The Status of Computer-Oriented Microwave Practices

(Panel Discussion)

IVAN A. CERMAK, STUDENT MEMBER, IEEE, WILLIAM J. GETSINGER, SENIOR MEMBER, IEEE, BERNARD W. LEAKE, MEMBER, IEEE, ANDRÉ S. VANDER VORST, SENIOR MEMBER, IEEE, AND DAN VARON, MEMBER, IEEE

THE PANEL members were asked to respond to the Guest Editor's questions, given below. They were then given copies of each other's comments and asked to respond with a second round of opinions.

Guest Editor's Questions

In order to put the ensuing discussion into perspective, please state what you understand by the term "computer-aided design" (CAD). In what way does CAD differ in approach and methodology from other design philosophies, or do you feel any philosophical distinction to be irrelevant?

What, in your opinion, has been the most significant advance in the CAD area in the past five years as it affects microwave engineers?

Consider the areas of modeling (active and passive devices), analysis (including simulation), optimization (including tolerance studies), and measurements. Which, if any, have reached a state of maturity and which do you feel require further development?

How can engineers be better educated to make effective use of present day design capabilities? Consider all aspects from the classroom situation to the technical literature.

First-Round Comments

I. A. Cermak

In its strict interpretation, CAD may be taken to mean any design process where the computer is used as a tool, in the same way that a slide rule or handbook or any other tool is used. This kind of definition has also commonly been qualified by the proviso that without the computer as a tool, that particular design process would have been impossible or much more difficult, more expensive, more time-consuming, less reliable, and may more than likely have resulted in an inferior product.

In its use of the computer as a tool, CAD is philosophically no different from other approaches. It does permit, as a practical matter, however, design and design verification in a way that was almost inconceivable in the past.

I. A. Cermak is with Bell Laboratories, Holmdel, New Jersey 07733.
W. J. Getsinger is with COMSAT Laboratories, Clarksburg, Maryland 20734.
B. W. Leake and D. Varon are with the Raytheon Company, Wayland, Massachusetts 01778.
A. S. Vander Vorst is with the Catholic University of Louvain, Louvain-la-Neuve, Belgium.

Undoubtedly, the development of sparse matrix techniques has been one of the most significant advances affecting CAD, especially in the area of circuit design. These techniques have permitted economical analysis of realistically large systems. Other advances that are significant include the fast Fourier transform and statistical (Monte Carlo) analysis, such as in the study of a waveguide transmission system.[1]

I find it hard to separate the subjects of modeling and simulation, since simulation *is* modeling. This is an area that needs much more work, especially modeling for the purpose of predicting performance in the light of manufacturing variability. Analysis, which usually involves solving a set of equations once the modeling is done, is probably the most well-known part of CAD. Tolerance studies are only now beginning to be used effectively and very few practical uses have been found for optimization. An exception to this is filter design where the art is more mature.

A very exciting development affecting CAD is the increasing use of interaction as algorithmic advances and increased machine speeds make close coupling between designer and machine not only possible, but practical. In this mode, the role CAD plays for the designer is much closer to that of a slide rule. Interaction also offers more possibility for the designer to gain insight rather than just answers, and it is this kind of tool that, I believe, will be a very valuable supplement to classroom learning. Furthermore, industry should encourage institutions of learning to concentrate on problems that *need* solving as well as (or instead of) ones that we suspect *can* be solved. Editors and publishers of technical journals can help this trend by giving more consideration and encouragement to papers that report on solutions of problems that are *real* as well as intellectually stimulating.

W. J. Getsinger

I think of CAD as a large step along the path of reducing empiricism in engineering design. The CAD engineer places increasing emphasis on modeling of circuits and on the tools of high-speed computation and logic. As a result, predictability and reliability of circuit performance are greater because CAD provides the designer with more

[1] R. G. Olsen, "The application of Monte Carlo techniques to the study of impairments in the waveguide transmission system," *Bell Syst. Tech. J.*, vol. 50, p. 1293, Apr. 1971.

quantitative understanding of the circuit before it is built.

My remarks are from the viewpoint of the computer-aided designer of microwave components, rather than the viewpoint of the CAD theory and technique originator, because my recent experience has been with a group of design engineers who turn out state of the art microwave components that must be capable of operating for years without attention in satellite communication transponders and earth stations.

Their single most widely used computer aid is the interactive microwave circuit analysis program. After five years of seeing these programs work, I am still impressed with their versatility, ease of use, and speed of analysis in actual design work. Our interactive analysis program GCP-CSC now has on-line graphic output. This has improved its effectiveness as a design aid because engineers can make more sophisticated technical interpretations of graphical information than they can equivalent columns of figures, and much faster, too.

Typically, the computer-aided aspects of our engineers' design efforts fall into two stages.

1) In the early stage of the design work, the engineer spends much time at the computer exploring wide-band performance and sensitivities, and in working up dimensions to give the wanted performance.

2) The designer returns to the computer after measurements have been made on the experimental component, in order to resolve discrepancies between expected and realized performance.

Both stages require the rapid changes and evaluations allowed by interactive microwave analysis programs.

Optimization is the area of microwave CAD least accessible to design engineers but much needed. Although optimization theory is well advanced, the complexity of application limits its use. I would like to see efficient general-purpose interactive optimization capability that can be used advantageously by design engineers with little background in optimization theory.

The effective computer-aided designer is able to construct realistic circuit models, and has a good physical feel for how the circuits should behave. Needing only basic circuit mathematics, the designer's greatest asset is broad technical judgment: that is, physical understanding of what is going on in the circuits. I think this has been so since Faraday, but perhaps the time has come for a new emphasis in engineering education on the development of technical insight.

B. W. Leake

Computers can be applied to the solution of microwave design problems in three distinct ways.

1) Synthesis—where the solution to the problem is obtained algebraically and the computer is used to relieve the engineers of the need to do complex numerical calculations.

2) Analysis—where the ideal solution to a problem is not known, or is not realizable, and the computer is used to evaluate a specified circuit.

3) Optimization—where the computer is provided with some measure for comparing the response of a network with a specification and can generate alternative values for the design variables, such that the calculated response converges to that required by the specification.

The approach of the electrical engineer to CAD is influenced by the types of program and the capability of the machine available to him. The program author has the power to choose the methods by which he solves a specified problem, and the user must appreciate the program limitations so that he can interpret the results correctly. A good computer program will generate the solution as defined by the programmer. It is the responsibility of the user to specify the correct problem.

The most significant recent advance in microwave CAD is the development of automatic optimization methods, and the adjoint network method for gradient calculations was a milestone in its progress. Automatic optimization can not only adjust the circuit variable parameters to achieve a desired performance, but can fit a circuit to a measured response. This technique is valuable in modeling devices and circuits. The measured performance of an actual circuit sometimes differs from that predicted by computer because of construction errors, or because parasitics or junction effects were ignored. An optimization program can be used to define the circuit that was built. Corrections can then be made to produce the required performance. The availability of measuring equipment with digital output allows a designer to exchange information between computers that control measurements and those that perform a circuit design task. It is perhaps not unreasonable to expect that automatic design correction will be available in the future.

The definition of optimality of a circuit design can be affected by the inclusion of tolerances on the circuit elements. The parameter values that give the best response may not be centered in the contour that represents equal degradation. Symmetrical random tolerances would require design values that differ from those that give the best response.

The area of computer optimization is developing fairly rapidly, but much more needs to be done. Two-port linear circuits may be optimized efficiently in the frequency domain with respect to reflection and transmission characteristics, and this may be extended to the control of all four S parameters. Simultaneous optimization of different responses at different frequencies is useful for filters that cannot be synthesized. Objectives that include stability, dynamic range, dissipation, and noise figure of amplifiers are receiving attention, but have hardly reached the stage of maturity. Multiports, nonlinear circuits, and unlimited topologies pose problems to the programmer that have not been completely solved. The ability of a program to choose or modify the circuit topology within certain constraints is a goal still some way off. The extent to which an engineer can make use of computers in the solution of his design problems varies widely. A number of applications programs are available commercially, but many have been developed by engineering companies and are considered proprietary. The cost of developing a general-purpose program for the solution of a broad class of problems, together with user-oriented input–output options is not small.

There will always be a need for engineers to develop special programs to solve special problems, and for this reason a familiarity with programming electrical networks is important for all of us. The proper application of programming ideas developed in universities and those that appear in computer literature seems to require that some engineers devote their energy to the generation of CAD programs for their colleagues to use. We must not lose sight of the object of the game: to solve engineering problems. For this reason I believe that it is easier for an engineer to develop programming skills than for a professional programmer to appreciate the engineer's needs. The use of any CAD program does not relieve the engineer of the need to think. The true value of a program must be measured in terms of the efficiency with which a good engineer produces an acceptable design.

A. Vander Vorst

I do not call CAD the procedure by which a computer is used as a giant slide rule to make calculations that are too long or too difficult to do by hand. By this term, I understand a method in which the computer plays an essential role such as offering a discrete model for a continuous medium, offering intricate optimization schemes, etc. It seems to me that one key feature is that one solves a *numerical model* of the problem. In this way, CAD is very close to an experimental study, with the experiment being performed by the computer on a numerical model and not by a man using circuits and devices in a laboratory. Hence, the philosophy of this method should be closer to that of experimental research than to that of theoretical research.

It seems to me that one important advance has been the development of efficient methods to replace a continuous medium by a discrete model: finite difference methods, for example, have been very much improved and algorithms have been developed to decrease the computation time by a factor that may be of the order of 50 to 1. Other procedures, such as the finite element method, are now available and this is, in my opinion, a substantial advance. Recently, such procedures have been extended to lead to the solution of two-dimensionally inhomogeneous lossy structures: this requires the solution of a complex vector eigenvalue equation. Such a solution is now available while five years ago only scalar eigenvalue equations could be solved by numerical methods. This extension was made possible only by the development of fast algorithms using much less computer memory than before.

One problem requires much more attention. CAD usually makes use of approximate methods, as opposed to analytical methods (I do not like to use the word "exact" solution, which is quite an ambiguous expression: the computer calculation of the roots of a transcendental eigenvalue equation does not give an "exact" result). Presently, one usually computes approximate results without being able to give insight into the quality of the approximation. Also, one usually accepts that some procedures are converging and some are not, without paying too much attention to the reasons why convergence is obtained or not. I could give one typical example. Five years ago, the Rayleigh–Ritz method was often used to calculate the dispersion characteristics of a waveguide loaded with a dielectric slab. Usually, good results were obtained for symmetric geometries; these results were then extrapolated to asymmetric geometries. We showed at that time that, by doing so, the error should be of the order of 100 percent. It seems to me that special attention should be given now to the development of methods by which bounds can be obtained for the error and to convergence criteria (necessary conditions).

Being a teacher myself, I would like to stress one particular point. Engineering curricula have to include the regular design methods, and CAD is now one of these. In my opinion, it has to start with circuit theory and electromagnetic theory courses. Later these methods have to be used in courses such as on electronic circuits. Such fundamental topics as circuit theory and electromagnetic theory have to be looked at not only from a theoretical point of view, but also from the practicing engineer's point of view. They have to include calculation methods and, in particular, numerical methods. This will be a sufficient basis for developing computer-aided methods at a more "applied" level for training the student. The emphasis should be put at the fundamental level on convergence criteria, error bounds, and efficiency (small computing time and memory space). Unfortunately, as I said before, there is still a lack of attention to these topics.

D. Varon

Engineering design is normally accomplished in two stages. First there exists a creative mental activity that results in a description of a concept. Then follows a mechanical process by which the concept is reduced to actual hardware. The role of the computer in enhancing the creative process is understood to be a CAD function. The utilization of the computer in hardware production is *design automation* and is not included in our discussion. The computer is a tool that, if skillfully used, can greatly enhance the designer's understanding of his problem and enable him to achieve better tradeoffs between conflicting design requirements. However, as long as the human mind remains the only medium in which the creative process can take place, there will be no fundamental change in design philosophy attributable to a computer. CAD is not a new design philosophy. It is only a better means for aiding the design process.

When computers first became available for use in the engineering community their capabilities were regarded primarily as powerful extensions of the slide rule and the desk calculator. Engineers used computers mainly to alleviate the computational chores involved in their design work. In the past five years a great deal of microwave technology has been "packaged" in the form of interactive and batch computer programs. This is an advancement of fundamental significance. The scientific and engineering computer programs have become a new means for communicating analysis between contributors and users. Unlike books and journals, packaged analysis on a computer is there ready to provide "instant" results. The users of CAD programs can conduct analyses programmed by specialists without having first to understand and follow the steps of the analytical derivations.

When does a technical field reach maturity? When a specific set of investigative practices and tools is being used by most specialists and practitioners of the discipline in question. There is a consensus within the community that the methods commonly used are good and no sizable effort is underway to invent better ones. With this definition in mind it must be concluded that none of the fields mentioned in the question has yet reached maturity. Are any of these areas close to maturity? That is hard to say, since a temporary lull in new developments may suddenly flare into a new rash of activity following a new breakthrough in computer hardware or software. For example, availability of multiprocessing computers for engineering computations would make it possible to achieve greater speed in analysis and optimization, or perform simultaneous measurements in real time.

One aspect that is very much neglected in all phases of engineering education is the training of the student to work as a member of a team. Engineers who are good team workers have acquired such capability someplace else: at home, in sports, scouting, or maybe in the military service. Upon entering industry the engineer may become one of several contributors to a single project. He must interact with other engineers on the project to ensure that his design matches theirs. He must complete his design within a given timeframe and he must accomplish all this without exceeding a given cost limit. While in school the engineer should be given the opportunity to work in a simulated environment of project design with his classmates as the project team. The project's "top management" (the teachers of the course) can manipulate the specifications, change budgets and alter schedules, and conduct "design reviews" to demonstrate the merits of various design methods and show the student how his own design contributes to the ultimate success or failure of the entire project.

Second-Round Comments

I. A. Cermak

Having commented on what CAD is today and what its most recent breakthroughs have been, it might be appropriate to mention areas that need to be explored and conquered next. Most of these, in my opinion, lie in the area of modeling, such as the following.

1) Generalized methods of reducing to tractable mathematical quantities complex structures such as cavities or conductor patterns on ceramic.

2) Efficient mathematical tools for compactly representing the terminal behavior of circuits and systems containing nonlinear subsystems or elements.

3) Realistic modeling of circuits and systems for optimization, along with optimization schemes that use these realistic criteria, rather than an arbitrary scalar figure of merit.

The first two items are almost self-evident; the third requires some amplification. The literature contains numerous papers that essentially announce yet another optimization scheme that is n times as fast as previous schemes. Papers that announce successful real designs using optimization, however, are practically nonexistent. One reason for this is that a real design often requires optimizing to a set of criteria that may include such quantities as sensitivity to temperature, power supply variations, and even harmonic or intermodulation distortion.

CAD has come of age in the sense that it is possible today for a designer to sit down at a teletype, be it the console of a minicomputer system or part of a large time-shared system, and have at his disposal many powerful analysis tools. Providing all the right tools is a formidable task that still lies ahead.

W. J. Getsinger

I sense in the comments of each of the panel members a feeling that CAD is seeking a closer relation to actual engineering practice. Cermak says, "concentrate on problems that *need* solving." Leake puts it directly, "the object of the game" is to solve engineering problems. Vander Vorst has it that "CAD is very close to an experimental study," and Varon: "CAD is . . . a better means for aiding the design process."

Implicit in these remarks, I believe, is recognition of the gap between CAD and actual design practice, a gap that is especially prominent in the microwave area.

With certain filters and step transformers, almost exact circuit models, relating physical dimensions to electrical parameters can be devised. But for most components, circuit models are approximate and poorly defined, and values for circuit elements in these models are often guessed at. As I pointed out in my preceding comments, about half the battle in microwave CAD occurs after measurements have been made on the hardware designed by computer-aided methods, to resolve major discrepancies between predicted and realized performance. The discrepancies often arise from situations where no analytically based representation is available and/or characterization by measurement has not been done.

In spite of the fantastic performance of computers in logic, computation, high-speed interaction, and the abilities to accept and present information in direct clear form, and in spite of the enthusiasm of its promoters (myself included), CAD for microwave circuits has had only lukewarm success at the engineering level.

In my opinion, this is the situation because too often performance on the test bench bears too little relation to predicted performance, and CAD has been ineffectual. In fact, CAD theoretical developments have outstripped the microwave designers' ability to come up with realistic circuit models and element values, especially for active components. Further effectiveness and success for microwave CAD will now depend on advances in microwave theory and technique that allow microwave engineers to be better able to generate physically meaningful circuit models and make accurate characterizing measurements.

B. W. Leake

Because the topic under discussion is the *status* of COMP it is understandable that much of the first round discussion revolved around analysis.

Analysis has certainly received most attention and is consequently the most advanced area of CAD. In some cases, for example, field problems discussed by Vander Vorst, analysis is all that is required. In other design procedures, mentioned by Getsinger, it forms but one part of the complete design process.

There seems to be a tendency to welcome the use of computers for analysis, where the drudgery can be done automatically, provided all the decision-making is left to the engineer. This gives rise to the need for graphic or similar output more easily appreciated by the engineer (but not the computer) so that he can develop "insight" into the problem. There then presumably follows a further dose of drudgery for the computer to do.

This is probably overstating the situation, but it allows me to make the point that if we know enough about analysis to program a computer to do it properly, then we should also be able to decide *beforehand* what to do according to the results of the analysis.

An engineer needs to be presented with the results of an analysis only so that he can decide which of various previously known options he should pursue next. This can clearly be done automatically by the computer if we understand enough to define the options. If this is done, every user of the program will benefit from the experience and insight built into it by the programmer, which may well include knowledge of topics, like optimization theory, not normally familiar to the engineer.

It is important for a user to understand what a program does—not necessarily all the details of how it does it. If this were not so, high-level programming languages like Fortran would not exist.

A. Vander Vorst

Several remarks were made regarding educational aspects, namely, the following.

1) Industry should encourage institutions of learning to concentrate on problems that need solving as well as (or instead of) ones that we suspect can be solved.

2) Engineers can make more sophisticated technical interpretations of graphical information than they can equivalent columns of figures, and much faster, too.

3) The time has come for a new emphasis in engineering education on the development of technical insight.

4) Engineering curricula have to include the regular design methods and CAD is now one of these. One has to start with circuit theory and electromagnetic theory courses.

5) One aspect that is very much neglected in all phases of engineering education is the training of the student to work as a member of a team.

Some of these remarks have been made several times before. Unfortunately, universities have quite a large time constant and, while an interactive circuit analysis program gives the user an almost immediate answer, the response of an education program may not be effective for several years.

I was impressed by the comment on graphical information. In several places in Europe, technical drawings have always been an important part of the engineering curriculum. Unfortunately, the emphasis has almost always been put on how to teach an engineer to make drawings and not on how to extract information from graphical information. This is quite strange: the emphasis has been put on that part of graphics that is probably not related to the professional activity of the engineer. With the advent of CAD, the question now is: how to teach a student or an engineer to make sophisticated technical interpretations of graphical information.

More precisely, institutions of learning have to integrate graphical interpretation into the broad concern of the development of technical insight. This does not seem easy. It may be necessary to start this as early as possible in the curriculum and to introduce it with the cooperation of engineers working in the field. A major drawback, however, is that a number of applications programs have been developed by engineering companies and are considered proprietary. Are these companies ready to make some of these programs available to universities for the purpose of training? By not doing so, institutions of learning might be "forced" to rely on academic problems and not problems that need solving.

On the other hand, the cost of developing general-purpose programs is so high that a common effort made by several universities together will be necessary if they want to produce CAD programs for educational purposes.

The main conclusion is probably that cooperation between engineers, companies, and universities is necessary, even more than before, if we want to produce engineers who are able not only to take advantage of present facilities but also to make new developments and create more efficient interaction.

D. Varon

There seems to be agreement among my colleagues that computer programs for circuit analysis and optimization have become indispensible in achieving designs for many modern applications, and that the cost of efficient CAD programs may not be small. If CAD were a mere nicety, its high cost would have driven it out of practice for obvious economic reasons. However, CAD programs being so useful leave us with only one alternative—to reduce their cost.

I think that CAD has reached a milestone in that it has established itself as a design tool that produces credible designs. We are now entering a new phase where we shall no longer be satisfied with *any* program that does the job, but only with those that will give us what we need at an acceptable cost. Most programs in our specialty have been written by engineers, rather than by programmers, out of necessity. It is understandable that, not having as much expertise in software as in microwave technology, the engineers produced programs that were not the most efficient ones, neither in the usage of storage nor in the utilization of central processor time.

The time has come for us to recognize that we can reduce the cost of our CAD's by seeking help from those among us who have more than a casual knowledge of Basic or Fortran. As there are engineers specializing in instrumentation who build our measurement gear or those specializing in devices who build our components, so in the coming years there will emerge engineers who will interface with the computer world. They will write our CAD programs and will be the custodians of our computer-backed hardware. These specialists will exchange information within our own technical environment (including, it is hoped, over the pages of S-MTT TRANSACTIONS) about hardware and software techniques that produce good design aids, and we shall have to create standards of performance by which these tools can be objectively evaluated.

Semiconductor Device Simulation

CHARLES M. LEE, RONALD J. LOMAX, SENIOR MEMBER, IEEE, AND GEORGE I. HADDAD, FELLOW, IEEE

(Invited Paper)

Abstract—**Two of the numerical methods most widely used in solving the set of partial differential transport equations for holes, electrons, and electric field in semiconductor devices and the various numerical instability phenomena which can be encountered are described in detail. Also presented are approaches, using these methods, to calculate dc static solutions and small-signal solutions, and to simulate devices in voltage-driven, current-driven, and circuit-loaded operation. Sample results are given for each mode of operation for the case of Si avalanche-diode oscillators. The numerical methods and approaches are those developed at our laboratory and sufficient detail is presented to permit the development of similar Fortran codes by others.**

INTRODUCTION

THE DEVELOPMENT of semiconductor devices with complex modes of operation, such as avalanche diodes, has necessitated the development of detailed analysis for the behavior of holes and electrons and their interaction with electric fields in such devices. However, the nonlinearity of the equations which describe the behavior of these particles in high electric fields, particularly when space charge is significant or at high-frequency operation, imposes severe restrictions upon any attempt to obtain analytical closed-form solutions. Because of the collision-dominated conduction process, the particle trajectory methods developed extensively to study plasma phenomena have little application to semiconductors. Hence, numerical simulations [1]–[38] of semiconductor devices have emerged as powerful tools for their study. In this paper, some of these numerical methods, and in particular those that have been developed and used by the authors for simulating semiconductor devices and determining their operating characteristics, are presented and reviewed.

Manuscript received October 10, 1973; revised November 21, 1973. This work was supported by the Air Force Systems Command, Rome Air Development Center, under Contract F30602-71-C-0099.

C. M. Lee was with the Electron Physics Laboratory, Department of Electrical and Computer Engineering, University of Michigan, Ann Arbor, Mich. 48104. He is now with Bell Laboratories, Murray Hill, N. J. 08540.

R. J. Lomax and G. I. Haddad are with the Electron Physics Laboratory, Department of Electrical and Computer Engineering, University of Michigan, Ann Arbor, Mich. 48104.

THE TRANSPORT EQUATIONS

The behavior of holes and electrons in a one-dimensional model of a semiconductor can be characterized by the following partial differential equations:[1] the continuity equation for holes:

$$\frac{\partial P}{\partial t} + \frac{\partial JP}{\partial x} - G = 0 \quad (1)$$

the continuity equation for electrons:

$$\frac{\partial N}{\partial t} - \frac{\partial JN}{\partial x} - G = 0 \quad (2)$$

and Poisson's equation:

$$\frac{\partial E}{\partial x} - \frac{q}{\epsilon}(P - N - N_D) = 0 \quad (3)$$

where

[1] The notation in this paper is chosen for easy translation into a computer language (specifically Fortran).