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Memo to: Mr. R. A. Henle

From: Dr. F. H. Branin

Subject: Machine Analysis of Networks

The purpose of this memorandum is threefold: first, to outline our current plans for a network analysis program on the IBM 704 computer aimed at satisfying the needs of Department 545; second, to indicate the potential value to IBM of this program and of possible future developments in this field; third, to propose a course of action to stimulate and coordinate the evident interest and increasing activity in machine analysis of networks at IBM and elsewhere.

## Network Analysis Program for 1959

The network analysis program which we plan to develop for the IBM 704 computer during the coming year is intended to provide us with a means of handling a wide variety of RLC networks, including transmission lines and a large -- but as yet undefined -- class of nonlinear devices. This new program is intended to remedy several basic deficiencies of our recently completed Transistor Circuit Transient Analysis Program, called TCTAP. Since TCTAP represents our first effort at machine analysis of networks and was aimed at the treatment of a rather restricted type of transistor switching circuit, it suffers from certain intrinsic limitations. For example, it is able to handle only nonsaturating transistors, using a fixed equivalent circuit with somewhat specialized characteristics, and it cannot treat the generalized linear AC or transient network problem. It can handle the transient analysis of a large and important class of RLC networks, however, and it has proven the feasibility of a computational approach to at least some of our circuit design work in Department 545. Furthermore, it has given us both invaluable computational experience and some very useful design information.

In our next phase of program development, we will need to handle networks with both saturating and nonsaturating transistors and with complete freedom to change equivalent circuits. Later on, we will also attempt to treat parametric amplifiers, magnetic core devices, and cryogenic circuits. These later developments, of course, will necessarily have to await the successful completion of a flexible and workable basic program.

This program will consist of two major parts. The first part, called the assembly phase, will perform two separate functions: it will read in punched card or tape data specifying the network configuration and the characteristics of the nonlinear devices and then it will derive from this data the appropriate algebraic-differential equations describing the system. The second part, or solution phase, will solve these equations and then present the computed results in whatever output form is desired.

Output facilities at the PDL Computing Center now include printers, card punch, and tape. But in 1959, a new device, called a microfilm printer-plotter, will be acquired. This latter device will enable us to present response curves as well as alphanumeric data directly on the face of a cathode ray tube for subsequent microfilming and enlargement to full page dimensions. We intend to use this machine as the principal output medium for transient analyses.

On the basis of experience gained in connection with TCTAP, we believe that the matrix formulation of the network problem, combined with Kron's method of piecewise analysis which we have programmed, provides us with a tool which is admirably suited for use on a digital computer and which is capable of handling any linear RLC network problem -- DC, AC, or transient -- that can be fitted onto the machine. Moreover, since the principal technique for treating nonlinear networks at present amounts to approximating the nonlinear system at succeeding instants of time by a sequence of time varying linear networks, it seems reasonable to expect that known linear methods can be extended to cover a large class of nonlinear systems. It remains to be seen, of course, just what fundamental limitations on this approach will emerge.

In order to make our program easy to use, we will make a serious effort to simplify the programming requirements imposed on the user. In particular, we intend to make it possible for the user to employ FORTRAN statements in specifying the nonlinear functions. In addition, we are considering a scheme for calling from library tapes any of a number of previously specified network models for nonlinear devices. This technique, which can in principle be extended to include the calling out of entire circuits, will enable the user to assemble a network in large blocks rather than one circuit element at a time.

One of the key computational tools which we plan to develop is a matrix manipulator. This will be a kind of Autocoder consisting of a number of closely integrated subroutines for performing the various types of matrix operation required by both the assembly and solution phases of our program. The matrix manipulator, which represents a sizeable step in the direction of Macrocoding, will enable us to modify our basic program much more easily than is presently possible. Furthermore, by taking advantage of the peculiar properties of the different matrices encountered, we will be able both to minimize storage requirements and to maximize computational efficiency.

Since the matrix manipulator is to be the computational heart of the whole program, this will be developed first. However, our initial effort will be placed on writing only those subroutines which are essential for the DC initialization and transient analysis of transistor networks. Since more versatile subroutines can be added at any later time, we will eventually be able to augment the basic program so as to handle AC problems and reliability studies, as well.

In implementing the solution phase of this program, the transient response will be computed by numerical integration of the nonlinear differential equations at first. We recognize, however, that there are definite limits on the ultimate speed of integration which is possible by this technique. Accordingly, we will investigate other methods of solution in the search for a gain of five-fold or more in integration speed over that now attainable in TCTAP. In particular, we will study more fully the analytic solution of linear networks using the eigenfunction expansion which is the objective of the Laplace transform method. However, since the Laplace transform method is ill-adapted to the numerical treatment of large networks, we would plan to obtain completely equivalent results by the alternative route of solving the eigenvalue-eigenvector problem associated with the coefficient matrices which characterize the differential equations of the network. This approach is well suited for digital computation and a considerable literature is available for our guidance.

The correspondence between the language of the eigenvalues-eigenvector approach and the Laplace transform method is readily given: the eigenvalues of the network coefficient matrices are simply the characteristic or eigen-frequencies of the network while the eigenvectors are the initial conditions which, when imposed on the "dead" network will cause it to respond at each of the corresponding characteristics frequencies; the eigenfunctions are the appropriate linear combinations of exponential response functions involving each of the characteristic frequencies. Hence, when the eigen-problem solution has been programmed, it will give all the numerical information which is necessary to completely characterize the transient response of any linear network. The extension to nonlinear networks will be based on the piecewise linear approximation mentioned above.

Obviously, these objectives will not be reached easily or quickly. But the plan can be carried out step by step so that once the initial goal of a working program for DC-transient analysis has been attained, further elaboration of the basic program can be carried out as departmental and/or company requirements dictate.

The Importance of Network Analysis Programs to IBM

Since network analysis is one of the basic mathematical tools of the electrical industry and since the modern high speed digital computer is capable of implementing this tool on a scale far beyond that which has been practicable in the past, the potentialities for machine analysis of networks at IBM and elsewhere in industry are not hard to visualize. For example, in circuit design work, it is often desirable to carry out an analysis before building and testing a circuit; but frequently the labor of doing so by hand is prohibitive. Then, too, it may be desirable to analyze a circuit containing elements or devices which are mathematically realizable but either impractical or impossible to realize physically. Both of these situations can be handled by machine analysis, provided, of course, that an adequate equivalent circuit can be derived for the devices used. In this regard, TCTAP has already proved itself to be a useful adjunct to circuit design in Department 545, and an effective computer program for power supply designs has been developed by another department of PDL. More developments of this kind can certainly be expected in the future.

We have received a number of inquiries from within IBM -- and a few from outside -- concerning the TCTAP program and our theoretical studies on network analysis. In my opinion, these inquiries are unmistakable evidence that a basic needs exists both within and without the company for a flexible and versatile network analysis program. In view of the wide range of network problems already encountered in Department 545, a program sufficient for our own needs, if properly planned, will by its very nature constitute the nucleus of such a general purpose network analysis program. Indeed, we have tried to formulate our plans so as to anticipate and make provision for not only our own future requirements but also those of other IBM activities so that our basic program may be augmented or changed to satisfy a variety of different needs. Undoubtedly, there will be considerable usage of our program outside of Department 545 and so, in the interest of serving IBM better, we have thought it wise to build into this program from the beginning as much flexibility and versatility as possible. This approach, fortunately, is directly in line with our own departmental requirements of the immediate and distant future.

In addition to the more obvious electrical applications of a general purpose network analysis program, there is a wide area of application in other fields of interest in science and engineering. This assertion is based on the fact that network models are known to exist for a host of physical phenomena besides electrical circuits. For example, network representations have been established for such diverse systems as: elastic, electromagnetic, and hydrodynamic fields; heat flow and other (e.g. nuclear) diffusion fields; mechanical and electrical vibrating systems; and even the Schroedinger equation of quantum mechanics. There is also a partial analogy between the network concept and certain economic problems which may be useful in linear programming.

The existence of these models, which has a sound theoretical explanation, is what makes electrical analog computation possible and gives such tremendous scope to the applications of network analysis. It follows, therefore, that a properly conceived and executed network analysis program should be able to convert a large scale digital computer into a super-analog machine capable of treating a wide variety of physical problems with an essentially unified mode of problem specification, formulation, and solution.

As a specific example of an important nonelectrical application of network analysis, I would like to cite a problem about which we were recently consulted by one of IBM's customers in the oil industry. This problem concerns the optimum programming of oil production from the many different wells tapping an underground reservoir.

The physical situation involved is the relation between pressure throughout the oil field and the diffusive flow of petroleum through porous rock. This relation is described by a nonlinear partial differential equation -- the diffusion equation -- for which an analytic solution is unknown, in this case. In attempting an approximate solution, an RC network model may be used. The customer mentioned is actually constructing an analog machine to represent one of their oil fields. But the electric network being used consists of only linear elements whereas the physical problem demands nonlinear devices; this in itself poses the problem of whether successful treatment by an actual electrical circuit model is feasible. Accordingly, a solution by digital computation is also being investigated.

Here, however, it should be remarked that the present analog network, corresponding to some 2500 differential equations, represents only a two-dimensional slice of the oil field; a three-dimensional representation could require the solution of more than 100,000 differential equations. Even so, the solution to this problem may spell the difference between an ultimate recovery of only 20% of the total oil available from an underground reservoir and a possible doubling of this figure. It is clear, therefore, that this problem -- which is of fundamental significance to every oil company in the world -- is in the multimillion dollar category. It is also fair to assume that a sizeable effort can be expended by the oil industry to find a solution to this problem.

Admittedly, our present machines and methods of analysis are woefully inadequate to cope successfully with a problem of this magnitude. But the important point to recognize is that we have already made a start and are actively engaged in <u>solving problems of the very same mathematical kind</u> -- although on a much smaller scale and in a far different context. It is obvious, therefore, that whatever we learn in our own field can have a direct -- and possibly a decisive -- influence on this oil field problem, and on many other similar network problems of importance to modern technology. We should be alert to this fact and instant to exploit it as rapidly as practicable, for it is entirely possible that the value of these extraordinary applications of network analysis may ultimately exceed the value of its strictly electrical applications.

In line with this viewpoint, but subject to the demonstrated effectiveness of our forthcoming IBM 704 program, extension of this program to the IBM 709 and eventually to the IBM 7000 series machines should be considered as a legitimate future development. This extension could have two conceivable effects: first, it may exert an appreciable influence on future machine design, particularly if network analysis, and the matrix operations it requires, proves to be, or promises to become, a widely used computing technique; second, it may turn out to be a useful selling point for IBM computers. This judgment is based on the urgent need for breaking the serious bottleneck of preparing special purpose programs for a general purpose computing machine. If a general purpose network analysis program comes anywhere near realizing the potentialities indicated above, it may help considerably to break this bottleneck by virtue of its versatility of application. This feature could have considerable sales appeal to prospective customers of computers for which such a program is already in being or is in preparation.

Coordination of Outside Interest in Machine Analysis of Networks

In order to stimulate and coordinate interest in machine analysis of networks outside our department, the following steps are proposed; first, an engineering seminar should be given describing our theoretical and computational results to date; second, a roundtable discussion should be planned to which interested personnel would be invited to discuss existing and future requirements for network analysis programs; third, a coordinating committee should be established for the purpose of channeling intra-company activities towards similar goals, where such exist, and for interchanging information as company activity in this field increases.

An engineering seminar of the kind mentioned is already being planned for delivery in the near future. At this seminar, the proposal to coordinate future efforts within IBM in this field could be set forth. An additional factor, which could help this effort considerably, is the course in "Network Analysis and Its Applications in Science and Engineering" which I have been asked to give by the PDL Education Department, starting in February, 1959. Depending on the outcome of the seminar and roundtable discussion, appropriate further action could be undertaken.

In view of the evident fact that our programming efforts will be useful to many others within IBM, it appears legitimate to seek encouragement and even active support in the form of programming assistance from prospective beneficiaries. In return for this, our program could be expanded to meet their needs as well as our own. If properly handled, such a cooperative effort could result in our getting our own needs as well as the company's needs satisfied more quickly.

Ultimately, our programs should become a part of SHARE. This raises the question of when and how to cooperate with other members of SHARE. Our intra-company experience should be the guide in this matter. It is possible, however, that outside interests may precipitate some activity in this direction within the coming year. For one thing, it is planned to submit three papers, describing our theoretical and programming developments, to the International Symposium on Circuit and Information Theory to be held next June at UCLA. In addition, the interest already indicated on the part of one of the oil companies may lead to a request for some form of cooperative effort, but this has not yet crystallized. In any event we should give some thought to what can and should be done to cooperate with other companies interested in our work.

<u>Summary.</u>

Our current plans for a more flexible and efficient network analysis program for the IBM 704 computer have been outlined and the possible value of this program and its consequences to IBM has been indicated. Also a course of action to stimulate and coordinate interest in network analysis and its applications both within and without IBM has been proposed.

In conclusion, I would like to remark that the very existence of the modern digital computer provides the necessary tool for implementing network analysis on a grand scale, thereby making it available for solving a number of important technical problems of the present day. Solutions for many of these problems are urgently needed. Therefore, both supply and demand in this field are in full evidence; sooner or later, they will meet head on. We at IBM are in a strong position, I believe, to contribute effectively in this field if we are diligent and imaginative. We have a good start, but there are clear evidences that the machine analysis of networks is "in the air," so to speak. Doubtless, the next few years will see a sizable upsurge of activity in this phase of computation both inside IBM and outside. If IBM wishes to be a leader in this application of our own products, we must take the bit in our teeth and run with it.

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