative fuzzy electron transfers. A difficulty is that the pictures would have to be positionally stable to within 1 micron or better, so that optical precision engineering is involved.

A further difficulty would be that if the number of storage cycles is large there may be a slow diffusive deterioration in picture quality, as well as possible complications due to the bright parts remaining at maximum brightness whilst dark parts slowly amplify over many cycles.

The Highway-Ladder mesh

A problem which can now be considered is that of how to arrange the various picture locations to give maximum flexibility of transfers. It should be possible to get from any one location to any other, and with a functional destination organization or any other it would be advantageous to build up a hierarchy of access levels so that the closest pictures were the most easily accessible. Such an arrangement of pictures we can term a *mesh.* We can make such a mesh by the intersection of *ladders* and *highways.*

A ladder is an array of two-screen stores arranged serially, so that the contents of any store may be transferred from either of its fluorescent screens to the two stores immediately adjacent to the chosen store.

A highway is exactly similar, but the highways are all parallel to each other, the ladders are all parallel to each other, and the two systems intersect at right angles (see Fig. 2 and Fig. 3).

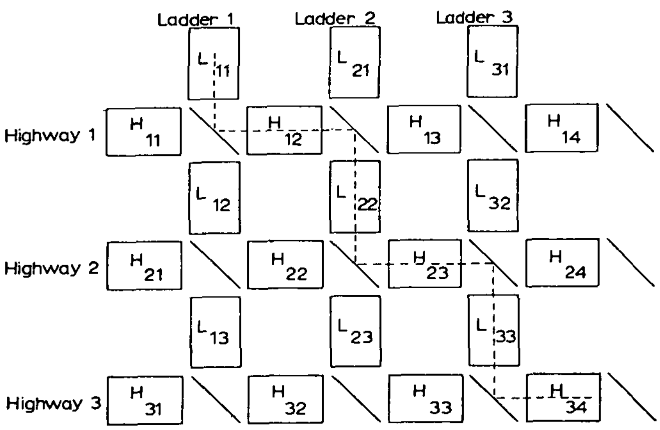

Fig. 2—Spatial arrangement of highway-ladder mesh

The cross-over transfers are effected by half-silvered plane mirrors inclined to the H-L directions.

L_{11} H_{12} L_{22} H_{23} L_{33} H_{34} illustrates a series of cross-over transfers.

At each intersection of a highway and a ladder a cross-over from one to the other is possible because the four stores are symmetrically placed, and then by introducing a half-silvered mirror at an angle of forty-five degrees to one of the light paths it becomes possible to transfer between the following typical pairs of stores, calling the highway stores H_{11}, H_{12} and the ladder stores L_{11}, L_{12}:

$$L_{11}, L_{12}, \qquad H_{11}, L_{12}$$
$$H_{11}, H_{12} \qquad H_{12}, L_{11}$$

but the transfers between L_{11}, H_{11} and L_{12}, H_{12} are not directly permitted. This mesh structure implies that the third-generation hardware will be magnetic-film rather than super-conductive because the latter would require numerous small cryostats for each group of picture stores, since the control unit must be within a few cm of the picture store to which it relates.

Multi-director unit

The standard cross-over between a ladder and a highway ensures that each picture store has direct access to four other stores. It may be advantageous to have special units which offer a wider variety of transfers. Such units may be useful in the vicinity of an arithmetic unit or some other fairly complicated device, so as to provide more data paths where the data flow in the computer is highest.

It must be remembered that it is not an advantage to have too many store-store transfer paths, nor too few. If we have too few the logical operations will be cumbersome and consume unnecessary time and storage capacity, whilst if too many the result will be too much passivity in the network. As an example, if we have a straight transfer from one store to another with the present level of four possible routes to each store, then the other three stores for each store in use are unusable in this time—a total of six unusable stores—whilst if as many as twenty stores were available, at least nineteen, and probably many more, would be out of action when any one was in use.

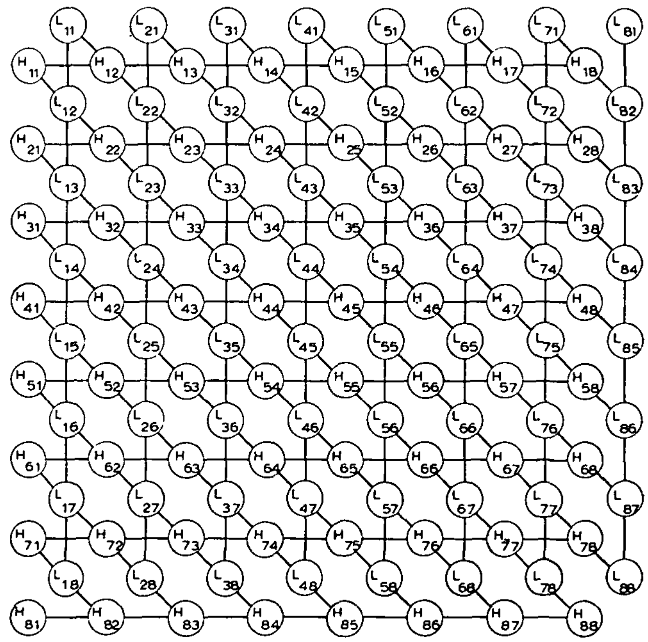

Fig. 3—Logical diagram of 8 highway × 8 ladder mesh

A multi-director unit must therefore be sited at a position of a slow operation involving large data flows, such as an arithmetic unit, or for slow units such as input and output units.

The arrangement shown in Fig. 4 is fairly typical.

Here we denote stores in the highway by H_1 and stores in ladders 1, 2, 3, 4 by L_1, L_2, L_3 and L_4. There are the usual half-silvered mirrors and some optical lenses

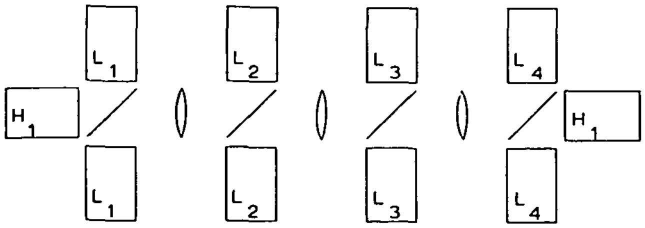

Fig. 4—Multi-director unit

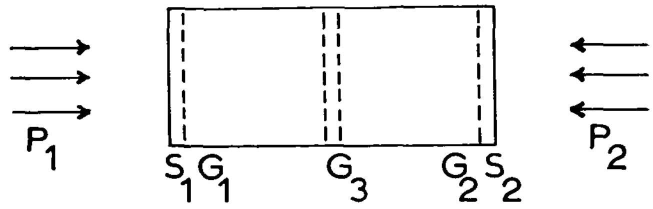

Fig. 5—Picture store (regenerator, and-gate)

which are needed to transfer the picture from stage to stage.

A variety of multi-director meshes may be constructed on the above principle, and it would be tedious to detail all the possibilities.

There are some difficulties here since, whilst the intensity of light from a H to L transfer is unique, the intensity is different for each L store. A possible solution might be to put neutral absorbing filters in the earlier L stores so that all stores have the same intensity. If this is done then the light intensity received by H in a L to H transfer is independent of which L store was the source; the same is true for L to L transfers.

Possible realizations of picture logic

We will consider the operation of the store shown in Fig. 5, with two insulating fluorescent electron-emitting screens S_1, S_2, and several fine grids (about 10 micron mesh or better will be needed eventually) G_1, G_2, G_3.

Initially a light picture P_1 impinges on S_1 liberating an electron-picture. A little later G_1, G_2, G_3 are all positive, G_2 being most positive, and the set of targets and grids G_3 give rise to cascade amplification of the electron-picture in number and energy, the electron-picture eventually impinging on S_2 liberating light and secondary electrons.

At this instant the grids switch over and G_2 assumes a potential which is just positive, relative to any element which has liberated a set of electrons corresponding to a bright-spot in the light picture P_1 or S_2. The grids then assume the potentials they had previously, but in the opposite direction, so that the electron-picture travels towards S_1G_1 again.

However, if a light picture P_2 had impinged on S_2 just when light picture P_1 had arrived, and liberated its secondary electrons, then there would have been electron densities corresponding to dark-spots, bright-spots, and double-bright-spots arising from the superposition of two bright-spots of the electron picture.

Now in this circumstance, when G_2 had gone to the potential just slightly positive relative to an area of S_2 which had emitted a bright-spot, it will be possible to have it negative relative to any double-bright-spot area. Consequently, whilst a small time-period elapses, the percentage of electrons drifting through the grid G_2 from bright-spot and dark-spot areas will be larger than that from the double-bright-spot areas, and the fraction of slow secondary electrons hitting the screen G_2 and recombining will be higher in the double-bright-spot areas than in the other areas.

Thus by controlling the grid voltage G_2 for a carefully determined time-period, it should be possible to reduce, at least partially, the disparity in brightness of the bright-spot and double-bright-spot areas, since the AND operation really needs them to be equal. The system would, however, tend to bring down the contrast since the dark-spot electrons will be passed even more easily.

The picture store will operate in two possible modes, a low-energy mode for regeneration and a high-energy mode for transfer. Present techniques are capable of producing good meshes with an element size of 25 microns. Such meshes can be used in the construction of the picture store for preventing inter-diffusion between adjacent elements, dividing the picture into separate micro-cubicles.

Picture Inverter Unit

A possible realization of the Picture Inverter Unit would consist of a picture store with a screen at each end, and an electron target and a fine grid. The electron picture from the screen at one end travels down towards an electron target, on which it impinges producing secondary electrons which escape and leave a picture in which the original electron bright parts are replaced by regions of the target with a positive potential due to the escape of the secondary electrons.

On the far side of this target is a fine grid about 10^{-4}cm away from the secondary emitting target. This grid is now raised to about 1000 volt positive relative to the secondary emitting screen. This will create a field of order 10^7 volts/cm and cold-field emission will occur.

There will be considerably more emission from the regions of zero potential (original electron dark parts) than from the regions of positive potential (original electron bright parts) and thus the electron picture produced by the cold-field emission process will be the light-dark complement of the original electron picture.

An alternative procedure is to produce the initial electron picture, and then counter-stream through its space-charge a uniform distribution of electrons, which will pass with maximum facility through the regions of minimum density of the original picture.

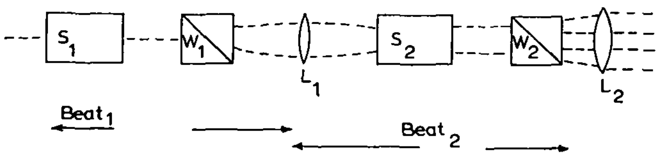

Fig. 6—Schematic vector recording unit

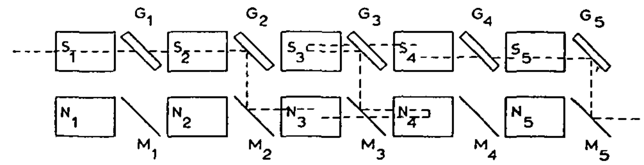

Fig. 7—Arbitrary shift unit

Vector Recording Unit

It is convenient to consider here the possible realizations of the Vector Recording Unit. The unit we shall consider is one which vector-records a single bit in all 64 bit locations, and which is used in conditional operations.

It is convenient to recall the phenomenon of optical double refraction and the properties of the Wollaston prism. This is a device which separates into two light beams an incident light beam. If we denote a two-screen store by S, an optical lens by L and a Wollaston prism by W, we can use the arrangement shown in Fig. 6.

The two-screen stores are assumed to have optical lenses on each side of them as part of the symbolic S.

We can now, having established the physical principles which are useful, proceed to realizations which are much faster.

Instead of having a two-screen store at every stage of the process there is no reason why three or four stages of the process should not be cascaded by a suitably designed arrangement of lenses and doubly refracting materials. The limit to this will be set by the maximum permissible loss in intensity in transferring a picture from one S-store to the next. It may well be possible to reduce this operation to a two-beat process with multiple recordings at each beat.

Optical variable shift unit

In pattern-recording matrices of arbitrary dimensions, and in standardizing words for floating-point addition/subtraction, it is necessary to be able to shift a picture by an arbitrary amount determined by the picture control units of third-generation hardware. It is possible to conceive of doing this by electro-magnetic procedures shifting the electron-picture. However, this will require specialized electronic control units and specialized store units, and it would be desirable, at least for the earlier computer developments, to obtain the necessary shifts by shuttering of various picture-stores of standard type.

We will recall that it is possible to shift a picture sideways by passing it through an oblique parallel-sided glass slab, or even by a physical displacement of the store-unit itself. We can then, in principle, produce an arbitrary shift by having pairs of stores, one of which has no shifts, and the other has a predetermined shift, so that by routing a picture through either "shift" or "non-shift" at each beat we can produce any desired shift in the unit as a whole.

In Fig. 7 S_j, N_j are the shift and non-shift stores and G_j are parallel-sided glass slabs with half-silvered front surfaces. The M_j are half-silvered mirrors.

We show in the figure a route that uses the shifts through G_1 G_3 and G_4 but not G_2 or G_5. The route is fairly straight-forward except in getting from N_3 to S_4 which requires the three steps:

(*a*) N_3 to N_4

(*b*) N_4 to S_3

(*c*) S_3 to S_4.

Abandoned lines of research

It is desirable to indicate very briefly lines of work which have been investigated and abandoned.

This investigation originally started from the observation that if the limit of computer speed was to be set by the inertia of electrons, then light pulses would have less inertia. An investigation of fast serial logic using light pulses was undertaken, and it was realized that light logic could involve the superposition of single or multiple words at single or multiple times. The pulse length L would have to be many wavelengths since the wavelength spread is

$$\delta\lambda/\lambda = 2\lambda/L$$

so that in green light $L = 10^{-4}$ cm was about the limit. This would give 3×10^{14} pulses per second serially.

The first method which was considered was the difference between single-slit and double-slit diffraction patterns, the latter having extra zeros that can be used logically. The difficulty here is the poor efficiency and the impossibility of a sufficiently rapid amplification of the logical output.

The next step was to consider a system in which the switching of the type of polarization was used:

$$\text{Plane Polarization} = 0 = P$$
$$\text{Elliptical Polarization} = 1 = E.$$

A quarter-wave plate was considered and it was realized that it could act as a NOT gate for a serial stream of pulses at 3×10^{14}/sec. Later it was realized that such a plate of cross section perhaps 1 cm^2 could be used to handle a stream of 10^4 parallel independent pulse-streams of 3×10^{14} pulses/sec each.

Thus a NOT gate operation speed of 3×10^{18} operations/sec was possible, given the pulse trains, with a device costing a few pounds at most and which could be held in two fingers quite easily!

The more difficult operation was the OR operation, which required the merging of two pulse streams. This was unsatisfactory, giving two sorts of elliptical polarization, one of which will interchange with the plane polarization and the other will not.

Since it was possible to run about 10^4 streams/cm^2 a "frame" of 10×10 cm was considered. In order to overcome the light-loss problems a laser was invoked, but as it was thought that it would have a characteristic response time of about 10^{-8} seconds, it would be necessary to decrease the pulse rate to 10^7 pulses/sec in each stream, with 10^4 streams/cm^2, which would still be a respectable figure.

The next step was to devise a "frame-store" in which there was a picture of 10×10 cm, containing 10^6 bits and being regenerated by focusing it through a laser by a *sharp* transfer (actually not possible at all), and reflecting an outgoing parallel beam back through an electro-optic shutter at the focus to image itself on the original light source.

This led to many difficulties which were only seriously recognized when it was realized that the regeneration method was not a sharp transfer. The possibility of image converter techniques was already noted, and the present scheme was started.

Conclusions

Considerable effort has been devoted to decreasing the characteristic switching times of a series of different computing systems over a period of almost twenty years. Despite this, little, if any, attempt has been made to explore the possibility of making the switching process more fruitful.

This paper has attempted to examine the logical problems involved in the construction of a *picture arithmetic* computer in which a whole picture of elements may be switched, simultaneously, in parallel without scanning the individual elements.

Both light pictures and electron pictures have been considered, and it has been shown that the logical problems are, in principle, soluble. The problems of realization are believed to be technological rather than fundamental. Each picture is controlled by a "one-bit" control unit of third-generation hardware, and it is possible to have perhaps 10,000 pictures with independent control units with restricted operation facilities, using a functional destination organization.

The maximum capacity of a single picture is switching about 10^8 elements in 10^{-8} seconds, whereas a conventional magnetic tape takes about 100 seconds to scan 10^8 bits.

Whereas conventional computers up to and including those of the third generation (magnetic film and transistors) are limited mostly by the finite velocity of light, the new fourth-generation computers will be limited mainly by the uncertainty principle associated with any form of wave motion, whether light waves or electron waves, and by power-supply problems.

Enormous technological advantages of picture operation arise because no material channels need be provided for light packets or electron packets, because there is an intrinsically large storage capacity, and because of the hardware economy possible, since no electronic selection of individual elements is necessary, although in some cases picture shifts are required.

A novel feature of the logic is the existence of a one-plus-one level of storage in a single picture, this distinction being formalized by the non-equivalent usage of the words "bit" and "element". Two types of transfer of a picture are distinguished, and are referred to as "sharp" and "fuzzy" transfers.

A valuable programming device is to sacrifice space for speed, by multiply-recording data in special patterns. Examples of this in matrix multiplication and inversion are given.

It seems reasonable to assume that a one-watt picture giving 10^{13} elements per sec will be feasible within 15 years, and it may be increased to 10^{16} elements/sec with very great difficulty. A large computer will have about 10^4 pictures.

This paper is regarded as an existence theorem, and not as a blueprint.

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