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SUBJECT: STORAGE DEVICES IN COMPUTING SYSTEMS, TEXT OF AN M.I.T. E.E. DEPARTMENT, COLLOQUIUM TALK

To: J. W. Forrester

From: R. R. Everett

Date: May 3, 1950

Abstract: This memorandum contains the text of a talk given at the E.E. Department Colloquium, May 3, 1950. The talk covers briefly: the need for storage in computation, the effect of storage characteristics on digital computer design, desirable storage characteristics, and the characteristics of existing storage devices suitable for digital computer use.

In this talk I shall be primarily concerned with storage devices for use in digital computers. It is by no means true, however, that storage devices are needed only in computers of the digital type. Storage is a necessary part of all computing systems, more generally, of all information-processing systems. Usually such storage is concealed by being an intrinsic part of the computing elements. Take, for example, a simple RLC filter, which is a specialized computing system (if you prefer, you can call a computer a specialized filter). This filter contains several different kinds of storage:

1) There is the storage of what the filter is to do. This storage is in the permanently selected sizes of the components and in their physical relationships. This is essentially storage of instructions.

2) There is the storage of input and output data and intermediate or partial results. This storage is in the components themselves, as evidenced by the voltages and currents. Since these components are actually doing the computing or filtering they are usually not thought of as storage devices.

Analog computers are very similar to the filter. They are usually thought of as assemblages of computing elements: they also contain storage of data in the positions of their shafts or voltage outputs of their amplifiers and storage of instructions in the interconnections of the elements.

Digital Computer

In the digital computer the storage function is distinct from the computing function and therefore appears as a special problem in its own right. (Slide #1)

The "so-called" general purpose digital computer consists of five elements, an arithmetic element that does the actual computing, a storage element that stores instructions and intermediate results, a control that directs the carrying out of the instructions, and input and output elements that insert data and extract results. One salient feature of this arrangement, the separation of storage and computing, is dictated by the high cost and high speed of the digital arithmetic element. This element is too complicated for more than one to be provided; at the same time it is fast enough to do all the necessary computing on a time-sharing basis. The digital computer may be compared to a man with a desk calculator and a notebook. The notebook contains the stored instructions as well as partial results, the desk calculator is the arithmetic element, the man performs the functions of control. (Lights.)

There are three types of data to be stored:

1) instructions
2) tables of functions, constants, etc.
3) partial results.

Different kinds of storage can be used, and in fact, have been used for these three types. The greatest convenience and flexibility is obtained, however, if there is but one kind of storage that can be used interchangeably for any purpose. Not only does this allow most efficient use of the available storage capacity - it allows the computer to treat orders as numbers and thus to change its procedures according to the course of the computation. The machine obtains some measure of judgement as well as the ability to calculate instructions, thus greatly simplifying the coding or setup of the machine.

The storage element is usually about one-fourth of a digital computer. The characteristics of the storage, however, determine the nature of the entire machine. Some of the questions to be asked are: Is the storage inexpensive enough so that instructions as well as numbers may be stored? Does the storage deliver digits serially (in time sequence on one line) or in parallel (simultaneously on a number of lines)? Can the storage conveniently deliver several words at once? How fast will the storage operate? These and other considerations determine the speed of the machine, its general arrangement, the complexity of control and arithmetic element, and the nature of the instructions.

We can easily set up some general specifications for a digital computer storage:

1) Extreme reliability - digital computers are peculiar in that a single error anywhere in the machine can destroy the entire calculation. For a high-speed computer such as WWI a desirable error rate would be one error or less in 10^{11} operations. We usually think of the telephone as pretty reliable. There are 130,000,000 telephone calls made per day in the United States. A failure rate of 1 in 10^{11} would be one wrong number in 2 years for the entire country - somehwat better than standard practice.

2) High operating speed - the arithmetic element and control that can be built using present day vacuum tubes and present day circuit techniques are faster than any available storage medium. The overall speed of the machine is almost entirely dependent on storage speed. An access time of a few microseconds is desirable.

3) Low cost - the demand for high-speed internal storage is insatiable. The lower the per digit cost of the storage the more storage can be provided and the more flexible and useful the computer will be. Somewhere in the order of 25,000 binary digits are needed as a minimum.

The nature of the storage available to the designer has determined the kind of computer he has built. The digital computer was first conceived by Charles Babbage in England in the last century. His machines, due to technical difficulties, were never built but his conceptions are still basic. For storage Babbage had available mechanical counter wheels and punched paper tape used for controlling weaving machines. His counter wheels were expensive; he therefore planned to use them only for a high-speed internal memory for variables and partial results. The paper tape, non-erasable, was to serve for the storage of orders. Note that his basic internal storage element and his basic computing element were the same.

The first successful large-scale digital computer was built within the last 10 years by Professor Aiken at Harvard. For Mk I, Aiken had available IBM electromagnetic counter wheels and punched paper tape. His solution was the same as Babbage's; the counter wheels serve as the basic element for a low capacity internal memory and for computing, the paper tape is used for orders.

The next step, made in the Harvard Mk II and the Bell Telephone Laboratory machines, was to use relays instead of counter wheels. The relay is faster than the counter wheel but is once again expensive and suitable only for a limited capacity internal memory and for computing. It was again supplemented by paper tape order storage.

The final step in this sequence was the ENIAC built during the war by the University of Pennsylvania. This computer used vacuum tubes for storage and computation. The vacuum tube storage element, the flip-flop or ring counter, is much faster than a relay but is also much more expensive. The resulting computer was thus much faster than the earlier machines but had much less internal storage - enough for only 20 numbers. Since paper tape order input was far too slow to keep up with the vacuum tubes the ENIAC was originally set up by cables and plug boards and now by selector switches.

These machines all have in common the use of a computing element as a storage element. The cost is high, the quantity small - hardly enough for variables and partial results. This storage must be supplemented by a slow, non-erasable, inflexible external storage for orders.

Another machine of approximately this type is the Selective-Sequence Electronic Calculator built by IBM and now in New York. This computer has a triple internal memory - a small amount of high-speed electronic storage, a larger amount of slower relay storage, and a large amount of very slow and inflexible paper tape storage. The orders are stored on a number of paper tapes, the ability to select among the tapes giving the machine its name.

The big step came with the development of high-speed erasable storages of low cost per digit. These new elements lost, necessarily, their computing abilities. They became storage only.

The fundamental storage problem is not that of discovering a suitable, compact, easily written, read, and erased storage element; it is the far more difficult problem of switching or selecting among large numbers of elements. The storage elements are necessarily in some spatial arrangement, and it is necessary to scan this array with the writing and sensing element. In the magnetic drum the storage element is a magnetized spot on the drum surface (a 2-dimensional array) and the writing and sensing element is a relatively massive magnetic head. Selecting a given element from rest at high speed is prohibitive because of the very high accelerations that must be given to appreciable masses. The use of a head for each element is too expensive. The solution is to wrap the 2-dimensional storage array into a cylinder and to rotate it at high speed past a set of fixed heads. The required accelerations are only the radial ones in the rotating cylinder and these require no energy. The selection is now one in space (among the heads) and one in time (among the elements as they pass the selected head). Physical questions limit the rotational speed of the drum. The average selection time is one-half a rotation period and is thus fairly high.

A second possibility is to store a sequence of digits in a delay line. The line is of finite length; as the digits come out the end they are amplified and reshaped and put back in the front. A sensing element in the feedback section selects among the digits in time as they pass by. A second selection, in space, can be made among a number of lines. The selecting system is very similar to that in the magnetic drum although the storage element is very different.

The storage tube has a great advantage over the other storage systems in speed of selection. It too uses a spatial storage array, charges on a dielectric plate. Its writing and sensing element consists, however, of an electron beam which can be given the high accelerations necessary to select any desired element from rest. There is no waiting time. It should be noted that the time required to actually read or write is comparable in the 3 types mentioned (of the order of a microsecond); it is the selection time that determines the storage speed.

Note also that the 3 types mentioned all make use of 2-dimensional storage arrays. A one-dimensional array is of little value unless the data is wanted in prearranged sequence because of the scanning time. The usual magnetic tape or wire can be useful as an auxiliary storage or for input and output but not for internal storage. It would appear that a 3-dimensional element array with arbitrary selection in the 3 dimensions would give the greatest promise for an economical high-speed storage and, in fact, such a storage is under development.

The 3 storage types mentioned above - magnetic drum, acoustic delay line, and storage tube - also determine to a large extent the physical nature of the machine. The first two tend to demand a serial machine with a multiple address order, the last a parallel machine with a single address order.

One interesting characteristic of most of the new machines is that the bulk of each machine outside the storage itself is made up of flip-flop (vacuum tube) storage elements. Some of these compute (count) or control computing elements (decoding matrixes, gate tubes, and such); the bulk of them form a very short access (1μsec) storage for such purposes as holding the multiplicand. Even in a digital computer we have not entirely succeeded in separating the storage function from the computing function.

(Slide #2)

Typical Magnetic Drum Storage

We will now examine briefly the characteristics of the 3 presently most useful storage systems.

The first, the magnetic drum, consists of a cylinder with a surface of magnetic material, rotated at high speed before a set of magnetic heads. This storage is characterized by large capacity, moderate cost, and long access time. The density is high, 1000 digits or more may be stored per square inch of surface. The total storage may be of the order of 100,000 to 1,000,000 binary digits. A moderate size drum of 120,000 binary digit capacity is shown. In general, higher capacities are obtained by increasing the size of the drum and reducing its speed, thus keeping the pulse-repetition-frequency constant under the head. The figures given are for a reasonable combination of capacity, speed and cost.

The access time is determined by the speed of rotation of the drum. For the example shown 3600 rpm is used; 7200 rpm or higher is sometimes used. The access time is largely spent in waiting for the desired data to go by. The maximum time is one revolution period or 16 milliseconds; the average time will be one-half a revolution period or 8 milliseconds. Higher speeds or the provision of additional sets of reading heads can reduce this time somewhat.

Although the pulses on any given track will be read out in time sequence or serially, a number of tracks are available. A set of tracks may be read out simultaneously or in parallel. The drum thus provides a choice of data form. The access time is not affected by this choice.

The cost shown is approximately that of procurable drums of this size. There is no allowance for development. The bulk of the cost is in the control and associated circuitry which includes amplifiers for the heads, an electronic flip-flop register to store information during the waiting period, counters to keep track of drum position, and switches to select between heads. About 600 tubes are required for these purposes.

The 5-year cost includes an allowance for maintaining the equipment. The life of the equipment is hard to estimate. After 5 years the drum will probably be operable but obsolete.

(Slide #3)

Typical Delay Line Storage

The delay line is most commonly an acoustic mercury delay line although electrical delay lines are sometimes used for low capacity storage (a few digits only). In the storage shown, a number of delay lines are provided in one large tank of mercury, although a separate tank can be provided for each line. An input crystal when pulsed, sends an acoustical shock wave travelling through the mercury which is detected by the output crystal and the resulting pulse amplified, reshaped, and put back into the line. The line capacity equals its time delay divided by the pulse interval. A 500 microsecond line is about three feet long and will hold 500-1 megacycle pulses, 1000-2 megacycle pulses, etc. Since the stored pulses appear in time sequence at the input, the access time will average one-half the delay. The cost of each line is nearly independent of the length of the line since the crystals, amplifiers, etc. are still needed. The design length is then a balance between access time and storage capacity - a condition that also exists in the magnetic drum.

The example given is of a typical modern design. Four-megacycle pulses are used (actually rf modulated at the crystal), and the lines are about 150 microseconds long and store about 600 digits. 64 lines are provided for a total capacity of 43,000 binary digits. The access time is assumed equal to the line length for purposes of checking: the data comes out in serial form at 4 megacycles.

The cost given is an estimate and once again is largely the cost of the control and auxiliary circuitry. The tank itself is probably worth about $2000.

(Slide #4)

Electrostatic Tube Storage

There are a number of electrostatic storage tubes ranging from commercial cathode ray tubes to very special types. The example shown uses the special storage tube developed by Project Whirlwind. Data as to the costs and performance of the various electrostatic storage devices is not as readily available as data on other storages since electrostatic storage is in an earlier stage of development.

The tubes shown in the example are assumed to have a capacity of 1000 binary digits each, with an access time of 10 microseconds. Whirlwind's present tubes store about 400 points with an access time of about 25μsec, but development is proceeding toward tubes of the specifications shown. These tubes can be made using Project facilities for about $1200 each. They have a life of about 2000 hours. They can then be reprocessed at a cost of about $200 to give another 2000 hours life. The net result is a $1400 tube with a 4000-hour life.

The storage capacity shown is that of WWI. 16 tubes in parallel make up one bank of storage, and two banks are provided for. The total of 32,000 binary digits is in the form of 2000 words of 16 binary digits each although this arrangement does not affect the cost or performance figures.

The 10 microseconds access time includes deflection setup, readout, and auxiliary operations. The control, deflection equipment, and auxiliary circuitry for this storage is only about 50% greater than the auxiliary equipment of the other 2 storages. The much higher cost represents our detailed knowledge of the cost of building this equipment to WWI standards. More realistically, the control costs should be comparable.

Assuming 10,000 hours of computer operation in 5 years, 80 original and replacement tubes will be needed for a total cost of $112,000.

(Slide #5)

Storage Figure of Merit

It is difficult to evaluate different storage systems on a fixed basis. The high-performance systems are more expensive than the low-performance ones. The best solution when a large amount of storage is required or when low cost is desirable will be different from the solution when high operating speed is of first importance. A useful figure of merit for storage elements is a performance-unit.

$$\text{Performance unit} = \frac{\text{Digit Capacity}}{\text{Access Time}}$$

The digit capacity can be measured in binary digits. Access time can be measured in microseconds. Either a higher storage capacity or a shorter access time increases the performance-unit rating of the storage.

On the basis of cost per digit the magnetic drum is best. On the basis of cost per performance-unit the electrostatic storage is best despite its high per-digit cost. Incidentally, on this same basis flip-flop storage costs about $500 per digit. Its access time is about 2 microseconds giving it a cost per performance-unit of $1000.

(Slide #6)

WWI Operating Speed vs. Storage Access Time

The performance unit rating is actually unfair to the higher speed storage units when they are considered for heaving computing loads such as occur in simulation and control or other real-time work. Storage access time is the primary factor limiting machine speed in present machine designs. This curve shows the operating speed of WWI as a function of storage access time. Cutting access time by a factor of two will increase machine speed by almost the same factor. The cost of the storage is less than one-quarter the cost of the machine. The cost of the storage could thus be multiplied by 4 and retain the same computer cost on the basis of operations per second.

(Slide #7)

Computer Figure of Merit

This slide shows a rough estimate of the cost and operating speed of computers using different storage elements. A very generous allowance is made for the economy in the rest of the computer due to reduced operating speed. The greater storage capacity of the magnetic drum machine has not been taken into account in these figures.

If the computer is used for problems where a large amount of storage is required (such as partial differential equations) the magnetic drum machine may hold its own, the operating speed of the faster machines being reduced by the necessity for continually referring to a low-speed auxiliary memory. For real-time work computer speed may be of more than linear importance. When the point is reached where the computer speed is insufficient to solve the problem in real time, then a second computer must be provided and the problem divided between them. This is usually possible with more or less efficiency, but it is undesirable. In this instance, digital comouters are much like people. When the job gets too big for one man, an assistant can be provided. This is seldom as good as doubling the working capacity of the first man. When you have more than one person or one machine working together you have the problem of communication and, with all due respect to Mr. Lephakis*, the best solution to the communication problem is to avoid it.

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* Co-speaker on Storage Devices in Communication Systems.

Signed Robert R. Everett
Robert R. Everett

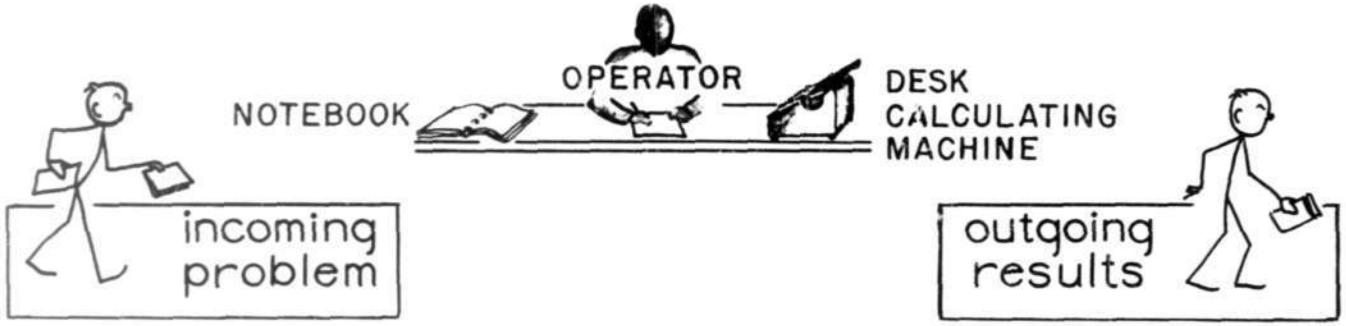
RRE:bm

SLIDE NOS.	DRAWING NOS.
1	A-35676
2	A-35645
3	A-35643
4	A-35642
5	A-35644
6	A-35646
7	A-35647

A-3567
F-1028
SC-207

BASIC COMPUTER ELEMENTS

comparison between manual computation



OPERATOR

NOTEBOOK

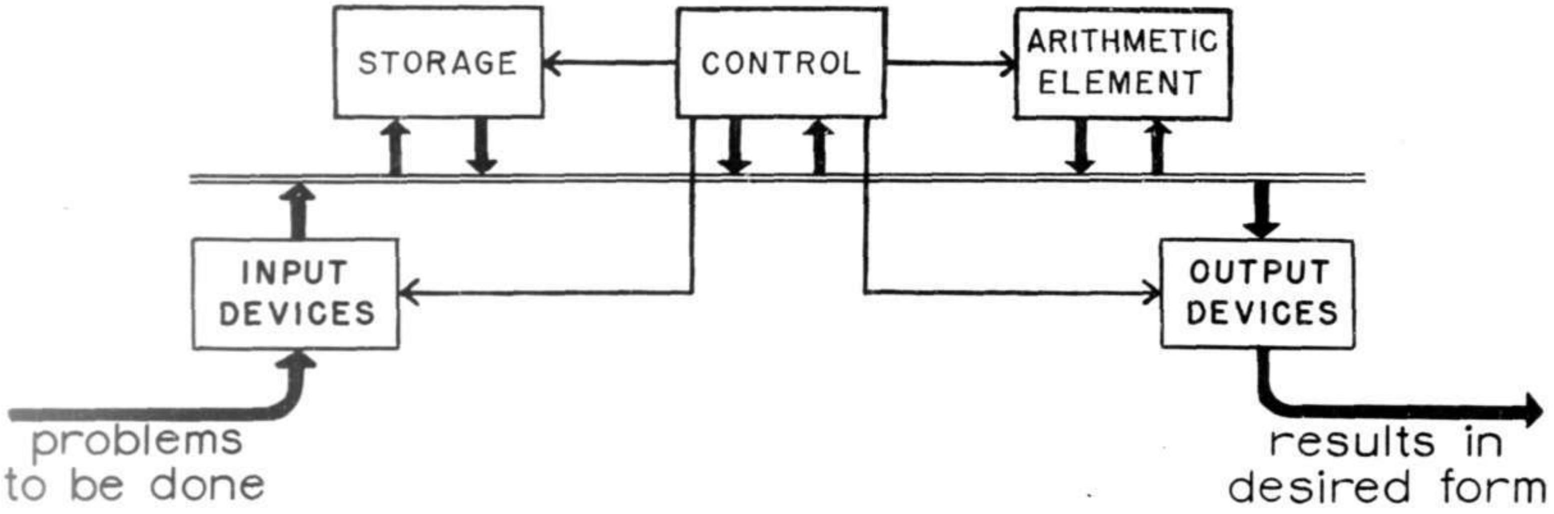
DESK
CALCULATING
MACHINE

incoming
problem

outgoing
results

and

WHIRLWIND I computation



STORAGE

CONTROL

ARITHMETIC
ELEMENT

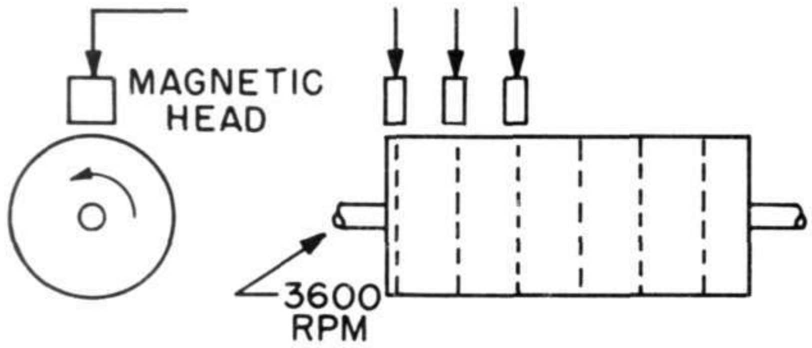
INPUT
DEVICES

OUTPUT
DEVICES

problems
to be done

results in
desired form

TYPICAL MAGNETIC DRUM STORAGE



STORAGE CAPACITY	120,000 BINARY DIGITS
ACCESS TIME	8000 MICROSECONDS (AVERAGE)
FORM OF DATA	SERIAL OR PARALLEL
ORIGINAL COST (EST)	$25,000
YEARLY MAINTENANCE (EST)	$3,000
TOTAL COST FOR 5 YEARS	$40,000

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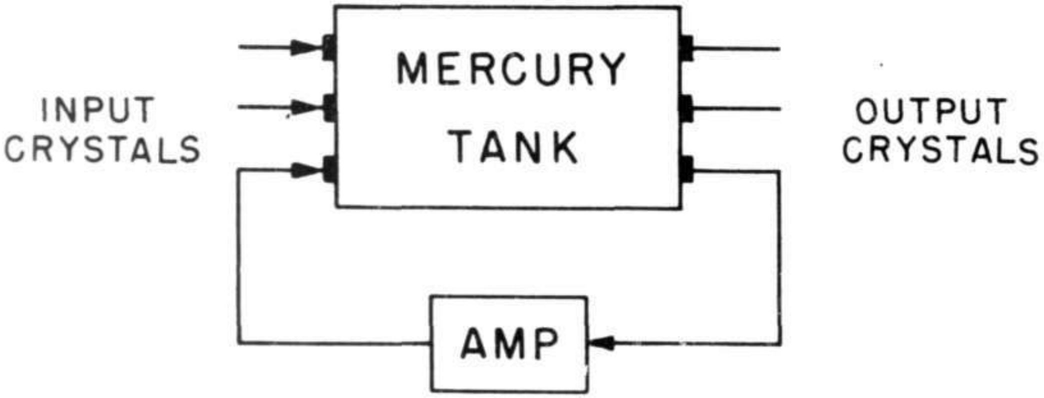
TYPICAL DELAY LINE STORAGE



STORAGE CAPACITY	43000 BINARY DIGITS
ACCESS TIME	150 MICROSECONDS
FORM OF DATA	SERIAL
ORIGINAL COST (EST)	$ 30,000
YEARLY MAINTENANCE (EST)	$ 3,000
TOTAL COST FOR 5 YEARS	$ 45,000

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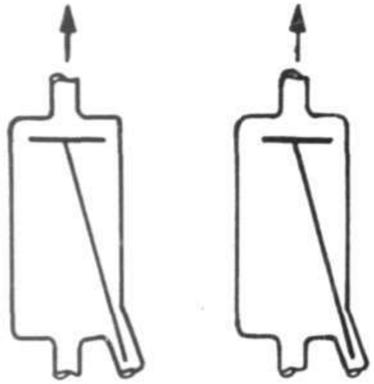
ELECTROSTATIC TUBE STORAGE



TUBE COST	$1400
LIFE	4000 HOURS

STORAGE CAPACITY	32000 BINARY DIGITS
ACCESS TIME	10 MICROSECONDS (PARALLEL)
FORM OF DATA	PARALLEL
ORIGINAL COST OF CONTROL	$115,000
YEARLY MAINTENANCE OF CONTROL	$5,000
5-YEAR COST OF ORIGINAL AND REPLACEMENT STORAGE TUBES	$112,000
TOTAL COST FOR 5 YEARS	$252,000

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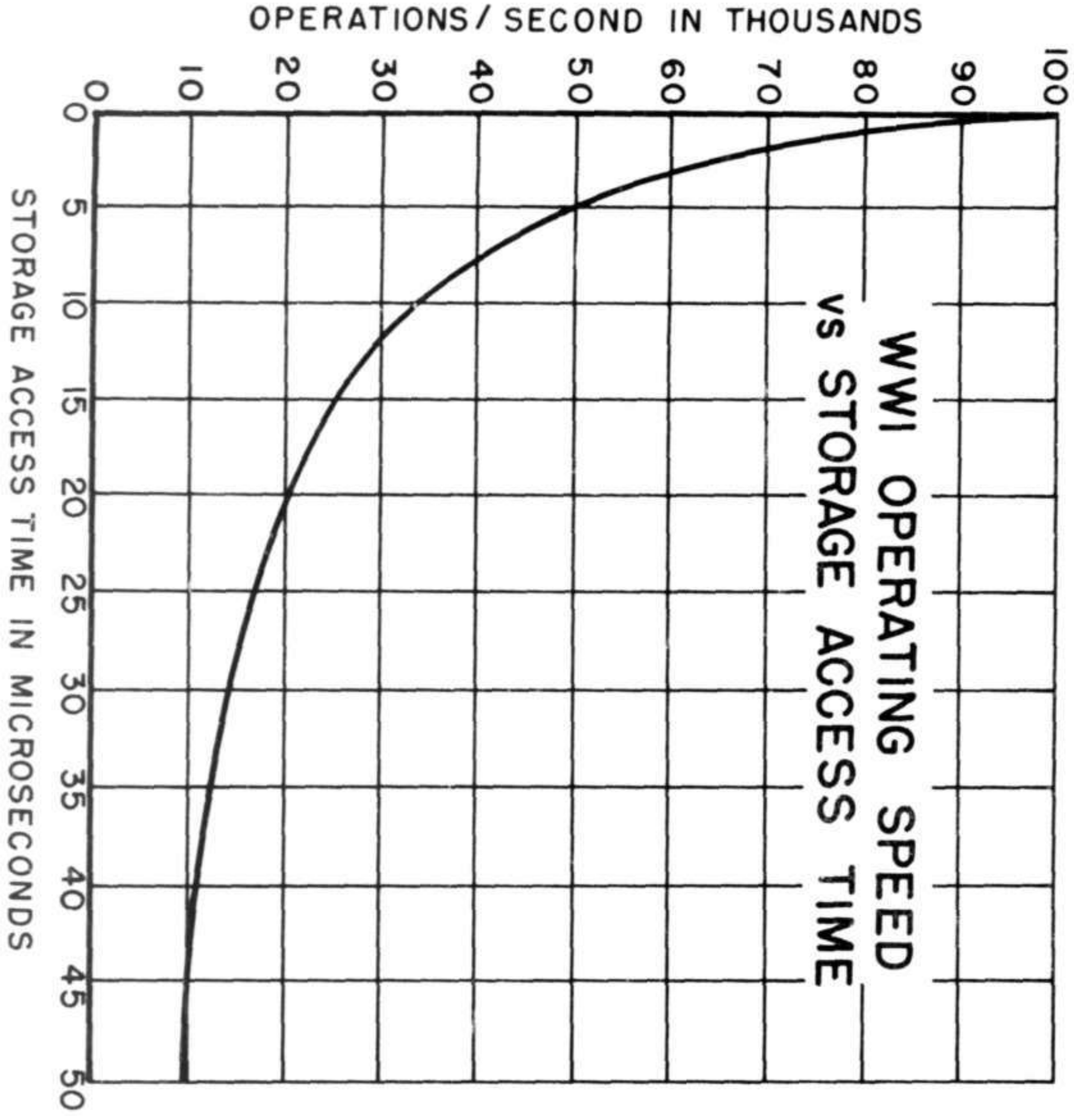

WWI OPERATING SPEED vs STORAGE ACCESS TIME

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COMPUTER FIGURE OF MERIT

TYPE OF MACHINE	COST	OPERATIONS PER SECOND	COST PER OPERATION PER SECOND
MAGNETIC DRUM	$ 100,000	100	$ 1000
ACOUSTIC DELAY LINE	$ 300,000	2000	$ 150
ELECTROSTATIC STORAGE	$ 1,000,000	30,000	$ 33