6. Early Computers

> In conclusion, I would observe that of the very numerous branches of pure and applied science which are dependent for their development, record, or application on the dominant science of mathematics, there is not one of which the progress would not be accelerated, and the pursuit would not be facilitated, by the complete command over the numerical interpretation of abstract mathematical expressions, and the relief from the time-consuming drudgery of computation, which the scientist would secure through the existence of machinery capable of performing the tedious and complex calculations with expedition, automation, and precision. P. E. Ludgate, *On a Proposed Analytical Machine*.

Introduction

In this chapter we shall give a brief survey of the development of the computer from the first mechanical program-controlled computers of the 1930s through the electromechanical and electronic computers of the Second World War to the first general-purpose electronic digital computers of the late 1940s and early 1950s. Our position will be that of a person interested in the organization, performance and programming of these machines rather than that of the engineer interested in their logical design and the development of the technology necessary for their construction and reliable operation. Rather than discussing in detail the programming of these early computers, we shall conclude the chapter by give a **J** simulator for executing programs written in a very simple machine language with a few examples of its use.

Elecromechanical computers I. Konrad Zuse

In 1934 Konrad Zuse, a civil engineering student at the Technische Hochschule in Berlin, began work which was lead by 1943 to the completion of world's first general-purpose program-controlled computer. This work was stimulated by Zuse's desire to find some relief from the tedious calculations with which he was confronted in his studies, Although he first considered the design of special forms to facilitate manusl

calculations, he soon abandonned these ideas and began to consider the construction of a mechanical general-purpose computer which would be controlled by a program punched by a hand punch on 35mm movie film as would the data which were and the results of calculations. Instructions were in a three=address code since each would give the operation to be performed and the addresses of the two operands and of the result. Arithmetic would be carried out with binary floating-point numbers with automatic conversion between binary and decimal. He set up a workshop in his parents' apartment in Berlin and by 1936 submitted a patent application and left his job with the Henschel Aircraft Company so that he could devote all of his time to the construction of the computer. Two years later he completed this computer known as the Z1. However as it proved to be unreliable in its operation, he began work on the design and construction of a second computer known as the Z2.

The Z2 was constructed with second-hand relays except for the memory which was mechanical as it was in the Z1. The Z2 was almost finished in 1939 when Zuse was drafted into military service. After a year influencial friends managed to have him released from the army so that he could return to his former work as an aircraft engineer. By working on his own time he managed to complete the Z2 sufficiently to give a demonstration but it was not considered to be sufficiently reliable for practical work.

Zuse then began work on the Z3 which he completed in 1941. It was a relay machine with approximately 2600 relays with about 1400 for the memory, which had 64 22-bit words, and 600 for each of the arithmetic and control units. Input was by keyboard and output by a lamp display. The Z3 is considered to be the first general-purpose program-controlled computer. It was destroyed in an air raid in 1944.

Zuse founded his own company, Zuse Apparatebau, which built special-purpose computers used for testing guided missiles during their production. During this period he built the Z4, an improved version of the Z3, which was the only one of his computers to survive the war. This computer was later reconditioned and in 1950 leased to the Eidgenossishe Technische Hochschule in Zurich. Five years later it was sold to the French Department of Defence where it was used for another four years. Zuse continued to design and build computers, and by 1962 his company had produced 50 Z22s, a vacuum-tube computer, and 200 transistorized Z23s.

Electomechanical computers II. Howard Aiken

In 1937 Howard Aiken, a physics instructor at Harvard University, wrote a proposal for an automatic computing machine constructed from the components of punched-card equipment. The proposal itself is of interest today because it begins with an excellent summary of the development of mathematical aids to computation and shows that Aiken had an appreciation of the work of Charles Babbage. The picture on the first page is a reproduction of a woodcut from the *Margarita Philosophica*, an early sixteenth-century

encyclopaedia containing an excellent treatise on arithmetic. It shows a contest supervised by Lady Arithmetic between Pythagoras, supposedly the inventor of the Hindu-Arabic numerals, and Boethius who was a Roman scholar of the sixth century. Pythagoras is using the new numerals and Boethius an abacus. The sad expression on the face of Boethius leaves no doubt of the outcome.

Aiken was able to interest the IBM Corporation in developing a machine to his specifications. In August 1944 the Automatic Sequence Controlled Calculator, or Harvard Mark I, was presented to Harvard by Thomas J. Watson, the President of IBM.

The Mark I was an electromechanical computer 51 feet long and eight feet high. It had 72 accumulator registers each capable of storing 23 decimal digits and a sign digit and could be used for the storage of numbers and for addition. Each decimal digit was represented by a counter wheel with ten teeth. There were also 60 constant registers into which numbers could be set by hand, There was a central multiplying and dividing unit, electromechanical tables for common logarithms, powers of 10 and the sine function, and three interpolation units for reading functional values punched on paper tape, Input of data was by punched cards, and output of results was by either punched cards or typewriter. There were two card readers, one card punch and two typewriters. Instructions were in two-address format and were punched on 24-column paper tape. Initially the machine had two conditional instructions, one allowing a choice of alternative function tapes and the other being a stop instruction conditional on a number in a specified register being larger than a specified quantity. A more general conditional instruction was added later.

Addition and subtraction took 0.3 seconds, multiplication 6 seconds and division approximately 11 seconds. Calculation of transcendental functions by the electromechanical tables was much slower with, for example, the evaluation of a sine requiring 60 seconds. Although the the Mark I was much slower than other computers that became operational soon after it went into service, it was used continuously at Harvard for 15 years on a variety of problems. When Zuse's work became known after the Second World War, it could no longer be claimed as it was for many years that it was the world's first operational program-contolled computer. It should be remembered, though, as an important step forward in the development of computers, and rightly deserves the epithet of L. J. Comrie, a British pioneer in the use of punched card equipment for numerical computation, that it was "Babbage's dream come true".

At the presentation ceremony for the Mark I Thomas J. Watson felt that Aiken did not give sufficient credit to IBM for its design and construction, and this caused bad feelings which were never healed. Thereafter Aiken worked independently of IBM and completed the Mark II which used electromagnetic relays in 1947. This was followed in 1950 by the Mark III which was an electronic computer with magnetic drum storage, and in 1952 by the Mark IV which had magnetic core shift registers..

Electromechanical computers III. The Bell Telephone computers

In 1937 the Bell Telephone Laboratories began to experiment with the electromagnetic relays used in telephone switching for the construction of computers. Two years later George Stibitz and S. B. Williams completed the Complex Number Calculator which was also called the Complex Calculator, and, when other models were built, simply the Model I. It was designed for the multiplication and division of complex numbers but was soon modofied to handle complex addition and subtraction. It was demonstrated in public for the first time in September 1939 at a meeting of the American Mathematical Society in New York City with the operator located in Hanover, New Hampshire. Stibitz developed a second calculator, the Model II, which became operational in September 1943. It was used mainly for the interpolation calculations required in the testing of fire control devices but was used for a few other problems including the solution of differential equations. This computer, as well as the improved Models III and IV, was programmed by punched paper tape, and was noted for its self-checking arithmetic.

The last in this sequence of computers was the Model V, two of which were built. It was a program-controlled computer with branching facilities which allowed one of several sequences of instructions to be chosen. It was a very large computer with over 9000 relays weighing ten tons and covering a floor area of about 1000 square feet. Addition required 0.3 seconds, multiplication 1 second, and each of division and extraction of a square root about 5 seconds. The Model V was used for a variety of calculations including the solution of systems of linear algebraic equations, the solution of ordinary and partial differential equations and the tabulation of functions.

Electronic computers I. ENIAC and EDVAC

The first electronic computer was the Electronic Numerical Integrator and Calculator (ENIAC) which was designed by J. Presper Eckert and John W. Mauchly and built at the Moore School of Electrical Engineering at the University of Pennsylvania. It was dedicated in February 1946 and was used during that year for calculations in both ballistics for which it was primarily intended and also in atomic physics. It was then dismantled and reassembled at the Ballistics Research Laboratory in Aberdeen, Maryland where it was used until 1955.

The ENIAC was a very large machine consisting of a U-shaped assemblage of forty panels occupying a room 40 feet by 20 feet. It contained 18000 vacuum tubes and 1500 relays and consumed approximately 150 kilowatts of power all of which was converted eventually to heat. There were 20 ten-digit decimal accumulator registers for addition and subtraction, a multiplying unit and a unit for dividing and extracting square roots. Punched cards were used for both input and output. There were three function tables into which up to 300 numbers could be entered manually by switches. Addition and subtraction

required 200 microseconds while multiplication and division required 2.8 and 6 milliseconds, respectively. Programming was done by plugboard connections and the setting of switches.

The ENIAC was much faster than other computers in operation at the time. For example, addition was 1500 times faster than with the Harvard Mark I. Its main disadvantages were the maintenance problems caused by its size and the large number of tubes, the small internal storage capacity of 20 numbers and the awkwardness of changing from one program to another. However the ENIAC demonstrated the feasibility of an entirely electronic digital computer and was a tribute to the perseverance and skill of those who designed and built it.

The deficiencies of the ENIAC became apparent even during its construction and discussions were begun on the design of its successor which was to be called the Electronic Discrete Variable Computer or EDVAC. John von Neumann of the Institute of Advanced Studies at Princeton, one of the leading mathematicians of the twentieth century, was appointed a consultant to the EDVAC project. He undertook to summarize the discussions relating to the design of the EDVAC, and in June 1945 produced the *First Draft of a Report on EDVAC*. The EDVAC was to be a serial binary machine with a single accumulator for performing arithmetical operations and an acoustic delay line memory which was to store instructions as well as data. In this report it was stated for the first time the concept of a stored-program computer. A sorting program which was to have been included in the report was found several years later and is considered to be the earliest known program for a stored-program computer. Work on the EDVAC continued at the Moore School until 1949 when it was delivered to the Ballistics Research Laboratory. It was completed in 1951 and was used for the next 11 years.

In the summer of 1946 a series of lectures based on the design of the EDVAC was held at the Moore School. These lectures were attended by 29 specialists from the United States and Great Britain and had a significant influence on the development of computers in both countries.

Electronic computers II. NPL, Manchester and FERUT

As was mentioned in the previous chapter, at the end of the war Alan Turing left Bletchley Park and joined the staff of the National Physical Laboratory in Teddington to work on the design of an electronic computer.The following year he submitted a report entitled *Proposal for Development in the Mathematics Division of an Automatic Computing Engine (ACE)*. This report was used as the basis for the design of a stored-program electronic computer called the Pilot ACE which was completed in 1950. After a few months of operation which included a successful demonstration to the press the computer was modified and then returned to service in November 1951 where it was used on a 13-hour day. Part of the Pilot ACE is now in the Science Museum, South Kensington. Turing's report represented a significant contribution

to the design and programming of computers but unlike the von Neumann EDVAC report it is now largely forgotten.

The first stored-program computer to become operational was a small experimental computer designed and built in the Royal Society Computing Machine Laboratory in the Department of Electrical Engineering at the University of Manchester. It was built primarily to test the cathode tube storage device designed by F. C. Williams and his assistant T. Kilburn, and to gain some experience before beginning work on a full-size machine. This project had been instigated by Max Newman who had left Bletchley Park at the end of the war and come to Manchester as Professor of Pure Mathematics and Director of the Computing Machine Laboratory. He was soon joined by Turing who was appointed Deputy Director.

The computer was a binary machine with a main memory of one Williams Tube that could store 32 32-bit words. There was an order code of eight one-address instructions with an execution speed of 1.2 milliseconds per instruction. The first program, run on June 21, 1948, was chosen to give a comparatively long execution time for a problem whose result could be checked independently of the computer. It involved finding the highest proper factor of 2^{18} by testing as divisors successive integers starting with 2^{18}-1 and working downwards with the divisions being done by repeated subtractions. Approximately 130,000 numbers were tested, a procedure which required 3.5 million operations and took 52 minutes.

We might mention here that in the **J** defined function

```
hpf=: 3 : 0
i=. <:N=. y.
while. i > 0 do.
   if. 0 = i|N do. break. end.
   i=. <: i
end.
i
)
```

finding the highest proper factor the repeated subtractions required in the Manchester computer are conveniently avoided by use of the residue function `|`. We have that `2^18` is `262144` and `hpf 2^18` is equal `131072`, a calculation which took approximately 1.3 seconds on a 2 GHz PC. Also with a prime argument the function gives a result of `1` which is to be expected.

Work began almost immediately on the design and construction of a full-size computer, and in April of the following year the Mark I prototype was operational. It was popularly known as MADM for Manchester Automatic Digital Computer. It had a main memory of two Williams tubes with a total capacity of 128 40-bit words and a 1024-word magnetic drum auxiliary memory.The order code had been increased to 26 including a multiply instruction which the experimental machine lacked. During the summer of 1949 the computer was used for the calculation of Mersenne primes, i.e., primes of the form 2^n-1 where n is prime, and at one time gave an error-free run of nine hours.

The protoype was enhanced in October 1949 with an extended order code and improved input and output facilities. It was closed down during the summer of 1950 by which time the first production model, the Mark I, was completed by Ferranti Limited in Manchester. In February 1950 it was installed in a newly completed building housing the Computing Laboratory. The second production model was delivered to the University of Toronto in 1952 where it was known as FERUT for Ferranti, University of Toronto. The following is one of the shorter sample FERUT programs given in the programmers' handbook produced for the Toronto computer.

Replace `[/C]±f` by its cube.

```
  |/|
→|E|I  S  T  /|    clear accumulator and set round-off
  |@|/  C  /  K|)
  |A|/  C  /  F|)  x^2
  |:|/  C  /  A|    plant x^2
  |S|/  C  /  F|    x^3
  |I|/  C  /  A|    plant x^3
```

Electronic computers III. Cambridge and EDSAC

Although the experimental computer at Manchester was the first computer to execute a stored program, the first stored-program computer intended for general use is considered to be the EDSAC, Electronic Delay Storage Automatic Calculator, which was designed and built at the University Mathematical Laboratory at Cambridge University. The project was headed by Maurice Wilkes who had attended the Moore School lectures in 1946. The EDSAC had an acoustic delay line memory of 1024 17-bit words, punched paper tape input and teleprinter output. There was an order code of 18 one-address instructions and a wired-in program for the input of programs and data. The first program was run in May 1949. The following month a conference was held to mark the inaugeration of the EDSAC. Two test programs were run as examples. The first calculated the primes less than 1024 and the second a table of positive integers less than or equal to 32 and their squares and the first differences of the squares.

Nim-playing computers

In an earlier chapter we introduced the game of Nim as an illustration of the use of number systems. We recall that Nim is a game where two players alternately remove one or more coins, or other objects, from one of several piles with the winner being the player who removes the coin or coins from the last remaining pile. In this section we will discuss briefly some of the computers that have been designed and built for playing Nim.

The first Nim-playing computer was designed in 1940 by Edward U. Condon, the former director of the National Bureau of Standards who was then at Washington University in St.Louis. It was called

Nimatron and was built by Westinghouse Electric Corporation. It weighed one ton and could accommodate up to seven counters in each of four piles. It was exhibited at the New York World's Fair and won 90,000 of the 100,000 games it played. In 1941 another Nim-playing computer was built independently of Condon's. Although of the same capacity, it weighed only five pounds and contained only four rotary switches.. The most famous Nim-playing computer was Nimrod which was built by Ferranti Ltd.for the Festival of Britain in 1951. It was displayed for six months at the Science Museum in South Kensington and later in Berlin and Toronto. Apparently is was so popular in Berlin where it was shown at a Trade Fair that visitors ignored a bar in the same room where free drinks were available and police were required to control the crowds.

A machine-language simulator

In this section we shall discuss a simulator written in **J** that may be used to illustrate machine-language programming for a very simple computer. The computer is a one-address decimal computer with an order code of 10 instructions and a memory of 100 words with addresses 00, 01, ...,, 99. Input is by paper tape and output is by printer, both of which are of course simulated. Instructions have the format "ixx", where "i" is the order code and "xx" is the address in memory. In addition to the main memory there are three registers: an accumulator register A for arithmetic, an instruction register IR for storing the current instruction, and a counter register CR for storing the address of the next instruction. Programs are stored in consecutive memory locations with the instruction in location 00 being executed first. Loading a program clears all memory locations other than those used by the Load program, and executing a program initially resets the printer.

The instructions are as follows:

000	Halt	Halt computation (Address portion irrelevant)
1xx	Add	Add contents of location xx to accumulator
2xx	Subtract	Subtract contents of location xx from accumulator
3xx	Multiply	Multiply contents of accumulator by contents of location xx
4xx	Copy	Copy contents of contents xx to accumulator
5xx	Store	Store contents of accumulator in location xx
6xx	Transfer	Take next instruction from location xx
7xx	Trans. neg.	Take next instruction from location xx if contents of accumulator neg.
8xx	Read	Read number from Tape to location xx
9xx	Print	Print number in location xx

The following annotated program – address, instruction, comment - reads two numbers from tape and calculates and prints their sum:

```
00 810  Read 1st number
01 811  Read 2nd number
02 410  Copy 1st number to Accumulator
03 111  Add 2nd number
04 512  Store sum in memory
05 912  Print
06 000  Halt
```

The progrm is executed as follows:

```
Ex0=: 810 811 410 111 512 912 0
Tape=: 2.5 6.8
Load Ex0
Run ''
Printer
9.3
```

The following program, given as the list `Ex1`, calculates the integer remainder when the first number read is divided into the second number:

```
00 810 Read 1st number
01 811 Read 2nd number
02 411 Copy 2nd number to accumulator
03 210 Subtract 1st number
04 706 Transfer if difference negative
05 603 Transfer
06 110 Add 1st number
07 512 Store residue
08 912 Print
09 000 Halt
Tape=: 5 12 7 4 12 12
Load Ex1
Run ''
Printer
2
Run ''
```

```
Printer
4
Run ''
Printer
0
```

The following program `Ex2` calculates and prints a table of factorials:

```
00 818    Read N
01 417    )
02 519    ) n = 1
03 520    )
04 418    N
05 219    N - n
06 715    Is N – n < 0
07 919    Print n
08 920    Print n!
09 419    )
10 117    ) Add 1 to n
11 519    )
12 320    Multiply
13 520    by n
14 604    Transfer
15 000
16 0
17 0
Tape=: 4
Load Ex2
Run ''
4 2 $ Printer
1 1
2 2
3 6
4 24
```

The last example finds the sum of a number of positive numbers which are stored in consecutive memory locations and are followed by an arbitrary negative number indicating the end of the list. The program followed by some sample data is given in the following list:

```
Ex3=: 416 505 400 200 518 420 713 118 518 405 117
Ex3=: Ex3, 505 605 918 0 0 420 1 0 0
Ex3=: Ex3, 5 9 3 7 _2
```

The details are left to the reader.