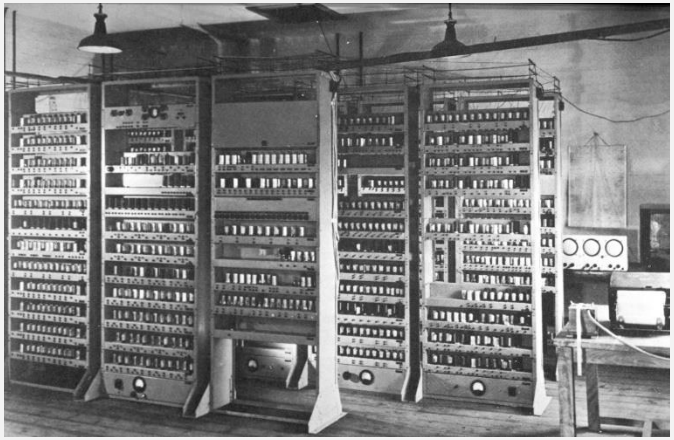
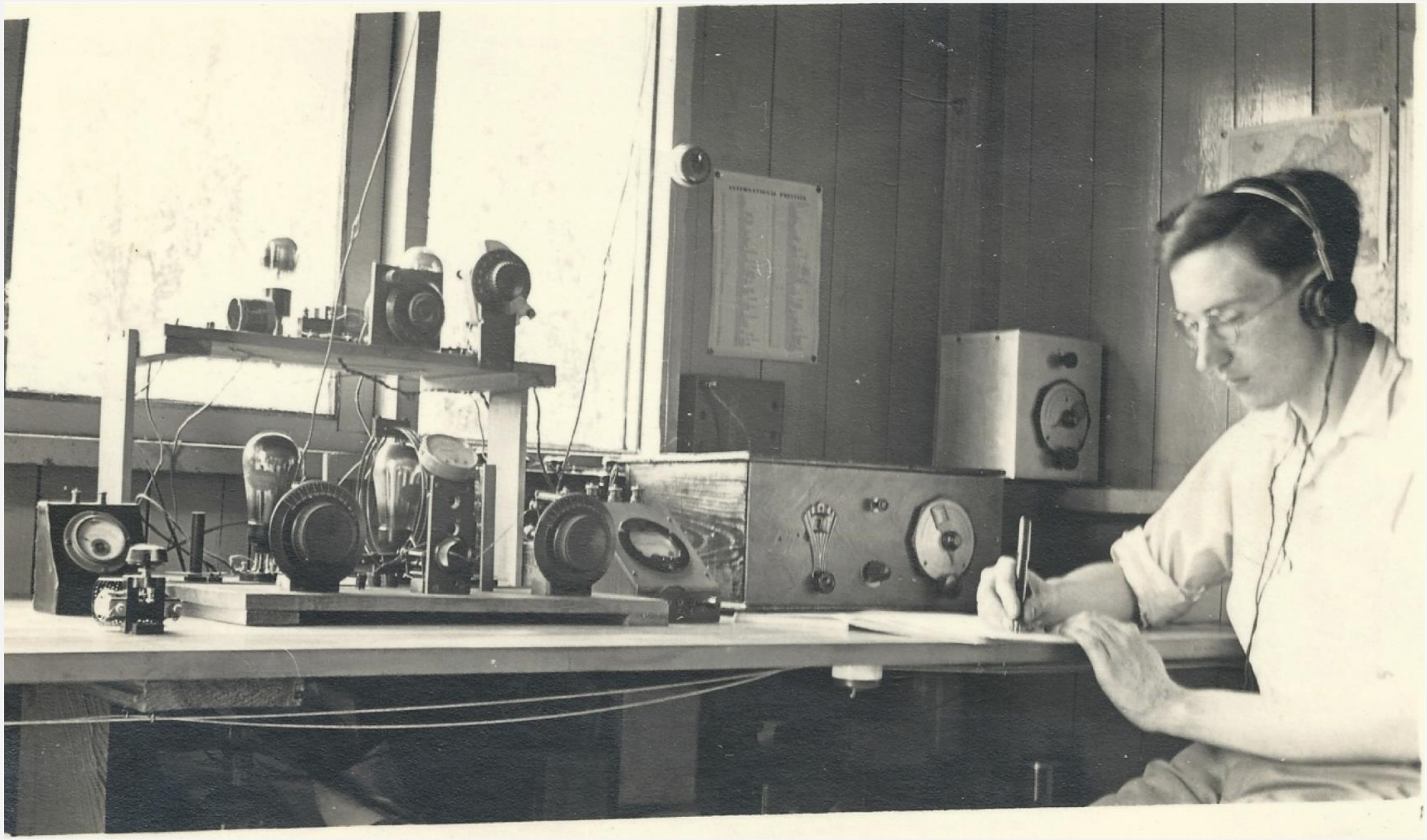
BUILDING THE EDSAC, 1946-1949

Martin Campbell-Kelly, Warwick University



EDSAC and replica



Maurice Wilkes’ background

Machine Solves Mathematical Problems

A Wonderful Meccano Mechanism

FROM time to time examples have been given in the "*M.M.*" of the readiness with which the most complicated mechanisms can be reproduced in Meccano. An excellent instance of this is the wonderful astronomical clock described on page 170 of our issue for March, 1933, which automatically gives a wealth of ...ng and useful astronomical information. More recently ... has been used in the construction of a remarkable machine ...es in a few minutes complicated equations that otherwise ...nly be dealt with by laborious calculations occupying ...urs. The original of this model is a machine known as ...erential Analyser that was developed by Dr. V. Bush, ...sident of the Massachusetts Institute of Technology, ...ge, U.S.A. In constructing this machine, which at present ...ly one of its kind in the world, Dr. Bush's purpose was to ... the labour of ...alculations from ...nplicated equa... ...t with in working ...lems in electrical ...er branches of ...ing, and also in ...and astronomy. ...olution of these ...s is often diffi... ...d the kind of ...ical work in... ...not well known, ... prolonged and ...ne. Further, ... calculators are ... error, especially ...ying out long ... similar calcula... ...ch as are often ...y in work of ...d. These diffi... ...are avoided by ... of the machine. ...w hours it can ...o provide solu... ...r equations of ...ing complexity, ... accurate results ...btained from it ...onvenient form ... minutes.

...eral view of the ...tial Analyser is ... the upper illus... ...on the opposite ... It has been de... ...as one of the most comprehensive pieces of mathematical ...ry ever built, but in spite of its formidable appearance ...lly simple in construction. It consists of an assembly of ...at mechanically add, subtract, and carry out other and ...mplicated mathematical operations, and by adding more ...can readily be enlarged to deal with problems of increasing ...ity. As a matter of fact it grows so continuously that ...gner has expressed the opinion that it will never really ...plete.

...most important mathematical operation that the machine ...ut distinguishes it from other kinds of calculating machine, ...kes it unique in the range and complexity of problems to which it can be applied. This operation can best be explained by an example. Suppose that a motor car is starting from rest, and that we have a record of its speed at each moment from the start. This record might be in the form of a graph showing how the speed varied with the time from the start; in handling the problem by the Differential Analyser the information actually would be supplied to it in the form of such a graph. From this information we require to know how far the car goes in, say, two minutes. We can find this approximately by dividing the period of two minutes into smaller intervals, for example into 12 intervals of 10 seconds each; and by imagining that the speed remains constant in each interval, then suddenly changes to another constant value in the next interval, and so on. Thus we can find the distance travelled in each period by multiplying each time interval by the supposed constant speed corresponding to it, and finally add up the distances travelled in successive intervals to find the total distance covered.

The result will be only approximate, because the speed actually is not constant in each interval, as we have imagined it to be. The error on this account can be decreased, however, by dividing up the period into smaller intervals, say 24 of five seconds each, or 60 of two seconds each, etc., until the variation of speed in each interval becomes too small to matter. By taking small enough intervals an accurate result can be calculated, however rapidly the speed varies during the total period concerned.

Professor D. R. Hartree and Mr. A. Porter, of the Department of Mathematics, The University, Manchester, with a wonderful Meccano mechanism they have constructed to solve complex mathematical problems. This mechanism is a reproduction on a smaller scale of the Bush Differential Analyser illustrated on the opposite page, and a simpler form of it is illustrated at the top of page 444.

The mathematical operation in which the distance traversed is derived from the speed, which is regarded as known, is technically called "integration"; and the essential feature of the machine is that it incorporates devices called "integrators" for carrying out this operation mechanically. How an integrator works will be described later.

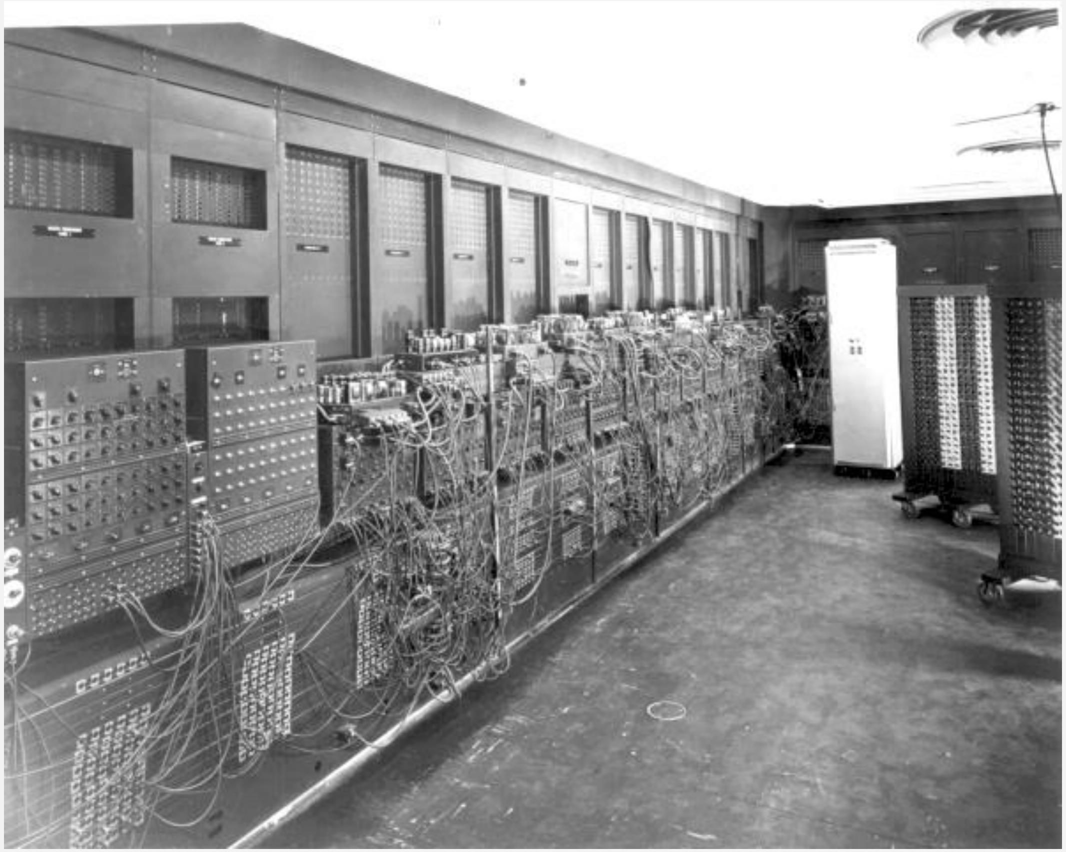
This operation of integration arises in the working out of the most varied problems, in astronomy, physics, chemistry, and engineering, and the scope of problems that can be investigated by the machine is correspondingly wide.

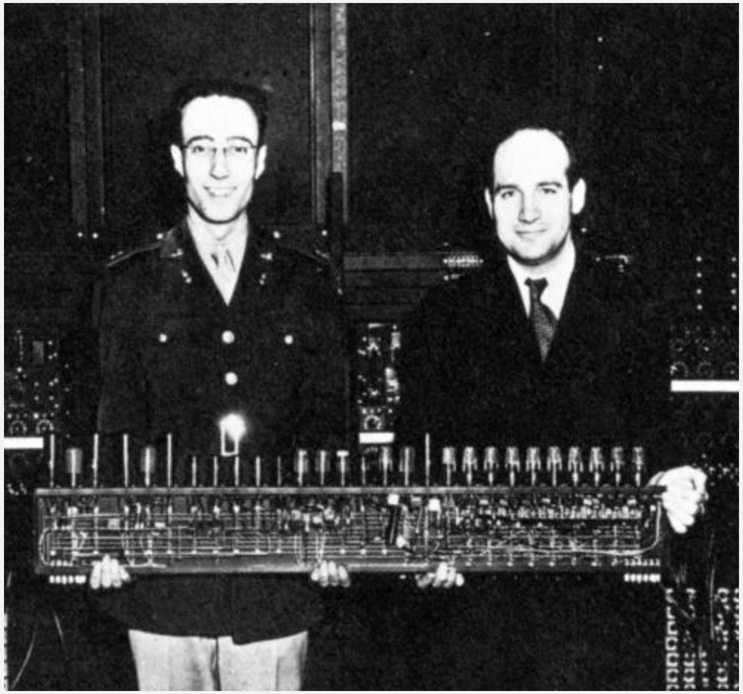
In the centre of the machine is a set of longitudinal shafts, which in our illustration can be seen running from the lower left-hand corner towards the right-hand upper corner. These shafts can be geared to each other so as to rotate at various relative speeds, and the rate at which each turns represents a term in the equation for which a solution is required. The manner in which they are geared depends on the relation between the terms. For instance, if any two terms are to be added together, the shafts representing them are connected with a third by means of differential gearing designed to make the third shaft turn at a speed representing the sum of the speeds of the shafts driving it. More complicated relationships are worked out through special devices such as the integrators already mentioned, which can be seen on the right of the longitudinal shafts; and others known as input tables, which are on the left. Both devices are driven by means of cross shafts.

When the necessary connections have been made, one of the shafts is driven by an electric motor, and in turn drives the other shafts, each at its appropriate speed. When this is done, the speed of the shaft representing the term of which the value is to be found then gives the required solution. For the type of equation dealt with on the machine, the kind of result most usually required is not a single number, but a series of related numbers. For example, in the case of the motor car already considered we wished to know the distance the car travelled in two minutes. To complete our information, however, we require to know how far the car goes in three, four, five, or any other number of seconds. The machine

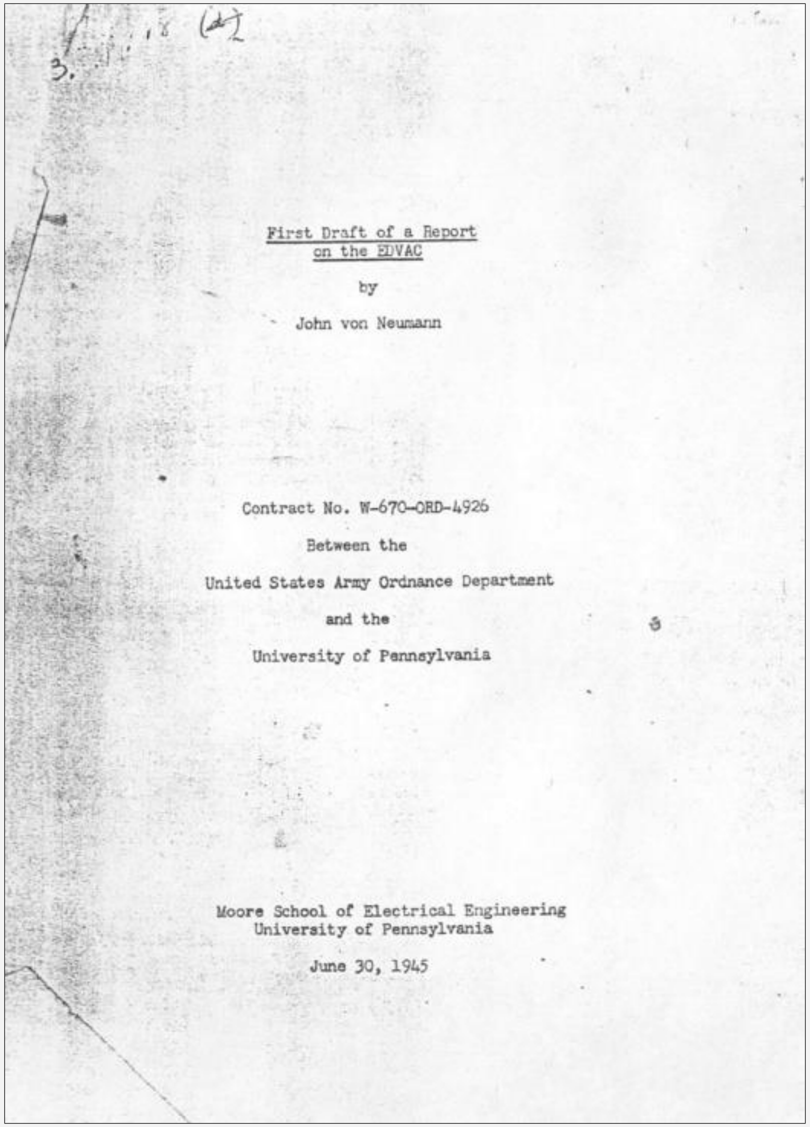
The Mathematical Laboratory, 1937; Meccano Differential Analyser

The ENIAC with Pres Eckert, John Mauchly and Herman Goldstine, c. 1945





Shortcomings of the ENIAC



First Draft of a Report
on the EDVAC

by

John von Neumann

Contract No. W-670-ORD-4926

Between the

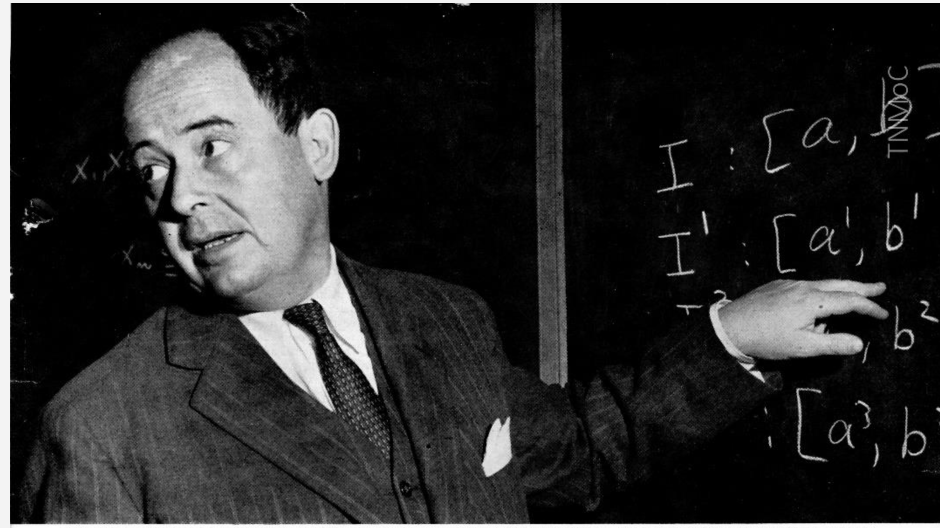
United States Army Ordnance Department

and the

University of Pennsylvania

Moore School of Electrical Engineering
University of Pennsylvania

June 30, 1945



IMPARTING HIS MATHEMATICAL INSIGHT TO STUDENTS, VON NEUMANN FILLS BLACKBOARD WITH SYMBOLS AS HE OUTLINES THE SOLUTION OF A PROBLEM

Passing of a Great Mind

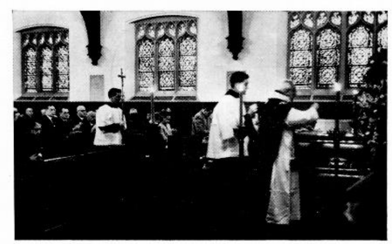
JOHN VON NEUMANN, A BRILLIANT, JOVIAL MATHEMATICIAN, WAS A PRODIGIOUS SERVANT OF SCIENCE AND HIS COUNTRY

by CLAY BLAIR JR.

THE world lost one of its greatest scientists when Professor John von Neumann, 53, died this month of cancer in Washington, D.C. His death, like his life's work, passed almost unnoticed by the public. But scientists throughout the free world regarded it as a tragic loss. They knew that Von Neumann's brilliant mind had not only advanced his own special field, pure mathematics, but had also helped put the West in an immeasurably stronger position in the nuclear arms race. Before he was 30 he had established himself as one of the world's foremost mathematicians. In World War II he was the principal discoverer of the implosion method, the secret of the atomic bomb.

The government officials and scientists who attended the requiem mass at the Walter Reed Hospital chapel last week were there not merely in recognition of his vast contributions to science, but also to pay personal tribute to a warm and delightful personality and a selfless servant of his country.

For more than a year Von Neumann had known he was going to die. But until the illness was far advanced he continued to devote himself to serving the government as a member of the Atomic Energy Commission, to which he was appointed in 1954. A telephone by his bed connected directly with his AEC office. On several occasions he was taken downtown in a limousine to attend commission meetings in a wheelchair. At Walter Reed, where he was moved early last spring, an Air Force officer, Lieut. Colonel Vincent Ford, worked full time assisting him. Eight airmen, all cleared for top secret material, were assigned to help on a 24-hour basis. His work for the Air Force and other government departments continued. Cabinet members and military officials continually came for his advice, and on one occasion Secretary of Defense Charles Wilson, Air Force Secretary Donald Quarles and most of the top Air Force brass gathered in Von Neumann's suite to consult his judgment while there was still time. So relentlessly did Von Neumann pursue his official duties that he risked neglecting the treatise which was to form the capstone of his work on the scientific specialty, computing machines, to which he had devoted many recent years.

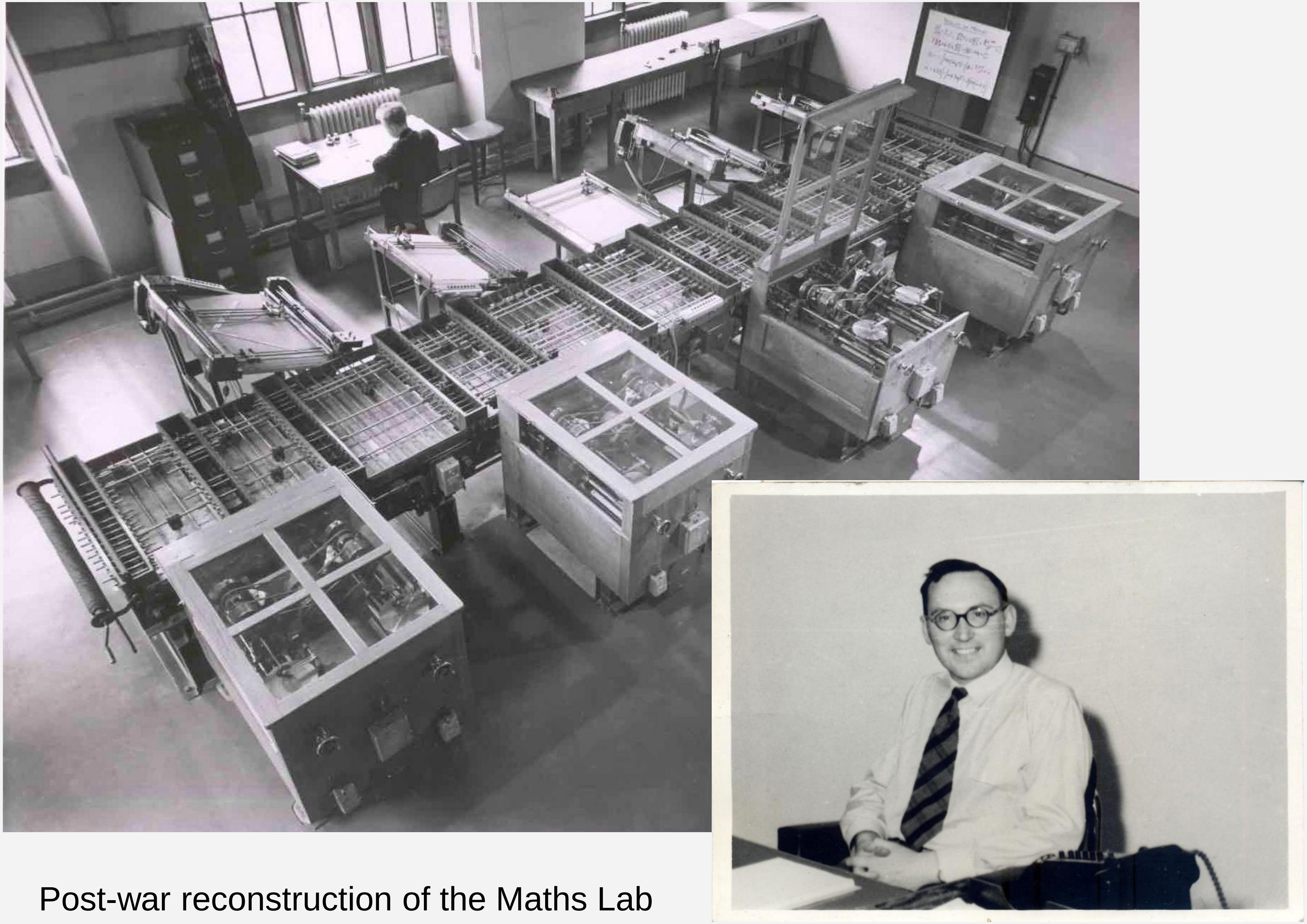


SMALL CHAPEL of Walter Reed Hospital provided unprepossessing setting for scientist's funeral. Next day Von Neumann was buried at Princeton.

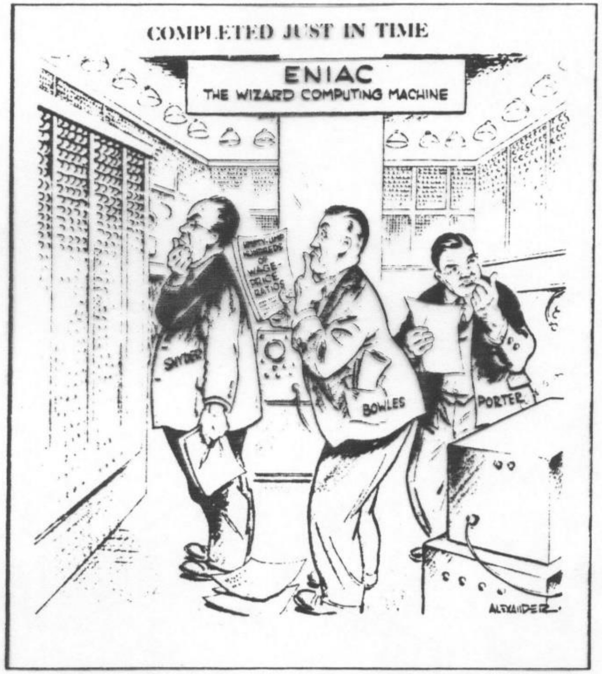
His fellow scientists, however, did not need any further evidence of Von Neumann's rank as a scientist—or his assured place in history. They knew that during World War II at Los Alamos Von Neumann's development of the idea of implosion speeded up the making of the atomic bomb by at least a full year. His later work with electronic computers quickened U.S. development of the H-bomb by months. The chief designer of the H-bomb, Physicist

CONTINUED

The EDVAC Report on the stored program computer, John von Neumann, June 1945



Post-war reconstruction of the Maths Lab

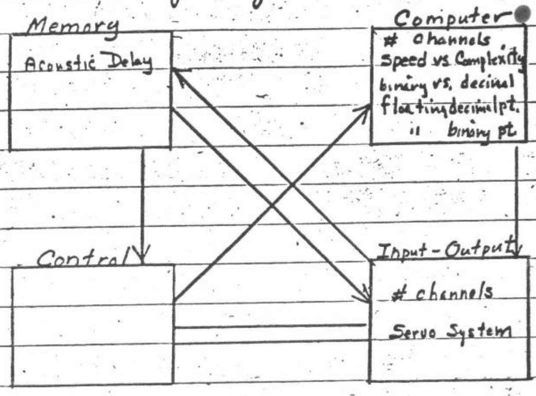


A newspaper cartoon suggests that ENIAC might be able to solve the perplexing wage-price problems that faced Treasury Secretary John Snyder, OPA Administrator Chester Bowles, and Sidney Porter in February 1946 (from the Philadelphia Evening Bulletin*).*

How did Wilkes find out about the stored program computer? Moore School Lectures

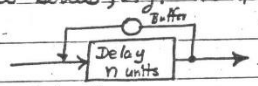
7-15
EPPARD
2 PM

Block Diagram of EDVAC Design



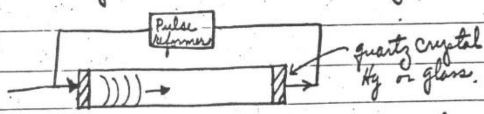
Types of Memory

1) Electromagnetic Type -- Relays, however this is too slow.
2) Acoustic Delay lines - serial representation of numbers in a time series, e.g. $n = a_1 a_2 \ldots a_n$ 32 equally spaced time intervals



If the delay = n, we have a memory for n units.

3) Magnetic disk with recording and reproducing heads (not regenerative)
4) Acoustic delay lines (limited memory)



the incident impulse sends out a wave from a which reaches b at some time later determined by the velocity of propagation

Moore School Lectures: stored program computer structure; mercury delay-line memory

Code (contd)

Sign ±	0	1	2	3	4	5	6	7	8	9	
		α			β			γ			order operation

Example of a possible Coded Program

Operation	α	β	γ	
a	(α)	(β)	(γ)	add α to β + put into γ register
s	(α)	(β)	(γ)	subtract " from β + " " "
m	(α)	(β)	(γ)	multiply " by β + " " "
n	(α)	(β)	(γ)	negative " " " " " "
m			0	clear
c	(α)	(β)	(γ)	compare α + β, if α > β proceed to (γ); α < β proceed serial fashion
x	α	β	γ	Compare a coded number γ with β.
t	(α)	(β)	γ	transfer α to β γ times
p	(α)	(β)	γ	place $\alpha \cdot (10^{\gamma})$ into β register
q	(α)	(β)	(γ)	" $\alpha \cdot (10^{-\gamma})$ " " "
i	α	β	γ	Insert #'s α to β into γ.
e	(α)	(β)	γ	extract #'s α to β " "
f. b₁	— (α)	(β)	γ	words read from α into tape #1 forward.

note: There is no logical reason for distinguishing a number from an order.

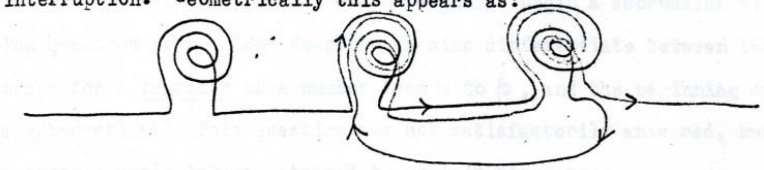
2). No register is cleared unless a number is to be entered.

3) γ specifies how many units of 25 words are to be read or recorded.

e.g. q | 849 | 900 | 002 | ≡ take the # in register 849, shift it 2 digits and place it into register 900.
(α = 849, β = 900, γ = 002)

AT THE BEGINNING OF A SUB-ROUTINE:

The control must remember at which point the main program was discontinued, must supply the numbers required in the sub-routine, and it must supply an order to pick up the main program at the point of interruption. Geometrically this appears as:



This indicates that sub-routines within sub-routines are possible.

The sub-routine must be furnished with:

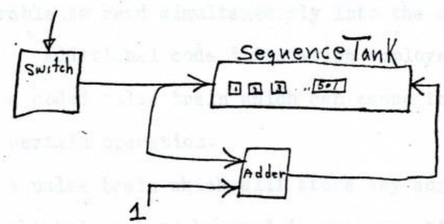
1) The numbers required in the sub-routine computation.

2) Instructions telling it where the result of the computation is to be stored.

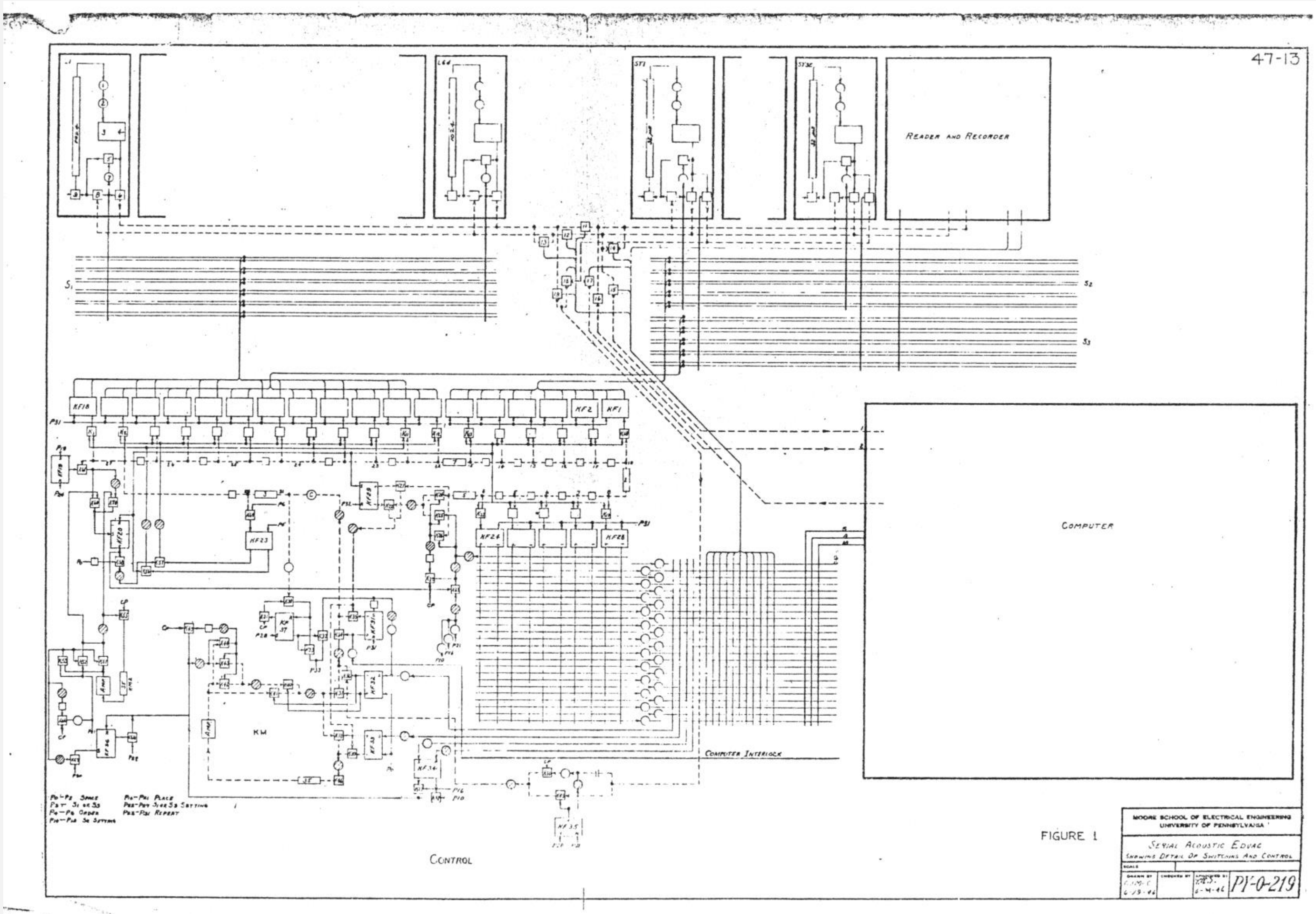
3) Instruction to return to the main routine.

CONTROL UNIT:

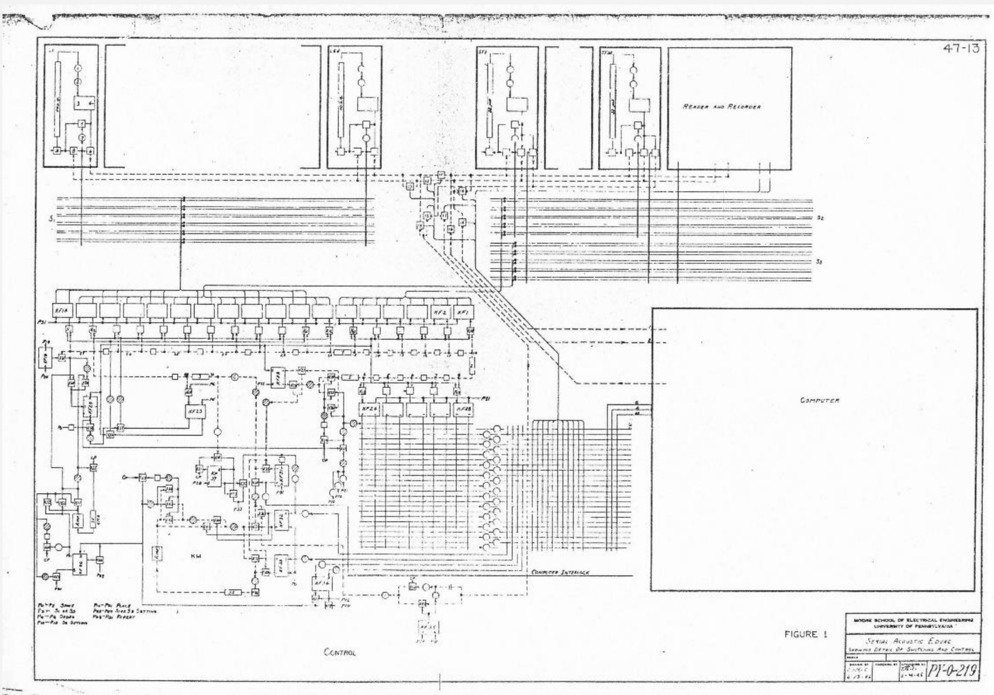
The control unit must progress along the program chain and execute the orders which exist therein. Such a device must contain switches, counters, synchronizing devices, interlocks, etc. Some record must be kept of the operations completed. This may be done by a sequence counter:

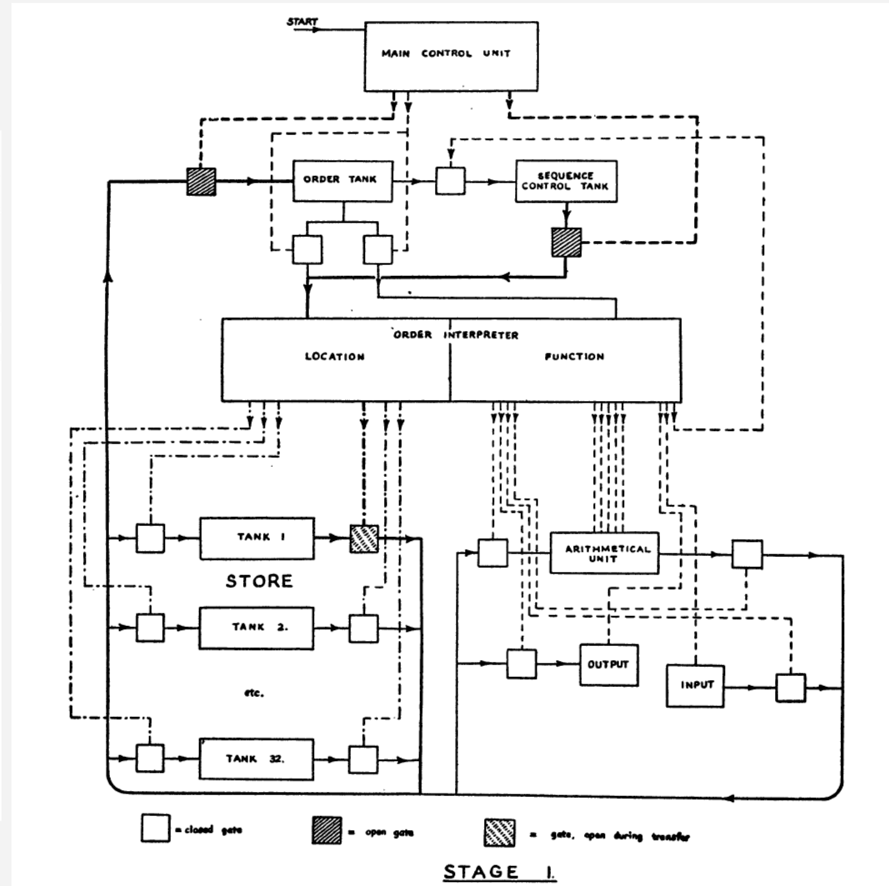


Moore School Lectures: order code and and subroutines

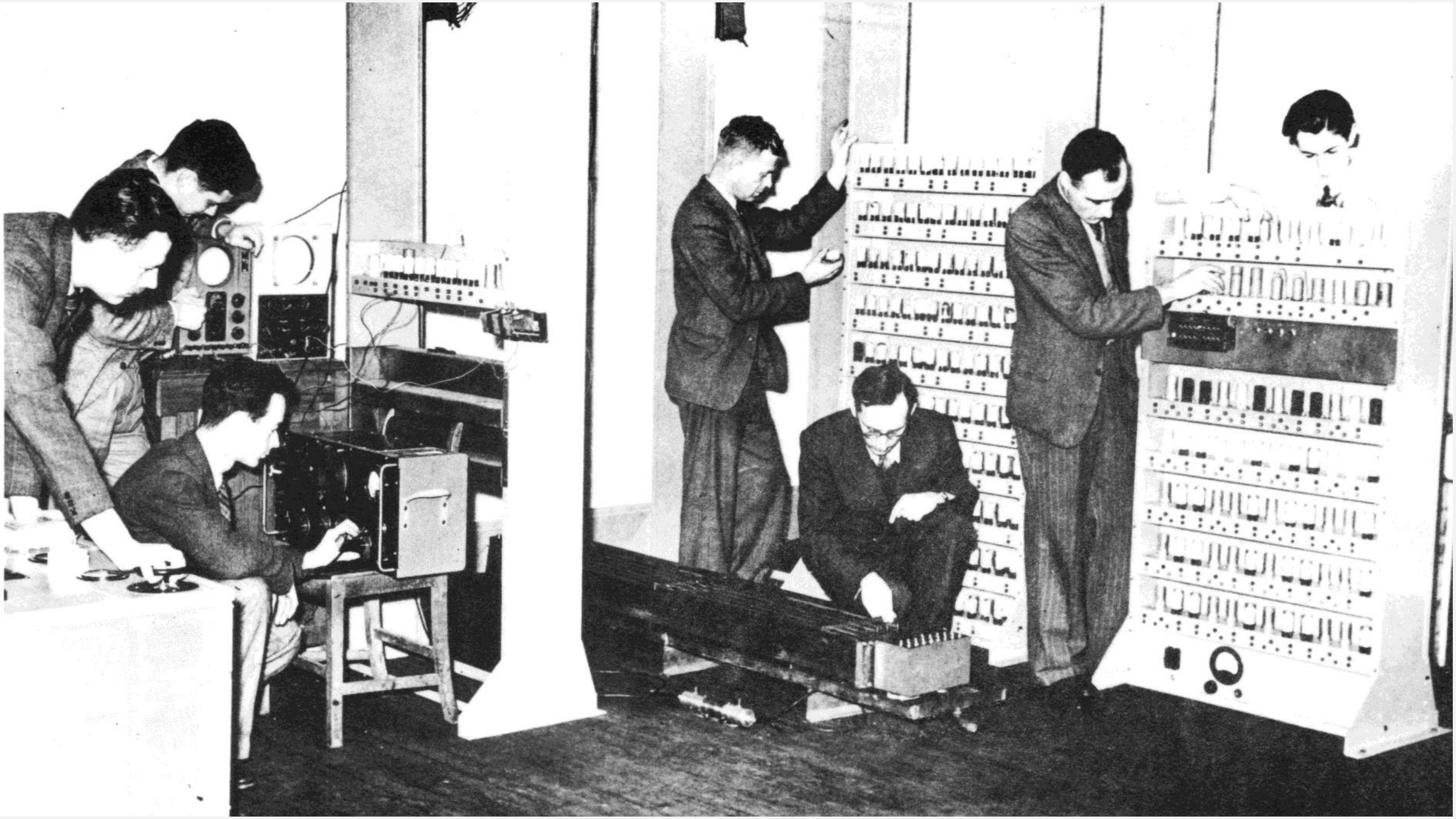


Moore School Lectures: stored program computer structure EDVAC block diagram





The EDSAC 1946-49: EDVAC and EDSAC block diagrams



The EDSAC under construction

CAMBRIDGE DAILY NEWS, Friday, October 3, 1947

"BRAIN" WILL KNOW THE ANSWERS

To 1,000 Questions a Minute

A "BRAIN" that will be capable of completing 1,000 questions a minute is in course of construction in the University Mathematical Laboratory.

Work on the "brain" has been going on for about 12 months. It is carried out by a team of six, who are lead by Dr. H. V. Wilkes, director of the laboratory, and wartime radar research expert.

Officially, the "brain" is known as "Edsac" (electronic delay storage automatic calculator) and Dr. Wilkes told a "C.D.N." reporter that it will be used for the solution of problems connected with mathematics, mathematical physics, engineering and, possibly, economics.

At present one "memory unit" has been completed and tested satisfactorily. It consists of 16 metal tubes full of mercury weighing about 200 pounds. Another has yet to be assembled, and when finally completed the "brain" will consist of these and eight racks containing between 1,000 and 1,500 valves.

Questions will be fed in on a punched tape and the answers delivered by teleprinter.

The "brain" will store constantly moving electric and supersonic waves, each representing a number, in the mercury filled tubes. From there they can be switched into circuits to add, subtract or whatever is required.

Dr. Wilkes hopes to be carrying out final tests in about a year's time.

Photo (Cambridge Daily News

Dr. Wilkes adjusting the four-fo.t mercury tubes—" the brains " of the machine.

The EDSAC: mercury delay-line memory

arithmetical unit or the input-output mechanism. The arithmetical and transfer orders used in the EDSAC are as follows:

- *A* *n* Add the number in storage location *n* into the accumulator.
- *S* *n* Subtract the number in storage location *n* from the accumulator.
- *H* *n* Transfer the number in storage location *n* to the multiplier register.
- *V* *n* Multiply the number in storage location *n* by the number in the multiplier register and add into the accumulator.
- *N* *n* Multiply the number in storage location *n* by the number in the multiplier register and subtract from the accumulator.
- *T* *n* Transfer the contents of the accumulator to storage location *n* and clear the accumulator.
- *U* *n* Transfer the contents of the accumulator to storage location *n* and do not clear the accumulator.
- *L* *n* Shift the number in the accumulator *n* places to the left; i.e. multiply it by 2^n.
- *R* *n* Shift the number in the accumulator *n* places to the right; i.e. multiply it by 2^{-n}.

The code used in the EDSAC is of the type sometimes known as *single address*, i.e. each order contains reference to one location only in the store. Three orders are necessary to add together two numbers from the store, and to place the answer in a specified location in the store; namely, two *A* orders to call out the numbers one after the other and to add them into the accumulator (which is assumed to be cleared before the operation begins), and a *T* order to transfer the result from the accumulator to the store.

An operation which is taken for granted by a human computor, but which must be programmed explicitly when using an automatic machine, is that of picking out a particular group of digits, for example, the integral part, from a number. In order that this operation may be mechanized, a special order, known as a *collate order*, is included in the EDSAC order code. The group of digits to be selected from the given number is specified by means of a second number, introduced for the purpose and placed beforehand in the multiplier register by means of an *H* order. Collation consists in adding a '1' into the accumulator in digital positions where both numbers have a '1', and a '0' in other positions; for example, the effect of collating 100110 with 110101 is to add 100100 into the accumulator. The collate order is as follows:

- *C* *n* Collate the number in storage location *n* with the number in the multiplier register.

If each arithmetical operation had to be ordered separately there would be little advantage in using an automatic machine, since the operations themselves could be performed on a desk machine in the time taken to punch the orders. Mathematical calculations of the kind it is desired to perform on an automatic machine are, however, highly repetitive, in the sense that the same or similar arithmetical routines are performed repeatedly on different sets of numbers. The orders defining each routine need be punched once only, provided they can be used as often as is necessary. This is made possible in the EDSAC by the provision of what is known as a *conditional order*.

At certain stages in a repetitive calculation the next operation will depend in some way on what has gone before. For example, an iterative process may have to be repeated until an error term becomes less than a certain amount, or terms of a series may have to be calculated until a term of magnitude less than a pre-assigned quantity is reached. In all cases it is possible to express the condition in terms of the sign of a quantity which can be calculated from the result of previous calculations. The programme can, moreover, be arranged so that this quantity stands in the accumulator at the moment that the decision is to be made. It is thus sufficient to have a conditional order whose action depends on the sign of the number in the accumulator.

The orders are normally placed in a block of consecutively numbered storage locations, beginning at location 0. When the start button is pressed, the order in location 0 is first executed, then the order in location 1 and so on. This routine is interrupted only if a conditional order is encountered. The conditional order is as follows:

- *E* *n* If the number in the accumulator is greater than or equal to zero, execute next the order that stands in storage location *n*; otherwise proceed serially.

A conditional order may be said to transfer control from one part of the programme to another. Once control has been transferred in this way the machine proceeds to execute orders serially starting from the new location.

The following example illustrates the use of the conditional order. It is the calculation of the residue of a given (positive) number θ with respect to the modulus 2π. To do this 2π must be subtracted from θ repeatedly until further subtractions would make the remainder negative. It is assumed that initially θ is in storage location 100, and that storage location 101 contains the number 2π. The programme is then as follows:

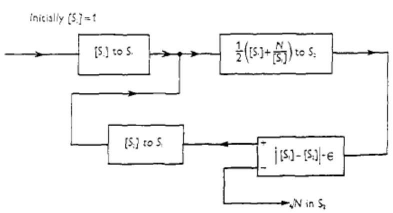
Location of order in store	Order
1	*A* 100
2	*S* 101
3	*E* 2
4	*A* 101

If the action of this programme is examined it will be seen that θ is first placed in the accumulator and 2π subtracted from it. If the answer is positive, control is transferred back by the conditional order, and another subtraction of 2π is performed. This process is repeated until the number in the accumulator becomes negative. The conditional order then allows control to proceed serially, and 2π is added; the number in the accumulator is then the required residue.

A more complicated example is the calculation of a square root by means of the iterative formula

$$x_{n+1} = \tfrac{1}{2}(x_n + N/x_n).$$

Instead of writing down the orders in detail, it is convenient to describe the programme by means of a flow diagram.



Calculation of $\sqrt{N}$ by means of the iterative formula

$$x_n = \tfrac{1}{2}(x_{n-1} + N/x_{n-1});$$

x_0 is taken to be 1

The symbol S_r is used to denote storage location *r*, and $[S_r]$ the contents of this storage location. Rectangles or 'boxes' with one inlet and one outlet stand for operations; for example, the box at the top left-hand side of the diagram

orders are automatically placed in the store in sequence, beginning with position 0. These orders enable further orders to be taken in from the tape and placed in the store.

(5) Arithmetical operations performed on orders

An important feature of machines of the present type is that, since orders are expressed in numerical form, arithmetical operations can be performed on them. For example, if an order refers to location *n* in the store, it is possible by adding 1 in the least significant position to modify it so that it refers to location $n+1$.

By use of this device it is possible to treat by iterative or repetitive methods operations which do not at first sight appear to lend themselves to such treatment. The advantage of doing this is that the number of orders required for the solution of a problem—and hence the number of storage locations required to hold them—can often be much reduced. An example is the evaluation of $\sum_{r=1}^{100} a_r^2$, where a_r is one of a series of 100 given numbers. Suppose that initially the accumulator is empty and that the contents of the store are as follows:

$[S_{101}] = a_1$, $[S_{201}] = 1$,
$[S_{102}] = a_2$, etc., $[S_{202}] = 99$,
......,
$[S_{200}] = a_{100}$, $[S_{203}] = 0$.

The programme is then as shown in the next column. For convenience the orders have been divided into groups and lettered. The first order takes effect once only; the others form a repetitive sequence.

At the beginning of the first repetition the accumulator contains the number 99. This is transferred to the store by the first order (*a*) of the sequence. The orders in group (*b*) cause a_1^2 to be calculated and placed in the store. Groups (*c*) and (*d*) modify the orders in group (*b*) ready for the calculation of a_2^2. Group (*e*) is concerned with keeping count of the number of times the sequence has been performed. At the end of the first repetition the number standing in the accumulator is 98. Since this is positive, control is transferred to the beginning of the sequence.

	Location of order in store	Order
	0	*A* 202
(*a*)	1	*T* 202
(*b*)	2	*H* 101
	3	*V* 101
	4	*A* 203
	5	*T* 203
(*c*)	6	*A* 2
	7	*A* 201
	8	*T* 2
(*d*)	9	*A* 3
	10	*A* 201
	11	*T* 3
(*e*)	12	*A* 202
	13	*S* 201
	14	*E* 1
	15	...

At the beginning of the second repetition the number 98 is transferred from the accumulator to the store. a_2^2 is then calculated and added to a_1^2, the result being placed in the store. The orders in group (*b*) are modified ready for the calculation of a_3^2. At the end of the sequence the number in the accumulator is 97. Control is therefore transferred once more to the beginning, and the sequence repeated.

It will be observed that the number in the accumulator at the end of each repetition is one less than at the end of the previous repetition. When the required quantity $\sum_{r=1}^{100} a_r^2$ has been calculated and placed in the store, the number in the accumulator is -1. No further transfer back of control takes place, and the machine proceeds to execute whatever order has been placed in storage location 15.

Programmes for matrix multiplication and analogous operations may be constructed in the same manner.

NOTES AND NEWS

Manufacturers' Publications

Copies of the publications mentioned in this Section are normally obtainable gratis from the manufacturer named. When requesting copies readers should mention this Journal.

Spectrographic Apparatus. Hilger and Watts Ltd., Hilger Division, 98 St Pancras Way, London, N.W. 1. A 52-page illustrated brochure S.B. 107/12 gives details of spectrographic outfits for metallurgical and general chemical analyses.

Electrical Instruments. Dawe Instruments Ltd., 130 Uxbridge Road, Hanwell, London, W. 7. Leaflet 1210A describes a direct reading frequency meter and photoelectric attachment for measuring rotational speeds without imposing a load on the machine to be tested. Leaflet 1250A describes a dynamic balancing machine for locating and measuring the unbalance in small rotating parts or assemblies weighing up to 7 lb.

Thermostatic Bath. A. Gallenkamp and Co. Ltd., 17–29 Sun Street, London, E.C. 2. Leaflet No. 513 describes a thermostatic bath suitable for general laboratory purposes consisting of a glass vessel, thermostat unit and control box.

Relays. Electro Methods Ltd., 220 The Vale, London, N.W. 11. Two leaflets describe the Type H. 15 a.c. and d.c. heavy duty magnetic relay and the Type XE d.c. magnetic relay.

Resistors. Morganite Resistors Ltd., Bede Trading Estate, Jarrow, Co. Durham. Leaflet R.P. 9 gives details of heavy duty carbon resistors.

Vacuum Equipment. W. Edwards and Co. Ltd., Lower Sydenham, London, S.E. 26. Leaflet D 20/3-1 describes the Philips cold cathode ionization gauge Model 3 for the measurement of high vacua in the range 0·005–0·00001 mm. of mercury (5–0·01 μ); leaflet B/903A/1 describes Type 903A oil diffusion vacuum pump with combination baffle valve.

Pressure and Vacuum Gauges. The Brown Instrument Co. Ltd., Philadelphia 44, Pa., U.S.A. Catalogue No. 700 is a 32-page illustrated brochure giving details of pressure and vacuum gauges for use in indicating, recording and controlling.

Conductivity and pH Recorders and Controllers. The Brown Instrument Co. Ltd., Philadelphia 44, Pa., U.S.A. Catalogue No. 15-12 is a 43-page illustrated brochure giving information on pH and conductivity control and describing instruments for this purpose.

Programming: symbolic instructions; instruction modification

MANCHESTER UNIVERSITY ELECTRONIC COMPUTER.

Programme Sheet 2.

ROUTINE INPUT (SHEET I).

/	/	E	/	/	/	A	/	@	/	E
	/	E	/	/	B	/	/	T	:	
	/	E	/	/	@	T	E	/	J	
	/	E	/	/	A	"	E	/	P	
	/	E	/	/	:	£	K	T	B	
	/	E	/	/	S	V	K	T	/	
	/	E	/	/	I	Z	E	/	C	
	/	E	/	/	U	M	K	/	N	
	/	E	/	/	½	M	K	T	A	
	/	E	/	:	D	R	/	/	:	
	/	E	O	/	R	V	K	/	E	
	Y	@	/	:	J	J	:	/	C	
	/	E	T	:	N	V	K	/	N	
	/	E	T	£	F	V	K	/	A	
	/	E	T	£	C	V	K	P	O	
	X	@	/	:	K	/	A	I	P	
	/	E	T	£	T	/	X	£	£	
	L	E	T	£	Z	R	/	/	/	
	/	E	T	£	L	/	/	/	/	
	~~/~~	~~E~~	T	£	W	H	K	T	/	
	/	E	T	£	H	N	S	/	P	
	O	E	T	£	Y	/	½	Y	B	
	/	E	T	£	P	/	D	H	B	
	Q	@	T	£	Q	J	@	L	V	
	/	E	T	£	O	A	/	@	/	
	/	E	T	£	B	Q	E	T	/	
	/	E	T	£	G	U	S	/	P	
	B	@	T	£	"	½	E	/	B	
	/	E	T	£	M	R	/	/	:	
	"	@	T	£	X	V	K	/	A	
	/	E	T	£	V	V	:	/	C	
	/	E	T	:	£	V	K	/	N	

Tape:- INPUT ONE SPECIAL

@	R	/	/	:	/	A	E	K	/	A
	V	K	/	A	E	A	E			
	Y	:	/	C	@	A	E			
	V	K	/	N	A	A	E			
	V	K	/	A	:	A	E			
	V	K	H	O	S	A	E			
	D	S	Y	O	I	A	E			
	C	@	T	:	U	A	E			
	B	@	/	P	½	A	E			
	M	K	T	F	D	A	E			
	U	@	/	P	R	L	@			
	@	/	E	@	J	L	@			
	V	S	T	A	N	L	@			
	/	/	/	P	F	L	@			
	M	K	T	½	C	L	@			
	J	S	Y	G	K	L	@			
	K	S	/	T	T	L	@			
	/	/	H	A	Z	L	@			
	/	/	/	P	L	L	@			
	J	S	Y	O	W	L	@			
	/	A	/	P	H	L	@			
	E	/	/	:	Y	L	@			
	J	@	/	:	P	F	@			
	@	/	/	@	Q	L	@			
	Q	@	/	:	O	L	@			
	U	E	/	/	B	L	@			
	"	E	T	£	G	L	@			
	G	@	/	P	"	L	@			
	J	@	/	:	M	½	@			
	E	/	E	K	X	L	@			
	Q	@	/	:	V	L	@			
	/	/	/	/	£	/	E			

INPUT TWO SPECIAL.

CALCULATION OF FUNCTIONS

BY THE USE OF RECURRENCE FORMULAE

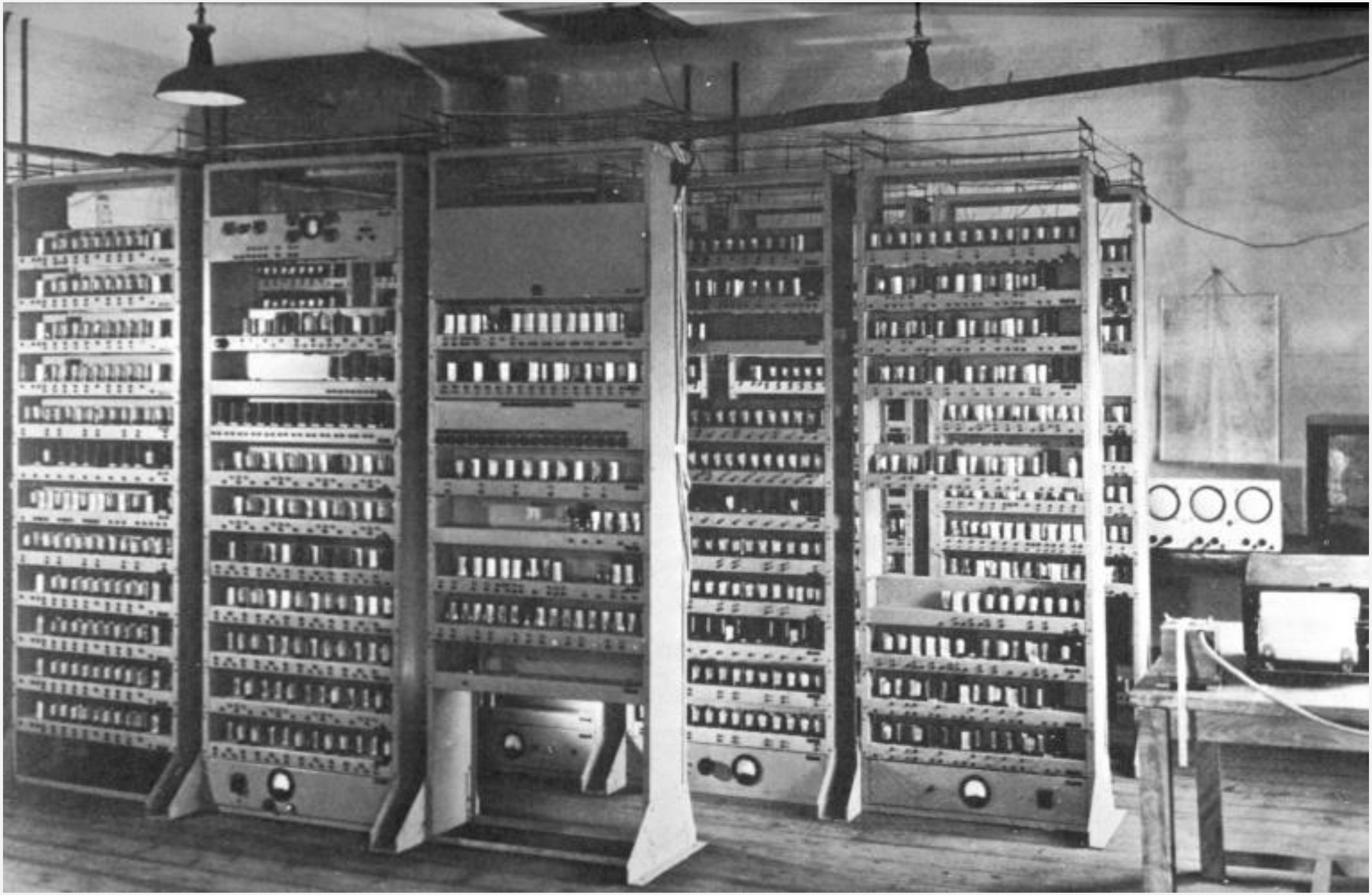
There are many functions in common use which are most easily calculated by means of recurrence formulae. Such formulae can be expressed as $S_n = f(S_{n-1}, n)$, where $n = 0, 1, 2, 3, \ldots m$ and f is some function. This very general form of relation usually degenerates to one in which the only change in the form of f arises from the use of a series of coefficients. For instance the formula used in evaluating a polynomial

$$\sum_{n=0}^{m} a_n x^{m-n}$$

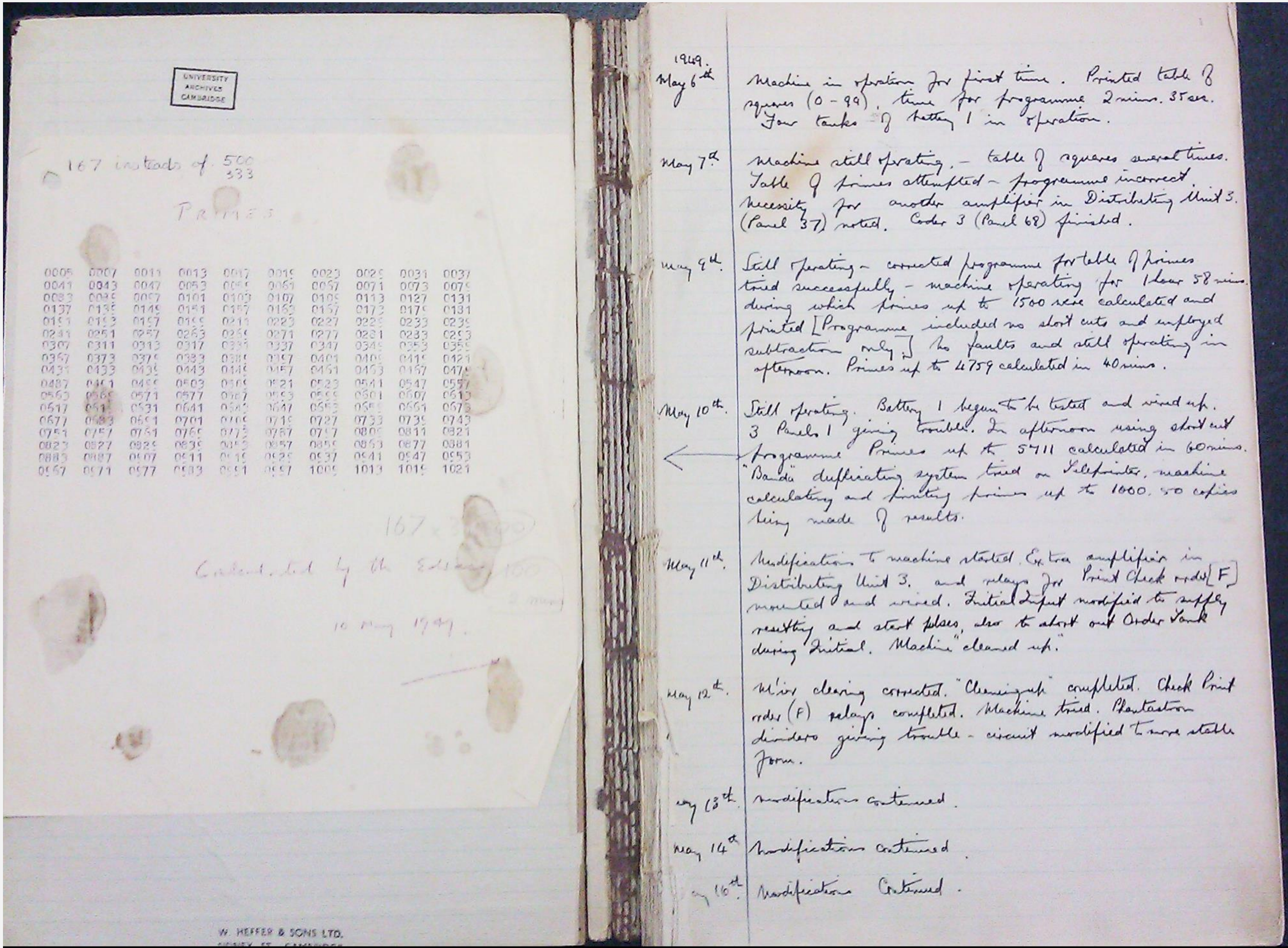
may be written as $S_0 = a_0$, $S_n = S_{n-1}x + a_n$, $S_m = \sum_{n=0}^{m} a_n x^{m-n}$.

	location of orders	orders			purpose
		G		K	control combination
θ	0	A	3	F	
	1	T	14	θ	plant link
	2	A	100	D	
	3	T		D	$S_0 = a_0$
	4	S	15	θ	
	5	A	16	θ	
	6	T	8	θ	plants order A(100+2s)D in 8, initially s = 1
	7	V		D	$S_n.x$
	8	(A		F)	$+a_{n+1}$
	9	Y		F	
	10	T		D	
	11	A	8	θ	}
	12	S	17	θ	} test for order 8 taking its final value A 120 D
	13	G	5	θ	}
	14	(E		F)	the link order is planted here
	15	P	20	F	}
	16	A	122	D	} constants used in subroutine
	17	A	120	D	}
	18				

Manchester vs. Cambridge coding style



EDSAC springs to life, 6 May 1949



167 instead of 500
333

PRIMES

0005	0007	0011	0013	0017	0019	0023	0029	0031	0037
0041	0043	0047	0053	0059	0061	0067	0071	0073	0079
0083	0089	0097	0101	0103	0107	0109	0113	0127	0131
0137	0139	0149	0151	0157	0163	0167	0173	0179	0181
0191	0193	0197	0199	0211	0223	0227	0229	0233	0239
0241	0251	0257	0263	0269	0271	0277	0281	0283	0293
0307	0311	0313	0317	0331	0337	0347	0349	0353	0359
0367	0373	0379	0383	0389	0397	0401	0409	0419	0421
0431	0433	0439	0443	0449	0457	0461	0463	0467	0479
0487	0491	0499	0503	0509	0521	0523	0541	0547	0557
0563	0569	0571	0577	0587	0593	0599	0601	0607	0613
0617	0619	0631	0641	0643	0647	0653	0659	0661	0673
0677	0683	0691	0701	0709	0719	0727	0733	0739	0743
0751	0757	0761	0769	0773	0787	0797	0809	0811	0821
0823	0827	0829	0839	0853	0857	0859	0863	0877	0881
0883	0887	0907	0911	0919	0929	0937	0941	0947	0953
0967	0971	0977	0983	0991	0997	1009	1013	1019	1021

167 x 3

Calculated by the Edsac

10 May 1949.

1949.

May 6th. Machine in operation for first time. Printed table of squares (0 – 99), time for programme 2 mins. 35 sec. Four tanks of battery 1 in operation.

May 7th. Machine still operating. – table of squares several times. Table of primes attempted – programme incorrect. Necessity for another amplifier in Distributing Unit 3. (Panel 37) noted. Order 3 (Panel 68) finished.

May 9th. Still operating – corrected programme for table of primes tried successfully – machine operating for 1 hour 58 mins. during which primes up to 1500 were calculated and printed [Programme included no short cuts and employed subtraction only.] No faults and still operating in afternoon. Primes up to 4759 calculated in 40 mins.

May 10th. Still operating. Battery 1 begun to be tested and wired up. 3 Panels 1 giving trouble. In afternoon using short cut programme Primes up to 5711 calculated in 60 mins. "Banda" duplicating system tried on Teleprinter, machine calculating and printing primes up to 1000. 50 copies being made of results.

May 11th. Modifications to machine started. Extra amplifier in Distributing Unit 3. and relays for Print Check order [F] mounted and wired. Initial Input modified to supply resetting and start pulses, also to short out Order Tank during Initial. Machine "cleaned up."

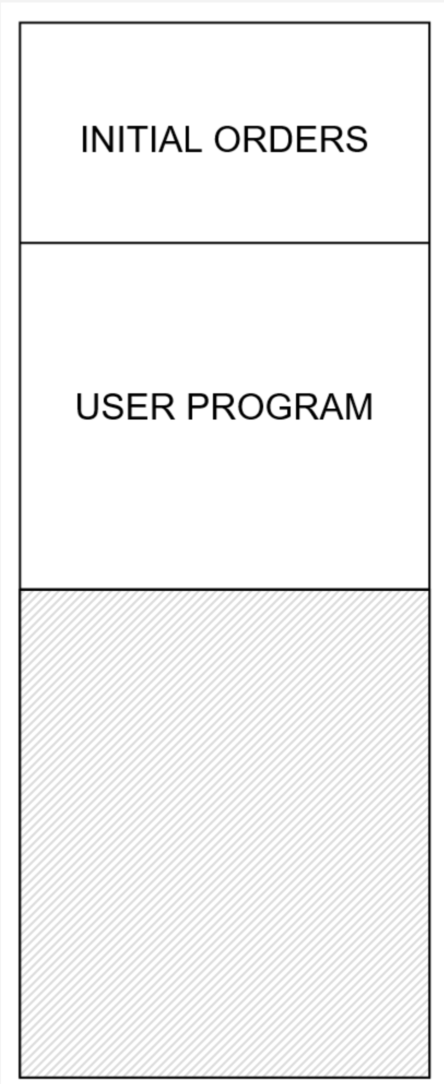
May 12th. M'ix clearing corrected. "Cleaning up" completed. Check Print order (F) relays completed. Machine tried. Phantastron dividers giving trouble – circuit modified to more stable form.

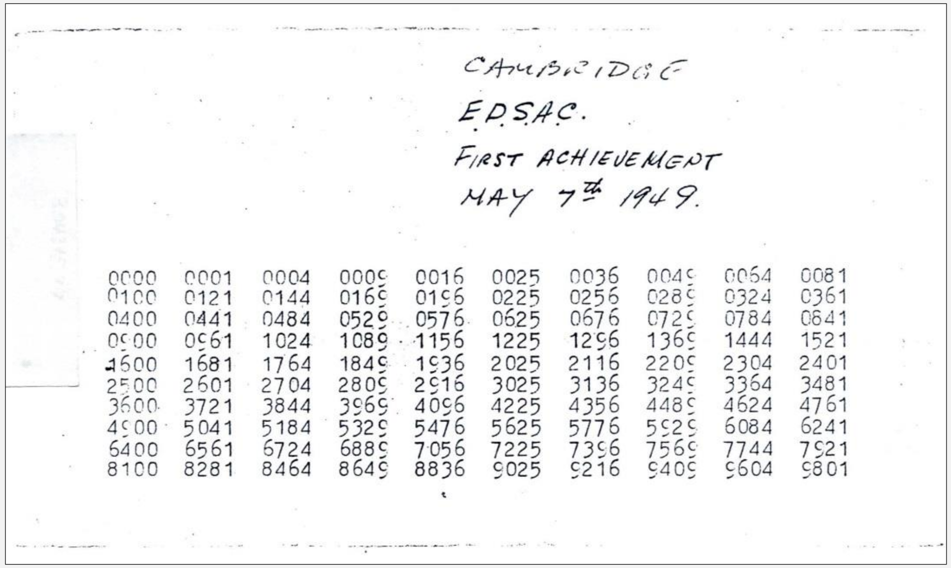
May 13th. modifications continued.

May 14th. Modifications continued.

May 16th. Modifications continued.

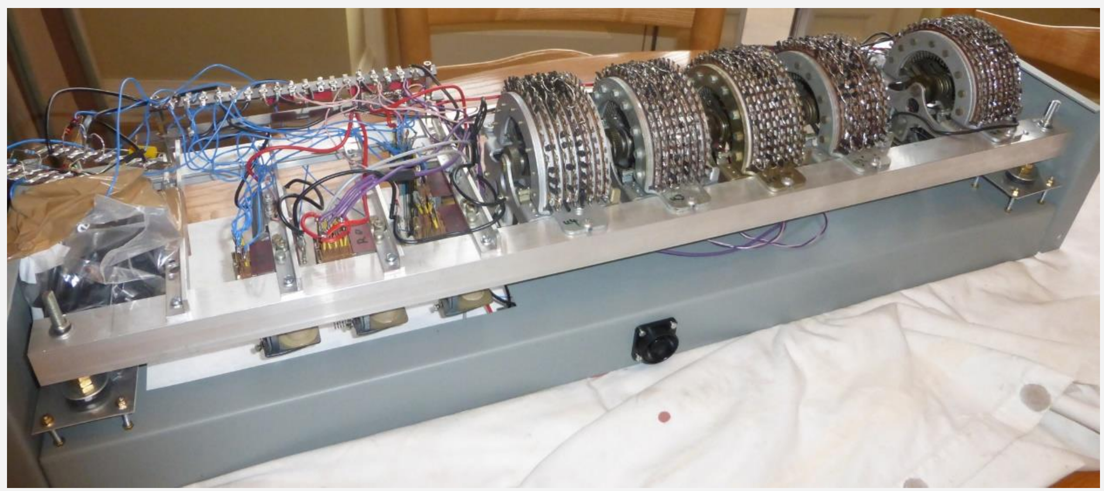
EDSAC springs to life, 6 May 1949



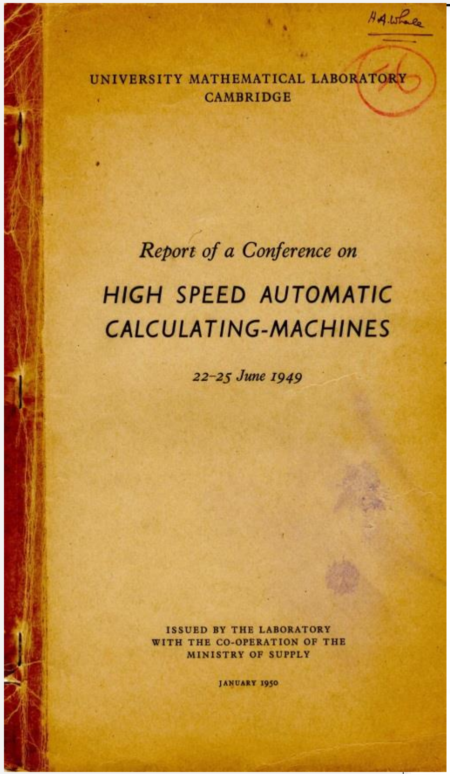


CAMBRIDGE
EDSAC.
FIRST ACHIEVEMENT
MAY 7th 1949.

0000	0001	0004	0009	0016	0025	0036	0049	0064	0081
0100	0121	0144	0169	0196	0225	0256	0289	0324	0361
0400	0441	0484	0529	0576	0625	0676	0729	0784	0841
0900	0961	1024	1089	1156	1225	1296	1369	1444	1521
1600	1681	1764	1849	1936	2025	2116	2209	2304	2401
2500	2601	2704	2809	2916	3025	3136	3249	3364	3481
3600	3721	3844	3969	4096	4225	4356	4489	4624	4761
4900	5041	5184	5329	5476	5625	5776	5929	6084	6241
6400	6561	6724	6889	7056	7225	7396	7569	7744	7921
8100	8281	8464	8649	8836	9025	9216	9409	9604	9801



David Wheeler’s Initial Orders – wired on to uniselectors



3. The initial input is only able to synthesize symbols into the standard order form. However, since, inside the machine, orders are represented as numbers, it is possible to input certain numbers in the form of orders. These will be called pseudo-orders. Thus, for example, P5S represents the number 5×2^{-15} inside the machine, and so may be interpreted as the number 5 multiplied by the scale factor 2^{-15}. In these test problems, it happens that all the numbers required can be built up from simple integers in this way.

4. The layout of the printing is also under the control of the programmer. Thus, for example, by using the order "OnS", where store position "n" contains "ΔS", he can effect a line-feed on the typewriter. Special attention has to be given to the suppression of non-significant zeros, if that is desirable.

5. In the routines, the store position is listed for external reference. Only the orders are punched on the input tape. Standard five-hole teleprinter tape is used, with a slightly modified code.

6. The arrow indicates an entry point from another position in the routine. Normally, orders are obeyed consecutively.

7. Quantities in brackets are changed in the course of the execution of the orders.

Notation.

S(n)	denotes store position n.
C(n)	denotes the contents of store position n.
A	denotes the contents of the accumulator.
R	denotes the contents of the multiplier register.
n	= 0. 1. 2 . . . . 1023, i.e. a short store position.
a to b	means to replace b by a.

ROUTINES:

(i) Initial Input

Memory position.	Order.	
0	T 0 S	
1	H 2 S	Set multiplier.
2	T 0 S	Transfer control to 6.
3	E 6 S	
4	P 1 S	Pseudo-orders.
5	P 5 S	
→ 6	T 0 S	Input function digits; shift to correct position in 0. $x_1 = 0$
→ 7	I 0 S	
8	A 0 S	
9	R 16 S	
10	T 0 L	
→ 1	I 2 S	Input next symbol. Test for digit or discriminant.
2	A 2 S	
3	S 5 S	
4	E 21 S	
5	T 3 S	
6	V 1 S	$10x_1 + b$ to 1.
7	L 8 S	
8	A 2 S	
9	T 1 S	

ROUTINES: contd.

(i) Initial Input

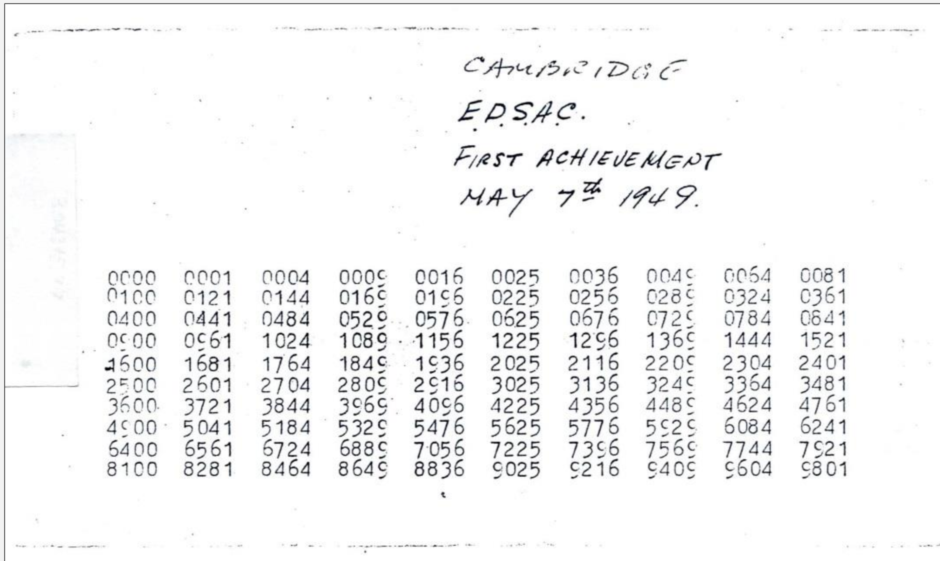
Memory position.	Order.	
20	E 11 S	
→ 1	R 4 S	Length discriminant digit to acc.
2	A 1 S	
3	L 0 L	Form order and transfer to n.
4	A 0 S	
5	(T 31) S	
6	A 25 S	n+1 to n.
7	A 4 S	
8	U 25 S	
9	S 31 S	Test for start of programme.
30	G 6 S	

Note: The first order to be punched on the tape for any routine must be T n S, where the last order is to be input to position n-1. Control is then automatically transferred to the beginning of the routine after the last order has been input by the above initial input routine.

(ii) Print squares

31	T 123 S	(As required by (initial input.		57	T 65 S	To control printing
2	E 84 S	Jump to 84.		8	A 33 S	
3	(P S)	(Use to keep count (of subtractions.		9	A 40 S	
4	(P S)	(Power of 10 being (subtracted.		60	T 33 S	
5	P10000S	For use in the decimal binary conversion	Pseudo-orders	→ 1	A 48 S	Print contents of S(48).
6	P 1000S			2	S 34 S	
7	P 100S			3	E 55 S	
8	P 10S			4	A 34 S	
9	P 1 S			5	(P S)	
40	Q S			6	T 48 S	
1	π S	Figures		7	T 33 S	
2	A 40 S			8	A 52 S	
3	∅ S	Space		9	A 4 S	
4	Δ S	Line-feed		70	U 52 S	
5	θ S	Car. return		1	S 42 S	
6	O 43 S			2	G 51 S	
7	O 33 S			3	A 117 S	
8	(P S)	(Becomes number to (be printed.		4	T 52 S	

David Wheeler’s Initial Orders and the first programs, 6-9 May 1949



CAMBRIDGE

EDSAC.

FIRST ACHIEVEMENT

MAY 7th 1949.

0000	0001	0004	0009	0016	0025	0036	0049	0064	0081
0100	0121	0144	0169	0196	0225	0256	0289	0324	0361
0400	0441	0484	0529	0576	0625	0676	0729	0784	0841
0900	0961	1024	1089	1156	1225	1296	1369	1444	1521
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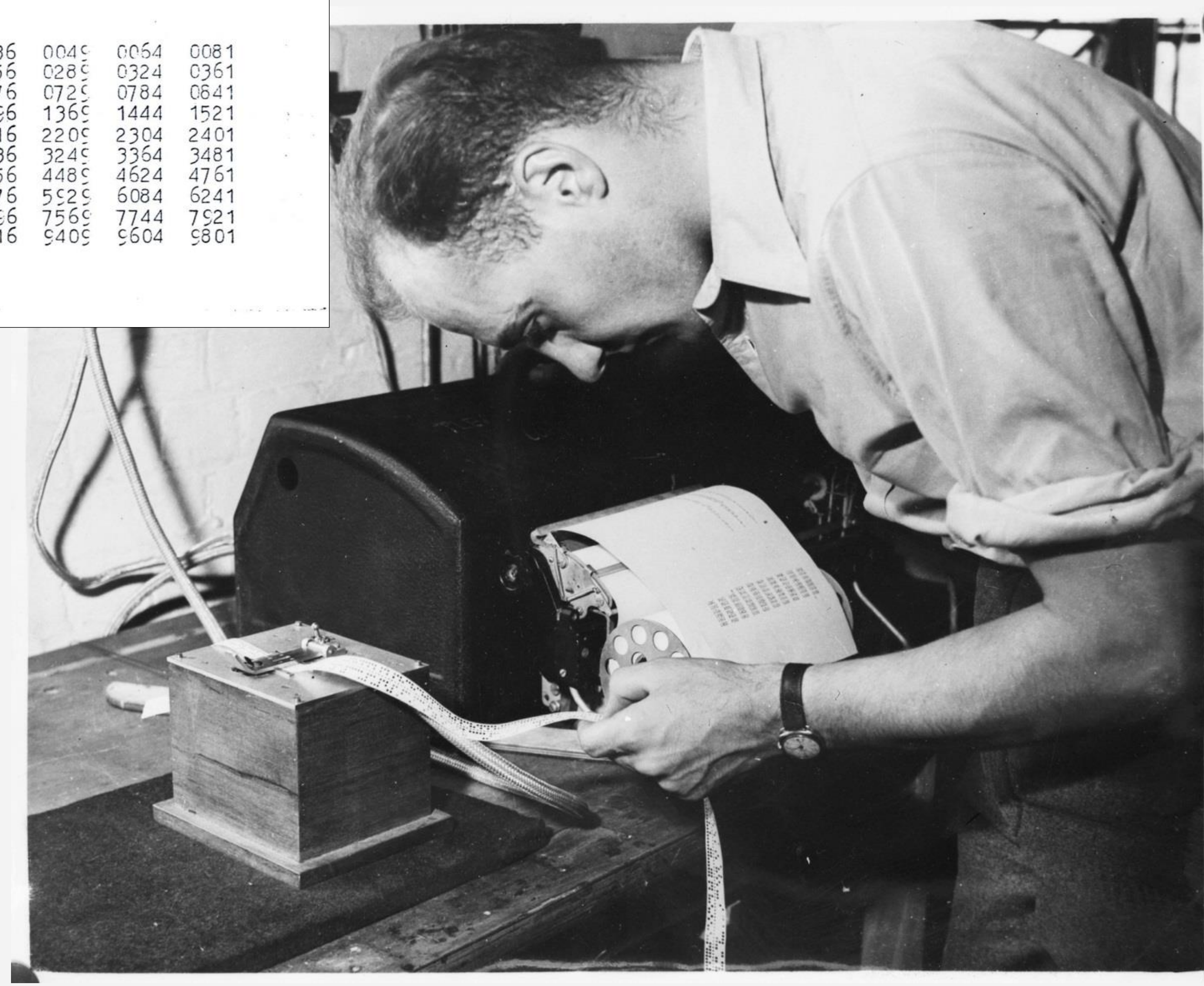
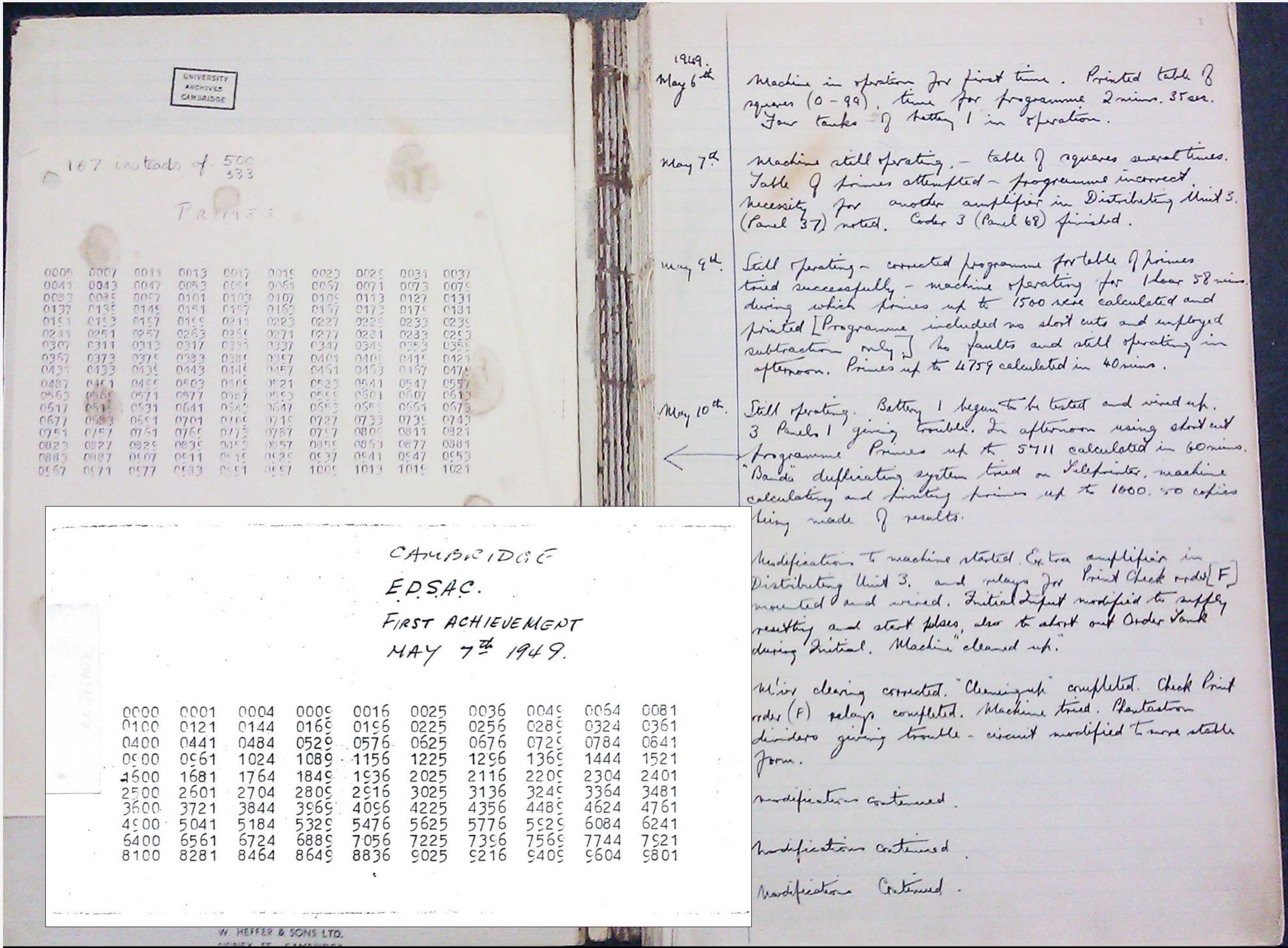
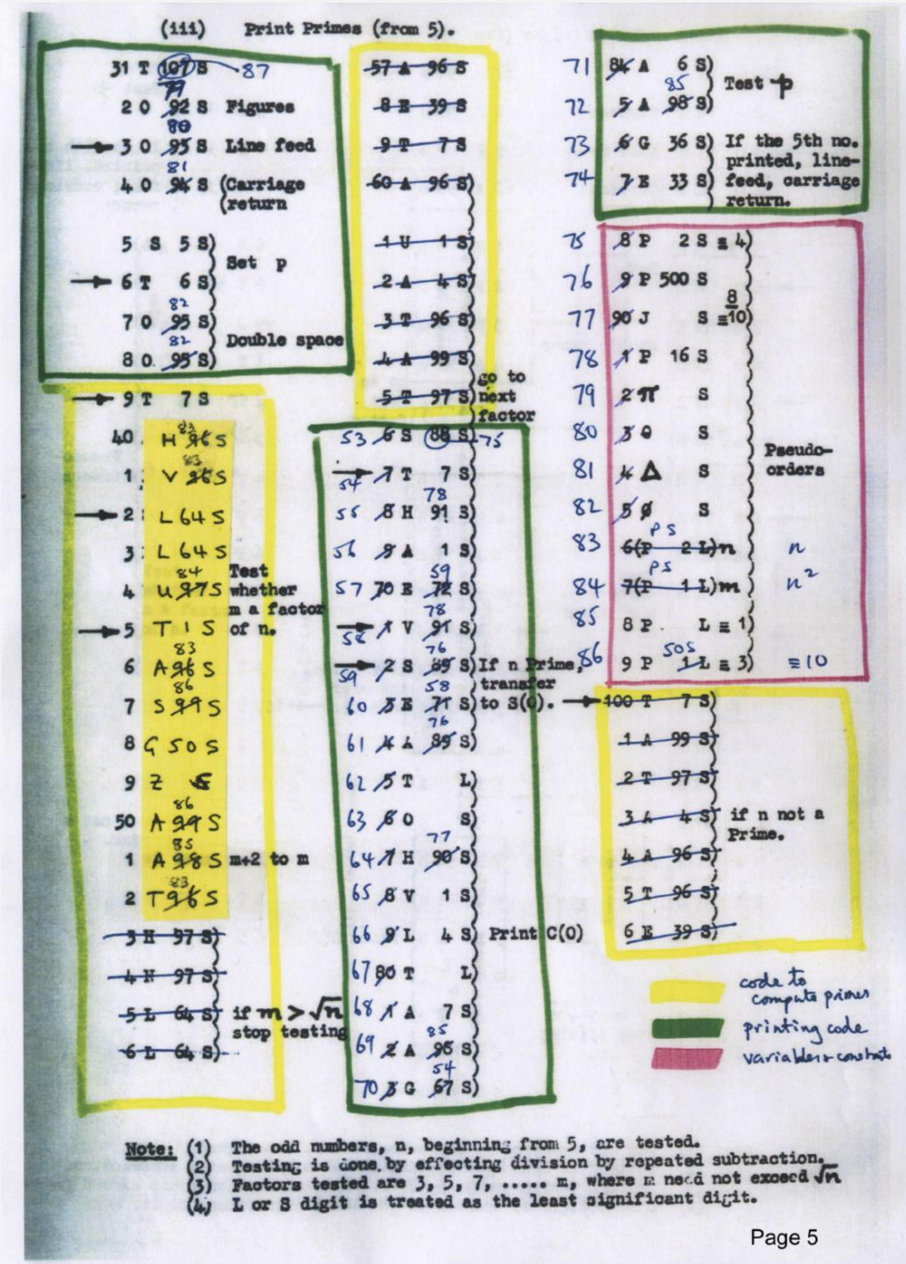
4900	5041	5184	5329	5476	5625	5776	5929	6084	6241
6400	6561	6724	6889	7056	7225	7396	7569	7744	7921
8100	8281	8464	8649	8836	9025	9216	9409	9604	9801



The lost first program



EDSAC springs to life, 6 May 1949



FIRST PROGRAM RECONSTRUCTION (2 April 2014)

```
        31 | T  87 S | As required by initial input
        32 | O  79 S | Figures
  74 →  33 | O  80 S | Line feed          ] New line
        34 | O  81 S | Carriage return    ]
        35 | S   5 S | Set position count, p = -10
70,73→  36 | T   6 S |
        37 | O  82 S | Double space
        38 | O  82 S |
        39 | T   7 S |
        40 | H  83 S |
        41 | V  83 S | Calculate n²
        42 | L  64 S |
        43 | L  64 S |
        44 | U  84 S |
        45 | T   1 S | Save n² for printing
        46 | A  83 S |
        47 | S  86 S | Stop if n >= 100
        48 | G  50 S |
        49 | Z     S |
  48 →  50 | A  86 S |
        51 | A  85 S | n+1 to n
        52 | T  83 S |
        53 | S  75 S | Set digit count, d = -4
        54 | T   7 S |
        55 | H  78 S |
        56 | A   1 S |
        57 | E  59 S |
  60 →  58 | V  78 S |
  57 →  59 | S  76 S |
        60 | E  58 S |
        61 | A  76 S | Print digit
        62 | T     L |
        63 | O     S |
        64 | H  77 S |
        65 | V   1 S |
        66 | L   4 S |
        67 | T     L |
        68 | A   7 S |
        69 | A  85 S | d + 1 to d
        70 | G  54 S |
        71 | A   6 S |
        72 | A  85 S | p + 1 to p
        73 | G  36 S |
        74 | E  33 S |

        75 | P   2 S | = 4 (digit count)                              ] Constants
        76 | P 500 S | = 1000        ] Used for binary
        77 | J     S | = 10/16       ]  to decimal
        78 | P  16 S | = 32          ]  conversion
        79 | π     S | figure shift
        80 | θ     S | carriage return
        81 | Δ     S | line feed
        82 | ϕ     S | space
        83 | P     S | n (=0 initially)
        84 | P     S | n² (=0 initially)
        85 | P     L | = 1
        86 | P  50 S | = 100
```

p = position on line of printed page
d = digit counter

The lost first program -- reconstruction