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A NEW TOOL FOR PHYSICISTS

by Beatrice H. Worsley and J.N.P. Hume

In the past ten years there has been a very great advance in the design and construction of universal, high-speed, automatic digital computers.[1,2,3] Principles known for well over a hundred years are only now being exploited fully in terms of modern engineering techniques. However, realization of the potentialities of the new computers has been retarded somewhat owing to the amount of skilled human effort required to code individual problems for machine solution. This situation has been much alleviated in the past year or two by the introduction of automatic coding techniques. These enable a program for instrucing a machine to solve a specific problem to be written in some simplified notation. The labour of organizing the calculation and of translating the instructions into machine code is then delegated to the computer itself.

Such a coding system, Transcode, has now been provided for FERUT, a computer built by the Ferranti Company of Manchester, England, and installed in 1952 at the Computation Centre in the University of Toronto. Transcode is proving a useful tool for research workers in outside fields, as well as for professional coders. It is the purpose of this article to acquaint readers with the principles of programing for automatic digital computers, to describe Transcode and to mention some of the problems for which Transcode solutions have been performed on FERUT.

Automatic Digital Computers

The term digital is used to distinguish computers from the analogue, or continuously variable devices, of which the slide-rule and differential analyzer are common examples. The earlier digital computers, such as the abacus, and desk-type adding machines, were designed to mechanize only the arithmetical operations which occur in hand calculations. However, these require an operator to carry out such processes as putting in data, transferring intermediate results from one register to another, transcribing the final answers into a presentable form and possibly employing judgment at some stage in the calculation to decide between alternative procedures. The term automatic is applied to computers which are designed to carry out these processes without the intervention of an operator.

Such machines must contain five basic units: an input unit, a set of storage registers, an arithmetical unit capable of performing logical or arithmetic operations on arrays of digits stored in the registers, an output unit and a control unit which arranges for the functioning of the computer as a whole. The set of available operations constitutes the instruction code of a given computer. The program, or set of these instructions required to solve a given problem, must be stored in the computer before being obeyed. The individual instructions then assume the same physical form as numbers, within the machine. The operation of the computer involves the following steps:

(i) feeding in the program along with any necessary data such as starting values, parameters, and tables of empirical functions.

(ii) initiating the calculation to obey the instructions in sequence.

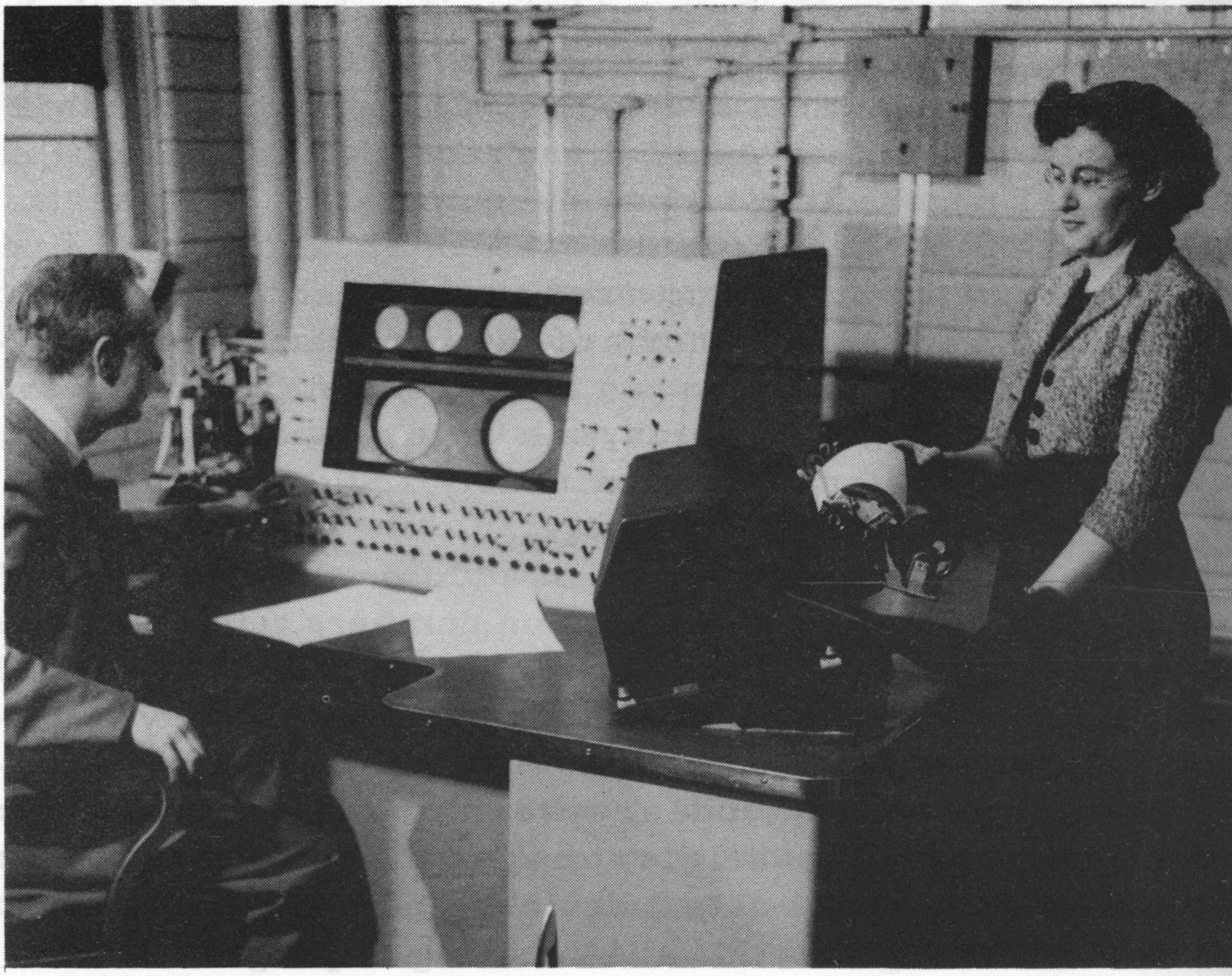
(iii) interpreting the output of the machine to obtain the final results.

FERUT

FERUT is equipped with a photo-electric paper tape reader, a high-speed electronic store consisting of 8 cathode ray tubes and a magnetic drum store of large capacity, electronic arithmetical and control units, and both printer and paper tape output units. It has recently been fitted with an I.B.M. punched card input and output unit. Representation on the paper tape is in the scale of 32, each row of five holes across the tape being used to represent one teleprint character. The teleprint form of the input data must be converted into binary form for use in the computer. The binary digits are grouped into words, one word containing 40 digits, which are equivalent to approximately 12 decimal digits.

The arithmetic operations of addition, subtraction and multiplication may be performed on numbers represented as integers or fractions, with or without sign. The logical operations, "and", "or", and "not equivalent to" may be performed on rows of binary digits. All other of the45 instructions in the instruction code are provided to facilitate transfer of words between the various storage units of the computer or between the input and output devices and the sotre, and to facilitate the organization and checking of programs.

The form of a FERUT instruction is somewhat complicated. It contains 20 binary digits, of which 6 are used to specify the operation to be performed, and 10 to specify the so-called address of the storage register containing the digits to be operated upon. Outside the machine, each instruction is represented by four teleprint characters. FERUT is also equipped with certain specialized electronic registers. One is an accumulator to hold the immediate results of an arithmetical or logical operation. Another is a set of eight B-registers, any of which may be used to modify a regular



The Authors at the Console of Ferut

A permanent staff of four engineers maintain the computer on a 24 hour - day, 5 day - week basis, and also there are approximately 15 professional programmers using the computer for 12 to 18 hours a day, 5 days a week.

instruction as it is obeyed, without altering its form in the store. The actual B-register selected for this purpose is specified by the remaining binary digits in the instruction mentioned above.

Practical Problems

A large amount of the detailed work necessary in preparing a specific problem for a given computer carries over to many other problems. Thus routines, that is, sets of instructions, can be written once and for all to perform such operations as:

(i) Reading-in instructions punched on the tape in teleprint form into the electronic binary form required by the computer, and storing these in sequence.

(ii) Reading-in decimal information punched on the tape, interpreting signs, and other special characters, converting such data into binary form and storing it as required by the program.

(iii) Evaluating certain functions, such as sine and cosine.

(iv) Performing calculations such as advancing the integration of a system of differential equations by one step in accordance with some established numerical method.

(v) Arranging to perform a sequence of instructions a prescribed number of times before proceeding to the next part of the calculation.

(vi) Printing-out data, with conversion from binary to decimal form, and with flexible layout on the printed page.

Operation (v) is commonly known as looping, and is usually accompanied by systematic modification of some of the instructions in the sequence. It is this technique which really makes a stored-program calculator workable, since it takes advantage of the repetitive nature of a calculation, and replaces a small amount of human effort by a large amount of mechanized labour. For example, it might take five minutes to write the instructions for the inner loop of the calculation, and the loop is to be transversed 100,000 times. Thus it could be stated that a computer such as FERUT could perform, in 10 minutes, work requiring 10,000 hours of desk calculation. However, the efficiency of a computer is not, in practice, so outstanding. Many days of human effort must be spent in fitting the inner loop into an entire program, preparing tapes and making check calculations to ensure that the work is free from error. Once this is done, the effective time ratio of a computer production run to a hand calculation averages, in the case of FERUT, something more like one hour to 1000.

Another practical difficulty often encountered by the programmer is that of scaling. FERUT's design is such that only numbers within a limited range of magnitude are allowed to occur in the course of a calculation. A common scheme for example, is that all numbers must lie between -1/2 and +1/2. Yet it is possible for the sum of a set of numbers to exceed these bounds even though each individual number lies within them. Suitable scale factors must therefore be attached to the individual numbers so that this does not occur. Compensation must then be made for such scaling elsewhere in the program and before the printing of the final results.

When such operations as division or integration occur, or when parameters vary over a wide range of magnitudes, the problem of scaling becomes more involved. Special representations of numbers are necessary, and new routines must be written to handle the basic operations on such numbers, as well as to convert to and from the normal representations. Because of the added complexity in such cases the machine takes considerably more time than for a corresponding normal operation.

To use a computer efficiently, it is necessary to consolidate and unify coding techniques. First of all, a scheme of input and organization of routines must be adopted. Compatible with this scheme, a library of routines must then be constructed to perform such operations as have already been described. This still leaves a considerable amount of work to be done for each problem by way of co-ordinating the routines into a completed program, and this entails a full knowledge of the code and specifications of the machine.

It seems reasonable that a final step could be taken towards the automatizing of coding techniques by arranging for the computer itself to do the organizing, coding, and scaling. Such an automatic coding system, Transcode, has been devised for FERUT.

Transcode

The input and organization of data and instructions is facilitated by a set of tape controls, four-letter words punched directly on the input tape.

Coding is done in terms of a set of simple pseudo-instructions. Each Transcode pseudo-instruction consists of an operation expressed as a four-letter word followed by three addresses. For example, the instruction to divide the number in storage location A by the number in storage location

B and place the result in storage location C is

DIVD A B C.

Finally, Transcode enables Ferut to be regarded as a floating-decimal machine: that is to say, every number n entering into calculation is represented by a pair of numbers a and b, such that $n = a \times 10^b$. This permits ready representation of numbers of greatly varying magnitudes, thus eliminating the need for scaling.

Transcode derives its name from the fact that it arranges for all information punched on the tapes in this simplified form to be read into the machine and to be translated into the form required by the computer for its normal operation. This translating takes place automatically once and for all at the beginning of each machine calculation.

Some of the problems which have already been solved using Transcode are the following:

1. The resolution, into sets of overlapping components, of curves obtained in experiments on hyperfine structure by means of a Fabry Perot etalon. For each observed curve a trial set of constants are selected, and the individual components are calculated from the well-known theoretical form

$$\sum_{i=1}^{n} \frac{I_i}{1+F \sin^2(\theta-\theta_i)}$$

for values of θ ranging from 0° to 180° at 2° intervals. A comparison with the observed curve shows which parameters need further adjustment. The program requires 29 instructions, and the running time is 19 minutes for $n = 10$.

2. The calculation of radiation patterns for a long-wire antenna. Here it is necessary to evaluate:

$$F(\theta) = \frac{\text{Sin}\ \theta\ \text{Sin}\ (\pi A\ (0.0078 + 1 - \text{Cos}\ \theta)\ )}{0.0078 + 1\ - \text{Cos}\ \theta}$$

for all values of θ from 0° to 20° occurring at intervals of 0.25°. This problem required 23 instructions and ran for 22 minutes.

3. The determination of the five geometrical elements of the orbit of a spectroscopic binary star from a set of observations of its radial velocity. Although several complications are introduced by astrophysical considerations, the problem resolves itself numerically into the formation and solution of a set of normal equations and the computation of the inverse matrix. Programs to reduce a set of 40 observations, in which all essential calculations are performed twice, run for 12 minutes and entail a total of 114 instructions.

4. Transcode has greatly facilitated the analysis of Infrared and Raman rotational and rotation-vibrational bands. The displacement of the lines can be expressed as a fourth order polynomial of the rotational quantum number, where the coefficients are functions of the molecular constants (or molecular moments of inertia). The operation of finding a best fit to this theoretical line from the observed frequencies has been programmed. This operation, involving the solution of a five-by-six matrix, requires five to six hours on a desk calculator. The average time required on FERUT is six to eight minutes. This ready method of analysis has been used on the rotation and rotation-vibration bands of ethylene, ethane, and methane.

5. There have been numerous other applications in such fields as chemical kinetics, acoustics, ballistics and low-temperature physics.

Certain conclusions are now evident from the experience of recent months during which Transcode has been available. A considerable number of graduate students have found it possible to prepare their own problems for solution by the computer. Their number has, in fact, increased from three to over twenty-five since the introduction of the new code. A student can learn the rudiments of Transcode within a few hours; and requires little or no assistance in applying this knowledge to his immediate needs. This is in contrast to the 10 hours of formal instruction and many weeks of practical experience required to learn the machine code. Persons outside Toronto have found it practical to learn Transcode and to submit programs by mail. These are transcribed to tape and run by operators who need have no knowledge whatsoever of the problem at hand.

An instruction manual for Transcode will soon be available and will be supplied upon request. Communications should be addressed to Dr. C. C. Gotlieb, Computation Centre, University of Toronto, Toronto, Canada.

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