Discussion

I. L. Auerbach (Burroughs Adding Machine Company): Could you tell us the temperature at which you are encapsulating the transistors and crystals and the effect it has on their life?

J. Felker: I do not know what that temperature is. I know it is possible to put these in the capsule and still have a satisfactory yield. In other words, we have working units that have been put in plastic.

J. C. McPherson (IBM): On the circuits you have already built, what is roughly the ratio of diodes to transistors?

J. Felker: The basic amplifier requires three diodes to help the transistor operate as an amplifier. Then if you put the logic functions on also, you can get by with as few as three additional diodes per transistor. If you want to use more logic circuits, the number of diodes will go up. But I would estimate something like eight to ten diodes per transistor in a balanced machine design.

F. C. Mullaney (ERA): Your diagram showed certain values on the components. Must these values be changed as different transistors are inserted in the circuit?

J. Felker: No. In our multiplier, for example, which had 43 or 44 transistors in it, all the amplifier circuits were identical to the extent that we could get them so, and all the transistors were interchangeable to the extent that anyone tried to interchange them.

E. D. Lawler (Naval Air Development Center): From what I have read, there are a number of different types of transistors. Could you specify exactly the one you used in the circuit?

J. Felker: The transistor that was used in these circuits carries the number, M-1734; the short title is "the high-speed transistor." I might mention that it is a point contact transistor, not the junction-type transistor.

Digital Computers: Present and Future Trends

JAY W. FORRESTER

The Program Committee asked me to summarize the present status of digital computers; also to point up the better features of the machines described at this Conference, and to forecast trends to be expected in the future.

We might start by determining where the digital computer field now stands along the road of progress. The first round of electronic digital computers has been completed, with a variety of machines showing varying degrees of success. The competitive spirit and rivalry between groups engaged in computer development has been strong in the past. We have met at this Conference for a frank discussion of the good and the weak points of the various machines. Some papers have stressed the good points and the successes. Others have stressed the future objectives. Still others have given us a picture of the shortcomings and weaknesses of the existing machines and, although conflicting, evaluations of what these results indicate for the future.

Present Status

A comparison of the present status of the digital computer field with any of our older branches of engineering shows that we are not far advanced. We are firmly on the threshold of a new field, but the digital computer work has reached no real maturity. Up to the present time people have made impressive contributions to the field of digital computation. Digital computation, however, has not yet made nearly the contribution to society that our enthusiasm might lead us to believe.

Maintaining the proper perspective here is important. It is entirely possible that the work of the world which has been accomplished by the modern automatic digital computer could have been more than accomplished if the man hours thus far put into the development of digital computers had instead been applied to the solution of the ultimate problems. We must look upon the results thus far as an investment in the future. We have first models of a new type of machine. There is no reason to believe that they are relatively any more advanced than were the first models of automobiles, the first aircraft, or the first radio sets.

Some rather remarkable attitudes have existed in the digital computer field. First models, without any tested predecessors, have been scheduled for production. Contracting officers have even bought first experimental machines on the assumption that they would be final production models rather than being useful primarily for evaluation. In few other fields would this be done. A first model of a new airplane is built for testing and evaluation, not for delivery to the fighting Air Forces or to an airline.

The machines reported at this Conference might properly be looked upon as exploratory models for evaluating physical techniques and design procedures, as vehicles for the assembly and training of organizations capable of designing computers, and, to the extent that the machines operate successfully, as devices for training people in the use of digital computers.

Big steps have been taken, but they represent only a beginning on the road ahead. We have first models of machines, but we don't even have adequate or recognized evaluation criteria for their assessment or discussion.

We are almost without experience in using these machines outside a development laboratory atmosphere. Most of the machines are still under the care of their designers or operated in a sympathetic research laboratory environment.

Until now we have been occupied by plans for proposed machines. In this new period ahead when the electronic digital computer is being evaluated, we will obtain results from the first round of computers and interpret these results for guiding future models of machines.

In building the first generation of electronic digital computers, we have learned the magnitude of the engineering involved. In the past 5 years, time estimates in the digital computer field have been a standing joke. Many of the cost

Jay W. Forrester is at the Digital Computer Laboratory, Massachusetts Institute of Technology, Cambridge, Mass.
The importance of high-quality engineering is pointed up by a few much publicized operating computers. There exists now a much better appreciation than we had a few years ago for the design stages, component testing, and engineering development that lie between the block diagram and the operating computer. There are already signs, however, that we may not have learned enough by this experience. The underestimation of construction time is giving way to an underestimation of the time necessary to place a machine in successful service. This, in turn, is followed by underestimation of the time which will be needed for learning how to use the computer for productive output.

Digital computers have varied considerably in the amount of shake-down time required. Perhaps one of the better experiences is the ERA 1101. The Whirlwind I machine has required a year to reach its present reliability. Mark III was announced 2 years ago, and you have heard the report on its operation. On the other hand, the EDVAC and the BINAC are still undergoing adjustment and modification. SWAC was dedicated over a year ago and is still under test operation.

Difficulties have resulted largely from more emphasis given to performance characteristics than to certainty of operation. The number of storage registers, the speed, or any of the other performance characteristics are certainly secondary to the question of whether or not the machine will, in fact, function.

Organizations have often undertaken too ambitious a program for the facilities and engineering manpower available. There are only a few examples of modest and exploratory beginnings in the digital computer field. The Burroughs Adding Machine Company people have reported on their program of learning by assembly of their trial machine out of test equipment units. The SEAC machine, the EDSAC, and the Ferranti machines have set modest objectives which were dis-charged without becoming involved in unduly elaborate devices. The ERA 1101 and the International Business Machines Company Card-Programmed Electronic Calculator were done by commercial organizations basing their designs on somewhat similar equipment already developed.

**Evaluation Criteria**

Various machines must now be evaluated. There are many machines to be compared, but for the most part we find ourselves without any test or comparison criteria. There is fair agreement regarding the definitions of speed and storage capacity in digital computers. The time has come for more sophisticated criteria of comparison. In the papers at this Conference, each group has used its own definition for reliability of its equipment. It would be almost impossible to make a comparison between the different machines based on the data. Likewise, there can be no significance in cost figures, unless accompanied by a measure of performance and reliability. We discuss the number of vacuum tubes in a machine, but this in itself lacks significance unless we have a measure of the utility of those tubes, in other words how much computation they will perform for us.

**Storage Criteria**

I might cite some examples of the kinds of criteria which will be useful. Consider first the storage systems. It has been customary to discuss storage systems in terms of capital cost per binary digit of storage capacity. This leaves out any concept of performance, and, since the access time is of first order importance, it might be better to use the criterion of cost per unit of performance. Table I illustrates typical numerical values. In the first column is cost in dollars per binary digit. This is capital cost and maintenance for a 5-year period and includes associated control equipment. For those applications which require large storage capacity without imposing demands for short access time, cost per digit is perhaps the proper and sufficient criterion. In dollars per binary digit, we find the magnetic drum most favorable, followed by the acoustic line and the electrostatic tube. A good measure of storage performance might be defined as:

\[
\text{Storage performance = \frac{\text{Performance units}}{\text{Binary Digits}}} \times \text{Access time in microseconds}
\]

<table>
<thead>
<tr>
<th>Storage Type</th>
<th>$/Bit</th>
<th>$/Performance Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic drum (1949)</td>
<td>$0.15</td>
<td>$1,200</td>
</tr>
<tr>
<td>Acoustic line (1960)</td>
<td>$1.75</td>
<td>$500</td>
</tr>
<tr>
<td>Electrostatic (1951)</td>
<td>$0.00</td>
<td>$160</td>
</tr>
<tr>
<td>IF (1960)</td>
<td>$1.00</td>
<td>$3</td>
</tr>
</tbody>
</table>

For high-speed internal memory, a more significant cost criterion would be dollars per unit of performance, and we then find the ordering of the three principal present-day storage systems reversed. Cost divided by digits of storage divided by access time gives us for the magnetic drum $1,200, for the acoustic line $500, and for electrostatic tubes $160. These are approximate values but typical of present-day systems. Part of my assignment here is to predict trends, and I suggest that in the next few years, we should expect to see the cost per unit of performance reduced to as little as $3. This improvement may result from advancements in solid state physics which will yield both simplicity and higher speed.

**Design Efficiency**

Another criterion is needed for measuring the machine design effectiveness. Digital computers discussed at this Conference differ by a factor of only 2 or 3 in complexity but by orders of magnitude in speed. We find that the higher speed machines are more efficient in terms of the work they will perform per unit of equipment. We can draw here an effective parallel with the internal combustion engine. The man with a very small job to be done or who will use his computing machine only occasionally is rightly interested only in total complexity and cost. Let us compare this with a one horsepower outboard motor for a fishing boat. In the engine, horsepower represents work done in a unit of time and can be likened to the arithmetic operations per unit time or speed of a digital computer. In the outboard motor, we have a small, simple inexpensive machine which may weigh 20 pounds per horsepower and costs $40 per horsepower. In designing an automobile one certainly doesn't use a multiplicity of outboard motors. Instead of 20 pounds per horsepower, the automobile engine weighs about 5 pounds per horsepower. Instead of $40 cost per horsepower, the automobile engine may run $3 to $5 per horsepower.

We find a similar situation in the performance per unit equipment or in the cost per unit of performance in the digital computer. Table II shows the approximate order of magnitude for various classes of present-day computers in terms of the performance efficiency index which I define as the operations per second divided by some standard unit of equipment. Deciding on a unit of equipment is difficult and controversial. For present-
day machines the vacuum tube cathode might be taken as this unit, as long as the complexity and cost of the computer is related to the number of tubes. For the drum computer this index is about 0.03; for the acoustic line computer about 0.5; and for the parallel electrostatic tube computer about 1.2. Again, if I should make a prediction for 5 years hence, I would say that we can reach an index figure of about 20 operations per second per unit of equipment. This index is meant to be comparable with the others, but it may be necessary to redefine the unit of equipment if the vacuum tube at that time has been replaced by other elements. This higher efficiency should be achieved with higher speeds and a substantial reduction in complexity. Table II also shows approximate capital cost per unit of computing speed for the various types of machines.

The index of efficiency can be used advantageously in determining the utility of auxiliary equipment for a machine. One is often tempted to make a special device for converting number bases or a piece of terminal equipment to simplify the work of the computer. Such equipment may operate at a very low duty factor and do a job of which the main machine is capable. One should ask himself how the average operations per second, averaged over a year's time, per unit of equipment in the special device, compares with the above index for the main machine. It will often be true that the simple job is more efficiently handled by the complex central machine.

Reliability Criteria

Considerable emphasis in the papers of this Conference has been placed on digital computer reliability. We do not even have a definition of reliability, to say anything of criteria for measuring those factors which produce reliability. To some people reliability is measured by the percentage of time that the machine is not in the hands of maintenance men. To others reliability is measured by the frequency of random mistakes in the results. These are two very different concepts. In many ways the frequency of random errors is much more important than the percentage of inoperative time, and yet we have heard almost nothing about this during the last 3 days. In the papers, the percentage of inoperative time has been used as an indication of digital machine quality; it is just as much a direct measure of the expertness of maintenance which the machine receives. We need a measure for the mainenance effort put into a digital computer. I suggest that total number of men assigned to maintenance is not adequate, especially when we talk about machines which differ by four orders of magnitude in speed. It would seem more appropriate to measure the amount of maintenance the machine requires in terms of the man hours expended per million arithmetic operations usefully performed.

In some applications continuity of operation is of primary importance. Two definitions of continuity have been used:

- One definition measures continuity as a percentage of the total number of hours in a week. The other measures continuity as the percentage of scheduled operating time without penalty for scheduled maintenance time.

Both definitions are useful if properly understood, but both have an important and fundamental fault in the impression they create. Continuity of performance should be measured in the percentage of inoperative time rather than in the percentage of operating time. If asked how good your watch is, you don't say that it gives 1,480 minutes correct out of the day, but rather that it loses 1 minute per day. Ratios of inoperative time are better indices of quality than ratios of operating time.

I suggest that a 2 to 1 ratio in engineering quality exists between 50 per cent and 60 per cent inoperative time and also that a 2 to 1 ratio exists between 5 per cent and 10 per cent inoperative time.

Error Frequency

There seems a strong tendency to measure mistakes in terms of errors per unit of time. The digital computer profession stands in awe of the very enviable record of the Bell Telephone Laboratories relay computers. These are reported to have made only one or two errors not caught by their checking equipment in the period of 5 years. A better criterion than the errors per unit time might be the millions of operations carried out between errors. On this basis the Bell Telephone Laboratories record stands, according to legend, at something like 35 million operations per mistake. To equal this record, some of the modern machines need to run error-free for a period of only an hour and a half, and this, indeed, has been done.

I think that as a future trend we can expect great strides in the reduction of inoperative time and the elimination of isolated machine mistakes. It is an unusual person who can make 500 arithmetic computations on the desk calculator without errors. Machines built today can do millions of operations between errors, and the next 5 years may bring us machines with reliability against random mistakes in the decade above 1,000 million operations per error. This should be accomplished without unreasonable cost. I therefore agree with the comments on the EDSAC by Mr. Wilkes and those on Whirlwind by Mr. Everett that checking devices will become unnecessary, and disagree with the conclusions in the paper on Mark III by Mr. Poorte that internal checking is mandatory. The engineer here has a challenge to build a reliability into his computing machine comparable to that existing in other modern machines. The airplane engine operates 1,000 hours between overhauls and many times that between failures. Why not similar performance from a computer?

Checking

The papers at this Conference disclose two different attitudes toward machine checking and isolated errors. One group attempts to provide checking equipment which will stop the machine when a mistake is detected. The other group places its reliance on the prevention of mistakes. The choice apparently depends on the error frequency which is expected and on the type of application for which the machine is designed.

For a very high error rate, say a few thousand operations between errors, and therefore performance which is only one or two orders of magnitude above manual computation, a detecting and self-correcting error system is required. The self-correcting feature might be obtained by self-correcting codes which, so far as I know, have not been used in computing machines. Computations on a self-correcting basis can be programmed and this has been done.

For a medium-error rate, which might be a million operations between mistakes, self-checking, either built in or programmed, is indicated. For short sequences such a machine has a good probability of getting a correct answer, and problems can be rerun and the answers compared if necessary.

For a small error rate, which might be one mistake in ten million or one hundred million operations, programmed checks where applicable are entirely adequate.

For a negligible error rate, which we might call one error per thousand million operations upward, it is unlikely that any
attention to checking is required.

The choice between detection of errors and the prevention of errors depends a great deal on the application of the machine. In ordinary scientific and business applications, the matter can rest entirely on studying the economics of how to assure a sufficiently reliable result. Built-in checking equipment may be desirable, but the complexity should be weighed against duplicate solutions of the problem. The equipment efficiency criterion which I referred to earlier is a helpful guide in making this decision. The choice must be substantially influenced by the desirability of having a logically simple machine which is easy to understand and maintain. One departs rapidly from the simple machine as checking methods are introduced. Very different considerations apply to digital computers intended for real-time control applications. A machine intended for military or industrial control must have a high probability of continuously correct answers. This means either a self-correcting error system or a negligibly small error frequency. Error detection alone is unsuited where the answer is valueless unless obtained at the time of the attempted solution.

Of the machines reported at this Conference, only the Whirlwind I was designed specifically for real-time control and an error frequency low enough for that application. Of the scientific machines, it appears that the IBM Card-Programmed Electronic Calculator, the ERA 1101, the Ferranti machine, the EDSAC, and the SEAC are getting satisfactory operation without built-in checking equipment. As near as I can tell from the papers, the other machines depend on built-in checking, or are as yet untried in operation, or have presented serious reliability difficulties.

Electronic Reliability

Consider now some of the factors affecting electronic computer reliability. The unreliability of electronic equipment has reached almost crisis proportions in military equipment of all kinds. Because of the special need for reliable performance in the digital computer, the digital computer engineers may be forced to evolve methods of insuring reliability which can help to alleviate the poor performance in other branches of electronics.

We do much talking about the unreliability of tubes and components. It seems to me, however, that the greatest obstacle to good electronic equipment is the frame of mind and attitudes of those participating in its design and procurement. No one will admit to being interested in reliability, but the fact is that theoretical performance, availability date, cost, and size are almost always placed ahead of reliability. The customer and the development engineer share the blame. It is so much easier to put definite numbers on storage capacity, speed, delivery dates, and cost, and these can effectively be used in publicity and the procurement of contracts and the appropriation of funds.

For lack of suitable criteria, reliability has not even been defined, much less evaluated. It is a controversial subject, resting on professional opinion rather than measurement. Reliability cannot be tested in a few hours or days as can other performance factors. The important aspects of reliability, such as freedom from errors and ease of maintenance, need to be evaluated under the conditions of the ultimate application rather than in the manufacturer's plant. Poor reliability is often dismissed on the basis of inadequate maintenance, unavailability of proper test equipment, and a multitude of other factors which either should have been foreseen as likely by the manufacturer or remedied by the customer.

Another difficulty here is that no one ever seems to be responsible for unreliable operation. It is charged to unavoidable and uncontrollable circumstances and accepted as inevitable. This again is an evidence of disinterest and defeatism. Once the proper attitude toward reliability has been developed in the supplier and the purchaser, we need have no fear for the reliability of the components. Funds and man hours would then be transferred from production of final equipment to the necessary development of suitable components. Adequate emphasis would be placed on good design and past failures would not be buried but studied for their weaknesses. I would caution against feeling that any magic will suddenly solve the dilemma of electronic unreliability. It will be solved only by hard work and long, meticulous, and expensive attention to detail.

We have had only a few suggestions at this Conference for specific technical ways for improving machine reliability. One of these is the marginal checking technique for depressing the performance margins of components to see if they do, in fact, have a safety margin between the normal operating point and the point of failure. We have had a favorable account of marginal checking in the Whirlwind I computer by Mr. Everett and Mr. Taylor. A modified form has been successfully used in the ERA 1101 where marginal checking is done by varying filament voltage. Varying filament voltage can be expected to catch deteriorations of tube cathodes which accounts for half or more of electronic failures. Filament variation is much less effective than varying other voltages and pulse repetition rates for finding changed characteristics in resistors, crystal diodes, and other circuit elements. Mr. Poorte in his discussion of Mark III suggests that marginal checking would have been a help to them. I believe that a good marginal checking procedure will be absolutely essential in achieving a negligible occurrence rate of isolated errors. Marginal checking is a relentless tool in pointing out design weaknesses in a new machine. It gives good assurance of freedom from random errors occurring from components operating near their failure threshold. It is of almost no value in finding true intermittents, such as opens and shorts which depend on mechanical vibration. These mechanical intermittents are the most serious remaining obstacle to eliminating isolated mistakes in the digital computer.

Future Trends

We have heard the transistor proposed for the elimination of failures now attributed to vacuum tubes. The transistor does indeed look promising. I would caution against considering it a panacea. Vacuum tubes in some computer applications have a failure record as low as any thus far proven for transistors. The transistor will improve with time but, on the other hand, in a factory will not be made with the loving care given to the first laboratory models. As Mr. Felker has told us, the transistor may require rather special conditions in circuits which enhance its reliability. The same care and concessions to the shortcomings of vacuum tubes can do wonders for their reliability. With the proper use of marginal checking, the vacuum tube presents no serious problems except from open welds and short circuits. Again, with the proper attitude toward reliable electronics, these difficulties could be greatly reduced. Any of you who have seen the frantic haste with which vacuum tubes are assembled in the modern tube plant must wonder that they come anywhere near their present freedom from mechanical flaws. For computer use, the transistor is not so interesting for its small size and power consumption as for the unproven possibility that it can be
more free of intermittent changes in performance than the vacuum tube.

I now wish to mention several interesting items from the papers presented at this Conference.

Only one of the machines, described, the IBM Card-Programmed Electronic Calculator, has had production and field experience. The International Business Machines people would have done us a great favor to have given us more information and numerical data on their service, maintenance, and field experiences. An important change is occurring in the ideas of how to administer a computing center and a computing machine. In the past, computer time has been so scarce and the changing from one problem to another so difficult, that only large blocks of time could be assigned to a user. In many computing centers, unless the client wants the machine for a month, he has almost no chance of getting machine time. With the new types of machines which can be changed in seconds from one problem to another, it is no longer necessary to put minimum limits on sizes of problems. The machine user can get time on the machine several times a week with intervening periods for studying results. This reduces greatly the amount of computation which must be done since he is under no compulsion to do large amounts of computing of uncertain future value for fear he will not have another opportunity. There is no economic foundation to the common assumption that the large computer is useful only for the large problem. The modern digital computer provides computation at a lower cost per unit of output than can be obtained by any other method. The lower economic limit for problem size is well down in the range of problems that are handled by manual computation.

Electrostatic storage tubes present a number of interesting aspects. Of the several electrostatic storage tubes receiving past publicity only the Williams’ tube and the MIT tube seem to be in digital computer operation. If I may venture some comments on the Williams’ tube situation, I think it points up a number of interesting facts in our attitude toward reliability and performance. The tube was developed by Williams’ for use in a serial type machine which has successfully become the present Ferranti model.

A serial machine of that type presents a favorable regeneration ratio and the tube can apparently be made to work well with proper care in engineering its circuits and environment. Even so, a special design of tube has been used. We see quite a different picture where the Williams’ principle is being employed in high-speed parallel type machines. Here many groups are planning to use the Williams’ tube, while few have adequate research facilities to fully explore the possibilities and limitations of the device in the more unfavorable parallel operation. With too small a research staff, each group is forced to a rather superficial attempt to place the tubes into a machine with the optimistic hope that operation will be satisfactory. Three years ago I saw the first read-around ratio test made on the first Williams’ tube operated in this country, and the regeneration ratio was determined to lie somewhere between 32 and 128 cycles. We are at about the same place today.

If I might refer to my earlier comments on reliability and to the early motivation for using the Williams’ tube, it seems that we have departed from two sound objectives. The Williams’ tube was adopted as a quick and inexpensive way of obtaining storage with a standard electronic component. There is every indication that used with a small enough storage density and a high enough regeneration ratio it would in fact function well. In the meantime, however, the goals have been raised to the point where the tube may not qualify. Might it not be better first to accept what can be accomplished easily before battling for an elusive optimum?

For future trends it seems that the electrostatic tube, regardless of type, is but a transient on the stage and that it is scheduled to be replaced in the next few years by new developments in solid state physics. A strong contender is the 3-dimensional magnetic core storage array with a good possibility for ferroelectric storage.

In the future development of computing machines, we should expect more attention given to terminal equipment. Such a plea was made by Poorte in his paper on the Mark III machine. Present terminal equipment is relatively inadequate. Also our ideas about the use of terminal equipment and the kinds of results to be obtained from high-speed computers may be outmoded. There is still a tendency to want entirely too much tabulated data where we have rather unsatisfactory printing machines. As a way of avoiding part of this problem, I think the cathode ray tube output for graphical plotting should receive more attention. Also we should direct the machine to go further in data analysis to condense results into a small volume of information for human consumption.

For future trends in machine performance, it seems to me that there is no immediate hope for higher-speed video circuits. There can, however, be higher speed machines. A great deal of machine time can be saved by analyzing computing programs and providing special machine logic or facilities for saving time in the more frequent types of operations. In particular this applies to time-saving in the red tape operations where the B-box technique of the Manchester machine might be cited as an example of substantial progress.

Machine speed has increased by several orders of magnitude over the last 10 years. In the future we can perhaps get another decade in speed, but I doubt that more can be accomplished without a fundamentally new type of computer. The great steps in the near future, I think, will be in the direction of simplification without losing performance. It seems clear that the complexity of computers can and must be reduced.

**Discussion**

The following extension of remarks made from the floor was submitted in writing:

**John W. Carr III (MIT):** During the course of the convention sessions, informal sessions were held by representatives of some of the various computers now in operation and under construction, to discuss problems arising in programming. Present during part or all of these sessions were the following people:

**Forrester—Digital Computers: Present and Future Trends**

M. V. Wilkes—University of Cambridge, England
J. M. Bennett—Ferranti, Ltd., formerly of Cambridge
D. J. Wheeler—University of Illinois, formerly of Cambridge

**Table II. Digital Computer, Cost-Performance Criteria**

<table>
<thead>
<tr>
<th>Computer Type</th>
<th>Efficiency</th>
<th>Cost/Unit Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum (1949)</td>
<td>0.03</td>
<td>.3000</td>
</tr>
<tr>
<td>Acoustic (1950)</td>
<td>0.5</td>
<td>750</td>
</tr>
<tr>
<td>Electrostatic (1951)</td>
<td>1.2</td>
<td>250</td>
</tr>
<tr>
<td>Williams ? (1950)</td>
<td>..20</td>
<td>...26</td>
</tr>
</tbody>
</table>

From the collection of the Computer History Museum (www.computerhistory.org)
be a heated subject of controversy at future meetings.

Preventing and Locating Mistakes in Programs

The discussion on methods of minimizing mistakes in programming and in locating the mistakes which do occur opened with a description of the methods of error or blunder diagnosis used on EDSCAC, as described in a book published recently by Wilkes, Wheeler, and Gill entitled "The Preparation of Programs for an Electronic Digital Computer, with Special Applications to EDSCAC" (Addison-Wesley Press), and similar methods on the Manchester Computer (explained by J. M. Bennett of Ferranti Ltd.). Dr. Wheeler mentioned a new order-by-order print-out technique developed by Dr. Clippinger of Aberdeen, which traced the path of control through the machine, printing, however, only on the first passage of each loop. Mr. Adams proposed a post-mortem routine which consisted of printing out the contents only of those registers which had been changed during the running of the program.

Dr. Smith of Toronto compared a programmer with a blunder in his program with a lecturer at the blackboard who has become entangled in his analysis; and suggested that in both cases it might be better if both retired gracefully and returned after re-studying the problem in the less strained atmosphere of his office.

Several suggestions were made as to methods of pretesting programs before they were run. The importance of double checking by a second programmer was stressed by Dr. Wilkes. Use of coding checkers with jobs similar to copy readers on newspapers was proposed by Dr. Smith. Dr. Carr proposed special checking programs to check only the logical structure of a program (where more blunders are likely to occur) with further arithmetical investigations being made later. Dr. Wheeler suggested that a programmer can more effectively check his own work if he puts the program aside for a week before checking it.

Of the special routines discussed, Cambridge’s input program, the more elaborate conversion program of MIT’s Whirlwind, the Manchester duotricenary (32-base) conversion program of MIT’s Whirlwind, and the ORDVAC sexadecimal input program were compared. Dr. Wheeler predicted possible changes in the ORDVAC scheme.

Dr. Wilkes proposed a “free address” system of coding in which only those words which are actually referred to by instructions in the program would be numbered, with all words being assigned to registers in sequence by the machine, and with the addresses assigned to the numbered words being inserted automatically where needed. This method would allow for corrections in programs without need for renumbering, and would generally free the programmer from his bondage to the machine numbering system. Various methods of representing subroutines by artificial instructions were also discussed, the assumption being that the input conversion routine would automatically select and assign addresses to the proper subroutines.

Universal Instruction Codes

The discussion on “Universal Codes” to facilitate communication between groups degenerated into a free-for-all over just how universal such a code should be. Dr. Rubino of Moore School defended a near-algebraic code, while others felt that codes applicable only to machines of one classification (such as single-address or three-address) might be more useful. It was finally agreed that actually two types of “Universal Codes” might be useful:

1. A truly universal code, perhaps similar to the Burks-Von Neumann device, that would explain the workings of a program independent of the type of address.

2. A generalized single-address code that would explain the workings of a problem in a language understandable to all users of single-address machines, with similar generalized 3- and 4-address codes.

Mr. Adams suggested the possibility of adopting a “universal” code which could be correctly interpreted not only by programmers but also by various different computers by means of interpretive subroutines. Such a scheme could permit the same program to be used on different computers, albeit at a loss of efficiency, and might aid in the adoption of a truly universal code for future computing.

Throughout this set of discussions, the absence of mathematicians and programmers from NBS, Eckert-Mauchly, IBM, Aberdeen, ERA, et cetera, obviously caused discussion to move in some particular directions rather than others, and therefore a complete sampling of programming opinion was not available. The consensus of the group was that further discussions of this type would be very helpful, and that formal sessions should be included in coming conventions, since the problems of programming at this point appear as yet mostly unsolved.