INFORMATION PROCESSING 68

VOLUME 2

INFORMATION PROCESSING 68

PROCEEDINGS OF IFIP CONGRESS 1968

VOLUME 2 – HARDWARE, APPLICATIONS

ORGANIZED BY THE
INTERNATIONAL FEDERATION FOR INFORMATION PROCESSING
EDINBURGH, 5-10 AUGUST 1968

Editor

A. J. H. MORRELL

1969

NORTH-HOLLAND PUBLISHING COMPANY
AMSTERDAM

CONTENTS OF VOLUME 2

PART 3. HARDWARE

Invited Papers

E. Bloch and R. A. Henle, Advances in circuit technology and their impact on computing systems 613

A. A. Borsei and A. C. Bos, Real-time information management: design criteria for system efficiency 630

D. W. Davies, Communication networks to serve rapid-response computers 650

E. Goto, Memory systems 659

E. C. Joseph, Computers: trends toward the future 665

W. J. Karplus and G. A. Bekey, The changing role of analog and hybrid computer systems 681

G. A. Rose, Computer graphics communication systems 692

Data Communications

K. A. Bartlett, Transmission control in a local data network 704

D. W. Davies, The principles of a data communication network for computers and remote peripherals 709

E. R. Kretzmer, Modern techniques for data communication over telephone channels 716

R. A. Scantlebury, P. T. Wilkinson and K. A. Bartlett, The design of a message switching centre for a digital communication network 723

R. T. Shaw, Basic control procedures for digital data transmission 728

P. T. Wilkinson and R. A. Scantlebury, The control functions in a local data network 734

Analogue and Hybrid Systems

B. A. Borkovskii and G. E. Pukhov, Quasi-analogue discrete simulating media 739

G. Cartianu and V. I. Vlad, The synthesis and processing of signals with discontinuities in the time domain 744

B. R. Gaines, A modular programmed DDA for real-time computation 749

G. G. Gorbatenko, An analog card capacity correlator as applied to OCR 756

T. Lamdan and I. Cederbaum, A suggestion for an analog function generator of two variables 762

E.-G. Woschni, Quality criterion for analog and digital computers based on the theory of information and its application to a comparison between the two kinds of computers 768

Component Technology

J. Daňda, An application of a digital computer for extended shmoo-plotting of ferrite-core memories 775

L. F. Gee, D. W. Parker and P. Swift, A M.O.S.T. store 778

S. Waaben, High-speed plated-wire memory with interlaced modes 783

J. H. Wuorinen and D. A. Hodges, Component technologies for future systems 787

Computer System Organization

D. Aspinall, D. J. Kinniment and D. B. G. Edwards, Associative memories in large computer systems *and* An integrated associative memory matrix 796

G. Bazerque, J. Ferrie and P. Hugot, Universal micromachine structure study oriented to simulation of computers 801

T Kilburn, D. Morris, J. S. Rohl and F. H. Sumner, A system design proposal 806

S. Matsushita, A microprogrammed communication control unit, the TOSBAC DN-231 812

A. N. Myamlin and V. K. Smirnov, Computer with stack memory 818

A. Svoboda, Boolean Analyzer 824

Analysis of Computer Systems

M. H. J. Baylis, D. G. Fletcher and D. J. Howarth, Paging studies made on the I.C.T. Atlas Computer 831

L. Kleinrock, Certain analytic results for time-shared processors 838

R. L. Mattson and J.-P. Jacob, Optimization studies for computer systems with virtual memory 846

R. L. Sharma, Analysis of a scheme for information organization and retrieval from a disc file 853

A. Weingarten, The analytical design of real-time disk systems 860

F. W. Zurcher and B. Randell, Iterative multi-level modelling. A methodology for computer system design 867

Real-Time Ultra-Reliable Systems

A. Avižienis, An experimental self-repairing computer 872

W C. Carter and P. R. Schneider, Design of dynamically checked computers 878

J. R. Lourie and A. M. Bonin, Computer-controlled textile designing and weaving 884

P. C. Macnaughton and E. S. Lee, The Virtual Multiprocessor - a new computer architecture 892

W. R. Whittall and K G. Bosomworth, Dual digital computer control system for the Gentilly Nuclear Power Station 898

Th. J. Williams, Computer systems for industrial process control. A review of progress, needs, and expected developments 907

Computer Networks

J. M. Bennett, C. S. Wallace and J. W. Winings, A grafted multi-access network 917

F. P. Brooks Jr., J. K. Ferrell and T. M. Gallie, Organizational, financial and political aspects of a three-university computing center 923

J. E. Denes, BROOKNET - an extended core storage oriented network of computers at Brookhaven National Laboratory 928

J. N. P. Hume and C. B. Rolfson, Scheduling for fast turnaround in job-at-a-time processing 933

R. C. Lesser and A. Ralston, The development of a multi-campus regional computing center 939

Son et Lumière

A. Appel, On calculating the illusion of reality 945

D. J. Hall, G. H. Ball, D. E. Wolf and J. W. Eusebio, PROMENADE - an interactive graphics pattern-recognition system 9

H. B. Lincoln, A computer application in musicology: the thematic index 957

W. H. Ninke, A satellite display console system for a multi-access central computer 962

I. T. Parkhomenko, Graphic data input in a computer when curves are arbitrarily recorded on the medium 970

G W. Romney, G. S. Watkins and D. C. Evans, Real-time display of computer generated half-tone perspective pictures 973

PART 4. APPLICATIONS

Invited Papers

G. T. Artamonov, Automation of design and construction 981

J. J. Baruch, The generalized medical information facility 993

H. le Boulanger and H. Gourio, Operations research: slave or master of the computer 1000

E. A. Feigenbaum, Artificial intelligence: themes in the second decade 1008

G. E. Forsythe, Computer science and education 1025

E. M. Horwood, Computer applications to urban planning and analysis: examples and prospects 1040

H. Kazmierczak, Image processing and pattern recognition 1056

A. Q. Morton and M. Levison, The computer in literary studies 1072

G. Salton, Search and retrieval experiments in real-time information retrieval 1082

A. D. Smirnov, Data processing systems for physical experiments 1094

P. Suppes, Computer-assisted instruction: an overview of operations and problems 1103

B. Vauquois, A survey of formal grammars and algorithms for recognition and transformation in mechanical translation 1114

S. Waligórski, On formula manipulation connected with computer design 1123

Systems Planning

W. M. Davies, The conceptual stage in planning a company information system 1128

J. Lehotzky and I. Petras, Long-range analysis of metal processing industries 1133

P. L. Morrison Jr., Toward a management planning and control system 1139

T. Nakanishi, A. Sato and Y. Ito, Development of a system simulator for a railway marshalling yard 1145

F. Steiger and M. Niederer, Aircrew scheduling by integer programming 1151

K. C. Thompson, The utilisation of direct access facilities for electricity board customer accounting purposes 1161

Management Aids

P. L. Cloot and C. N. Sutton-Smith. Management use of displays in critical path analysis 1166

B. Z. de Ferranti. Decisions in brains, machines and organisations 1171

M. S. S. Morton and J. A. Stephens. The impact of interactive visual display systems on the management planning process 1178

A. S. Noble. Input-Output cost models and their uses for financial planning and control 1185

Applications in Marketing and Production

A. J. Barnett and J. A. Lightfoot. A S/360 on-line production order location and reporting system using the Information Management System (IMS) 1192

R. Bird and W. W. Hedley. An integrated production management system 1197

H. W. Gearing, L. G. Reynolds and D. E. Sears. Sales management information retrieval 1205

M. Perry. Computer simulation of consumer reaction to new products 1212

File Structure

W. W. Chu. Optimal file allocation in a multicomputer information system 1219

S. P. Ghosh. On the problem of query oriented filing schemes using discrete mathematics 1226

W. C. McGee. File structures for generalized data management 1233

P. Namian. Algebra of management information 1240

File Management and Data Banks

R. E. Bleier and A. H. Vorhaus, File organization in the SDC Time-Shared Data Management System (TSMS) 1245

H. R. Koller, Safety data and social issues: the national highway safety data system 1259

S. McIntosh and D. Griffel, ADMINS from Mark III to Mark V 1260

T. P. Molnar, Planning and implementing international data networks 1267

J. R. Porter. The International Data Center concept 1273

D. A. Stevenson and W. H. Vermillion, Core storage as a slave memory for disk storage devices 1277

Information Retrieval

S. Alanen, A library of subroutines for bibliographic data processing 1285

K. S. Jones. Automatic term classification and information retrieval 1290

B. Lipetz. The continuity index of documentation abstracts 1296

P. K. T. Vaswani. A technique for cluster emphasis and its application to automatic indexing 1300

Systems for Information Retrieval

R. L. Chartrand. Information processing for the United States Congress 1304

H. Fangmeyer and G. Lustig, The EURATOM automatic indexing project 1310

W. R. Nugent. NELINET - The New England Library Information Network 1315

C. F. J. Overhage and J. F. Reintjes. Information transfer experiments at M.I.T. 1321

Computer-Assisted Training and Education

K. J. Engvold and J. L. Hughes, A multi-functional display system for processing and teaching 1327

B. F. Johnson, Design of an operating system for the control of student terminals in a computer based instructional system 1332

M. S. S. Morton and Z. S. Zannetos, Efforts toward an associative learning instructional system 1337

H. E. Tillitt, Information-retrieval instruction system on board ship 1343

F. M. Tonge, Design of a programming language and system for computer assisted learning 1349

Learning and Teaching

M. M. Barritt, The development of computer education in schools. A survey on behalf of B.C.S. Working Party no. 4 1356

J. Hebenstreit, A curriculum in computer science, oriented toward computer design 1363

H. C. Johnston and K. Wolfenden, Computer-aided construction of school timetables 1368

J. Lions, A generalization of a method for the construction of class/teacher timetables 1377

P. Naur, 'Datalogy', the science of data and data processes 1383

K. L. Zinn, Languages for programming conversational use of computers in instruction 1388

Mathematical Linguistics and its Applications

S. L. Abraham, Some problems of formal language theory and its applications 1395

W. Freiberger and U. Grenander, Computer-generated image algebras 1397

J. C. Reynolds, A generalized resolution principle based upon context-free grammars 1405

A. J. Szanser, Error-correcting methods in natural language processing 1412

Design Automation

W. S. Blaschke and K. R. Emerton, EDACT - Engineering Drawings to Automatic Control Tapes 1417

P. G. Henry and D. H. Mountford, Production of pipeline isometric drawings using a digital computer and an incremental plotter 1422

M. Krejčiřík, Computer-aided building layout 1427

C. M. Strauss and S. Poley, A three-dimensional piping design program 1431

Applications in Physical Science

P. L. Browne and K. B. Wallick, A brief discussion of a method for automatic rezoning in the numerical calculation of two-dimensional Lagrangian hydrodynamics 1441

N. Gastinel and D. Chenais, Pattern recognition in a signal 1447

T. Pearcey, F. Hirst and P. G. Thorne, The behaviour of subharmonics in a non-linear system and its application to binary storage devices 1451

V. L. Rvatchov, O. N. Litvin and L. I. Shklarov, Automatic construction of the solutions of some problems of mathematical physics by electronic computers 1459

Applications in Engineering

L. D. Bodin, The catalogue ordering problem 1463

W. S. Jewell, Allocation of route service in a transportation network 1468

L. A. Kozdoba, Application of combined electrical models for the solution of heat and mass transfer problems 1471

K. Mikami and K. Tabuchi, A computer program for optimal routing of printed circuit conductors 1475

J. A. O'Brien, Computer fault location using tabular functions 1479

J. Pruuden and B. Tamm, Problem-oriented computer languages for simulating engineering processes 1484

Applications in Biology and Medicine

J. H. Clark, The simulation of the human hypnotist by a teaching machine 1489

K. Erat, A. G. Jessiman and J. E. C. Walker, Application of a time-shared computer to the appointment system of a hospital outpatient department 1495

E. Kindler, Automatic modelling of compartmental systems 1502

Bl. Sendov and R. Tsanev, Computer simulation of the regulatory mechanisms of cellular proliferation 1506

Applications in the Social Sciences

D. H. Harper, An examination of information processing in the social sciences through the use of simulated data 1508

D. Klahr, A Monte Carlo investigation of the statistical significance of multidimensional scaling 1514

M. Levison, T. I. Fenner, W. A. Sentance, R. G. Ward and J. W. Webb, A model of accidental drift voyaging in the Pacific Ocean with applications to the Polynesia colonization problem 1521

J. C. Ogilvie, The distribution of number and size of connected components in random graphs of medium size 1527

Scientific Data Processing Systems

L. N. Gross and D. E. Walker, On-line computer aids for research in linguistics 1531

P. M. Hirsch, J. A. Jordan Jr. and L. B. Lesem, Digital construction of holograms 1537

K. B. Magleby, Applications of on-line computers to laboratory instrumentation systems 1543

A. N. Tikhonov, V. G. Shevchenko, V. Ya. Galkin, B. I. Goryachev, P. N. Zaikin, B. S. Ishkhanov and I. M. Kapitonov, On the overall automation of data processing for determining the photonuclear reaction cross-section 1549

Artificial Intelligence

V. Drozen, Mapping of topological relations in diffuse neuronal nets 1552

N. J. Nilsson, Searching problem-solving and game-playing trees for minimal cost solutions 1556

K. K. Pingle, J. A. Singer and W. M. Wichman, Computer control of a mechanical arm through visual input 1563

J. Pitrat, Realization of a general game-playing program 1570

B. Raphael, Programming a robot 1575

S. Wendt, A trainable classifier with piecewice linear separation using the learning-matrix 1582

Pattern Recognition

P. W. Cooper, Non-supervised learning in adaptive statistical pattern recognition 1586

T. G. Evans, A grammar-controlled pattern analyzer 1592

V. A. Fromkin, The computer as a research tool in the construction of models of linguistic performance 1599

V. A. Kovalevsky, Sequential optimization in pattern recognition and pattern description 1603

S. Watanabe, Object-predicate reciprocity and its application to pattern recognition 1608

Panel Position Papers

a) Structure and operations of a computer utility: the view presented to the user

L. Bolliet, Multi-access systems in university education and research 1614
A. P. Ershov, Time sharing: the need for re-orientation 1615
E. L. Glaser, The safeguarding of information: a user's view 1616
K. V. Roberts, The computer utility in a university or scientific environment 1619

b) Interactions between users, designers and manufacturers

B. Chorlton, Independent consulting and software organisations 1621
W. S. Humphrey, Jr., Future technical trends in software development 1622
T.B. Steel, Jr., Software interactions between manufacturers and users 1623
M. Bellisario, Software interactions between manufacturers and users 1624

c) The economics of program production

R. W. Bemer 1626
A. J. W. Duijvestijn 1627
M. H. Gotterer, Toward more effective management of programming 1628
J. L. Howells 1630
A. M. Pietrasanta, Two empirical studies of program production 1632

d) Education in information processing in schools

W. A. Atchinson, A report and commentary on some computer science curriculum developments for students of ages 12 to 18 1636
H. K. Kesavan, Computer sciences for ages 12-18: what to teach, how to teach it 1638

Closing address by Sir Paul Chambers 1642

Membership of Congress Committees 1647

Membership of Technical Area Committees 1649

Analysis of delegates by country 1650

INFORMATION PROCESSING 68 - NORTH-HOLLAND PUBLISHING COMPANY - AMSTERDAM (1969)

ADVANCES IN CIRCUIT TECHNOLOGY AND THEIR IMPACT ON COMPUTING SYSTEMS

Erich BLOCH
International Business Machines Corporation, Systems Development Division, Poughkeepsie, New York

and

Robert A. HENLE
International Business Machines Corporation, Components Division, East Fishkill, Hopewell Junction, New York

This paper describes changes in logic circuit technology, and relates these to the environment of changing requirements in computing systems and improvements in the control of materials and material processes. It discusses the fundamental problems and objectives for today's environment and future trends in circuit performance, density, power, cost, and reliability. Influence of supporting technologies and their limitations, such as cooling and power, are also discussed.

1. INTRODUCTION

The last twenty years have seen the growth of the computer from a fledgling curiosity to a pervasive industry. At the same time, circuit technologies have had a profound effect on the development of computers and on the industry that produces them.

As thermionic devices, with their inherent speed advantage, replaced the electromechanical devices used in early data processing machines, the computer designer gained the use of a technology that enabled him to design large circuit assemblies. In the late 1950's, solid state circuits brought about the reliability and flexibility required by the more demanding applications in business and real time. Today, the increasing availability of integrated circuits, with their greater complexity and higher levels of integration, has resulted in further improvement in cost, reliability, and performance. These changes in technology are influencing, and will continue to influence, computer development, therefore making possible systems of greatly increased capability.

Historically, "order of magnitude" improvements in a phase of a technology cause fundamental and far reaching changes within and beyond the reaches of that technology. The advances in circuit technology have brought changes of many orders of magnitude. These have not only caused changes in the products that use these developments, but have so significantly altered the technique and tools of circuit design that a designer of twenty years ago would find little that was familiar.

This paper is a survey of the industry state-of-the-art, the changes in emphasis that have taken place and a preview of the immediate future, and the results that these changes have caused. It is not a primer on circuit design. Instead, the paper will try to reflect on the present emphasis in materials, processes, packaging, cooling, reliability, and performance.

2. CHANGES IN REQUIREMENTS AND ENVIRONMENT

2.1. *Computer installation and size*

The pervasiveness of computers is evident if one considers the past and projected growth of the worldwide computer installation (fig. 1). More to the point, however, is the increase in the number of circuits employed per installation. Fig. 2 illustrates this increase.

The first, large transistor machines started at approximately 20,000 circuits and have been increasing at a rapid rate. Today, larger transistor machines may surpass 100,000 circuits. This trend is quite likely to continue in the future and has been made possible by the continued de-

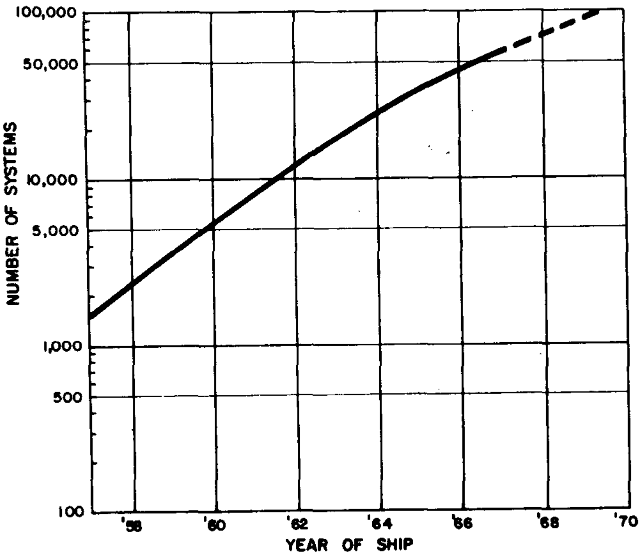

Fig. 1. Computer installations.

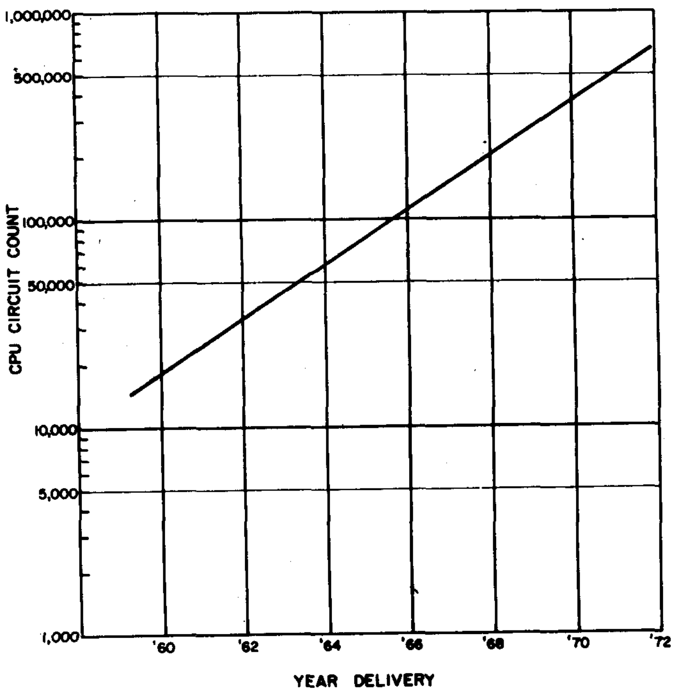

Fig. 2. CPU circuit count.

crease in size, power dissipation, cost, and improved reliability of semiconductor circuits. Further, the proliferation of memory types and I/O equipment has emphasized the need for advances and refinements in support circuits for these functions. Today, only 40% of the circuit cost of an average computer system is in the logic and packaging; the rest is in memory and I/O electronics. The trend of decreased semiconductor costs will continue and it is estimated that in the 70's the logic circuit cost will be small when compared to the cost of packaging and the cost of memory and I/O functions. This points to the need of accentuating developments in what were previously support functions, and will become prime areas of concern and endeavor.

2.2. *Performance*

Throughout this paper we will analyze and investigate the advances in technology in the high performance area of the computer market. Experience has shown that what is utilized in this area first will a few years later find application in the intermediate and low speed areas, whether it is in the performance requirements of circuits (see fig. 3 for a demonstration of this fact), their reliability, or the organizational properties of systems. Fig. 4 shows the performance improvement of systems as expressed by the "add" time of a system with the 1970 time period extrapolated.

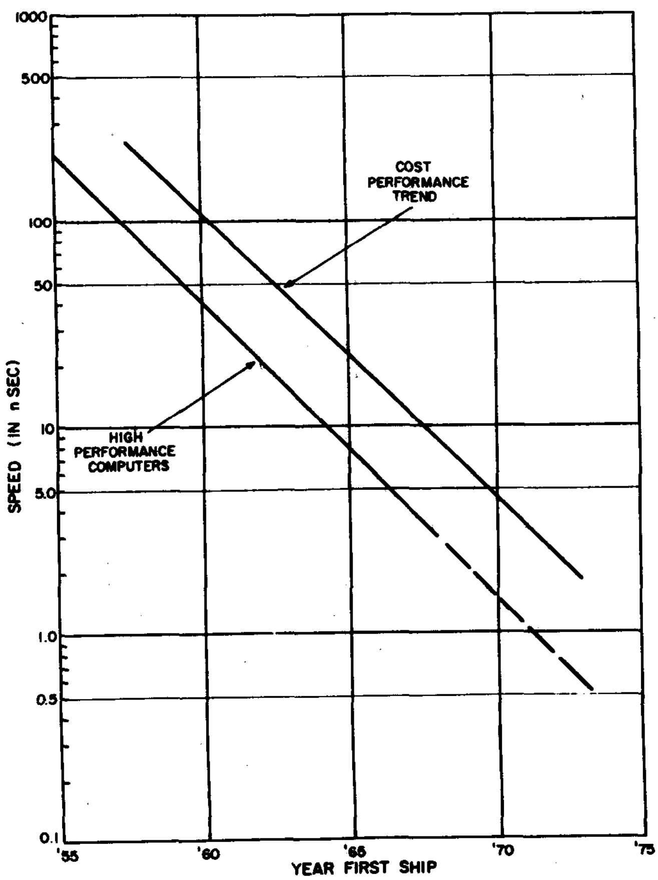

Fig. 3. Packaged logic circuit speed.

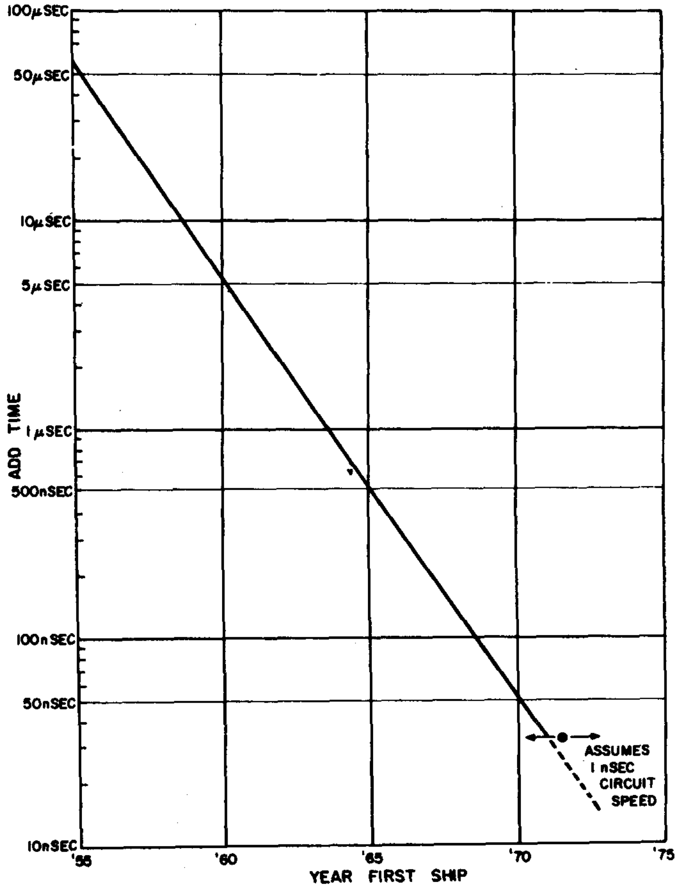

Fig. 4. Add time.

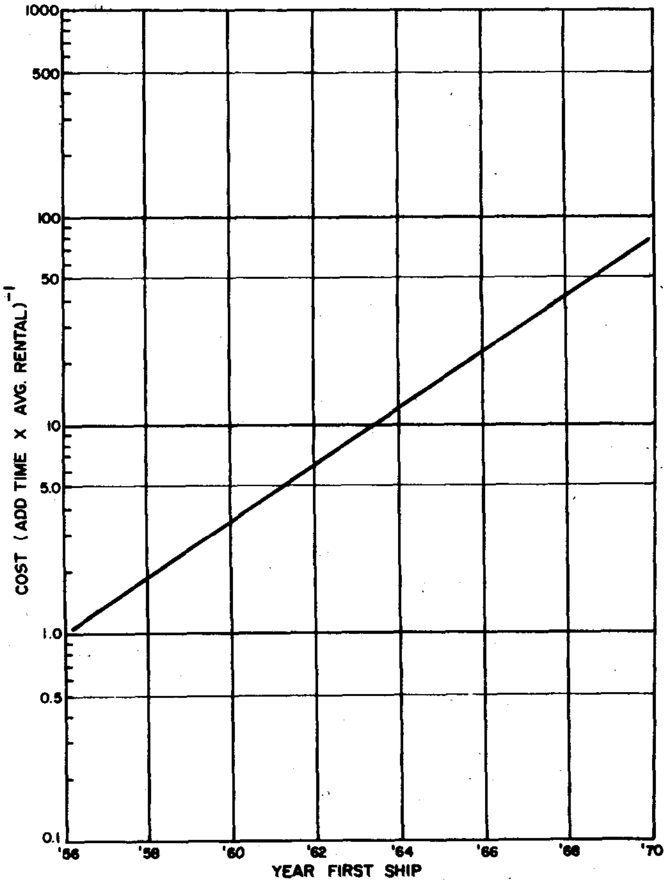

Fig. 5. Cost performance trend of computers.

2.3. *Cost*

Along with the increase in raw speed have come orders of magnitude improvement in the decisions/second/dollar obtained from a computer. Fig. 5 shows this trend, using the cost of the "add" operation as a figure of merit.

2.4. *Other trends*

Several trends are evident today in system design. Probably the most important requirements in future systems will be for data integrity and high availability. With the increasing use of computers in all aspects of economic life, there must be absolute guarantees that records cannot be destroyed, and, furthermore, that the system cannot fail in such a manner that its services become unavailable. Attempts will be made to design computer systems that fail softly, much in the manner of a telephone switching network, which has a high probability of being able to process calls even with faulty components in the system.

In a telephone switching system, component failures may affect the rate at which calls can be processed, but the probability of a total system outage is made extremely small. The dependability objective for AT and T No. 1 ESS [1] is for less than two hours of system downtime over its 40-year life.

Multiprocessing concepts, combined with component redundancy schemes, offer the most promising hope of attaining this high availability in computers. However, the problem in data processors goes further than trying to prevent the system from going down for a few seconds. A nanosecond transient in a computer can cause a bit to be lost, which may require repeating a two-hour run. Therefore, future systems must address the problem of transient faults that may be caused by internal or external circumstances.

Systems of the future will continue to utilize increasing amounts of storage. The storage hierarchy today is characterized by an access time gap, with the lowest cost-per-bit storage mediums (tapes and disk) having access times of greater than 1,000 microseconds, while electronically addressable memories have access times of generally less than 10 microseconds. Systems problems exist because of this wide disparity in memory performance. It appears unlikely that this gap will disappear within the next five years, but system designers will attempt to minimize the impact of this access time gap on system performances by applying various schemes of utilizing multispeed memories [2,3].

3. CIRCUIT ELEMENTS

Turning now to the more central topic of this paper, namely the characteristics of the circuit technology, we will first consider circuit elements.

3.1. *Materials*

Despite the fact that germanium was used almost exclusively in the early years of semiconductor development, the last years have seen the almost total replacement of germanium by silicon. Nothing in the foreseeable future indicates a serious change. Silicon has advantages over germanium such as being readily available at low cost, and as having a stable oxide suitable for use as a diffusion mask. One of silicon's disadvantages is its lower inherent performance due to the lower carrier mobility. This has been offset by the enormous technical effort that has been expended in understanding silicon and silicon processes. The relatively small germanium technology effort cannot readily match the achievements of the large silicon technology effort.

3.2. *MOS versus bipolar*

Basic to all semiconductor device fabrication is the *P-N* junction used to achieve active transistor elements, diodes, electrical isolation, and capacitors. The speed, flexibility, stability, and low power - as well as the theoretical and empirical understanding gained through large research efforts over the past years - have brought the *P-N* junction to a position of unchallenged leadership in almost all computer applications. The particular form utilized today and widely accepted because of its adaptability to integration in monolithic form is the planar type, which avoids the construction of complex three-dimensional geometries such as mesa types or older alloy junction devices.

Improved dimensional control will be required to decrease cost and improve performances in the future. Fig. 6 shows some projected trends

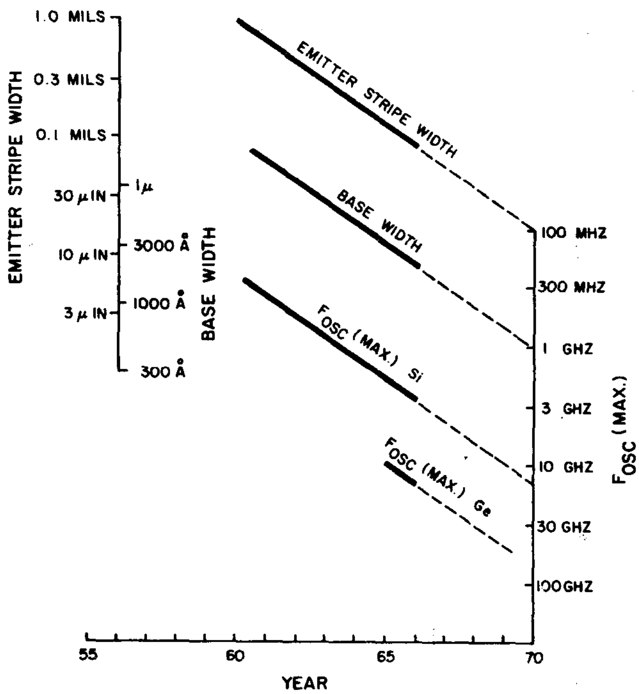

Fig. 6. Device trends.

in device dimensions and performance. The achievement of these goals is dependent on advances in photolithography and mask technology. In the device and packaging areas, these supporting technologies are becoming key to further advances in the state-of-the-art.

At this time, bipolar transistor technology's complete domination of data processing systems is challenged only by metal oxide field-effect devices. These devices require a single diffusion for their fabrication. The device operation depends upon the presence of a charge on the gate electrode; this charge is balanced by an equal charge in the semiconductor material. In the active region, the presence of this charge changes the conductivity of the surface layer and permits conduction of majority carriers between the source and drain electrodes. The device has a nearly infinite dc input impedance to the gate electrode. Most of the devices fabricated to date have been capable of operating at clock frequency of 1 megacycle or less. This speed will undoubtedly be improved in the future.

The claimed advantages for MOS technology are [4]:

1. Fewer process steps are required, resulting in a higher yield, lower cost product.
2. Diffused isolation regions are not required; therefore, the device itself can be used as its own load resistor. This results in a high cir-

cuit density of devices on a chip, again resulting in lower manufacturing cost.

3. Because of the device's high input impedance and the low operating speed of the circuits, single layer metallization is possible for most functions, again helping to keep manufacturing cost low.
4. Low-power operation is obtained by virtue of low-current operation of the circuits. MOS circuits also operate from higher power-supply voltages, thus resulting in greater power supply efficiency.
5. Greater reliability is claimed by virtue of larger integration, and, therefore, fewer external connections.

The disadvantages of MOS devices are their low speed, their need for a hermetically sealed package (because of the early stage of surface passivation work), and their limited large-scale manufacturing experience. Bipolar monolithic circuits, on the other hand, have been manufactured in large quantities by companies such as Texas Instruments, Motorola, and Fairchild, and have proven to be reliable, and are capable of being manufactured in a high yield process.

Because of the speed differential, MOS technology will not likely displace bipolar applications in a major way in computers. It also appears, however, that highly integrated MOS chips are more than an experimental curiosity and will have applications where high operating speeds are not a requirement. We expect, therefore, that both of these technologies will find an application area in computer hardware, but do not expect MOS technology to displace bipolar technology in any major way.

3.3. *Passive elements*

Returning now to the bipolar *P-N* junction devices, the passive elements required to complete the circuit will be considered, as will the tradeoffs forced by integration requirements on element value, types, and tolerances.

In the past, low-cost transistor circuits were designed by minimizing the number of required transistors. The components that were used had, for the most part, absolute tolerances. It was possible to test each of the components that made up a circuit, and, finally after component assembly, to test the entire circuit. Monolithic construction has necessitated some important changes in the selection and specifications of components.

Where the resistor was once the least expensive component in a circuit, it can now be the most expensive component. The cost of discrete resistors does not vary with their resistance values. Monolithic techniques tend to place an optimum value on resistors, which is that value of resistance requiring the least surface area.

Consider that the resistance R of a monolithic resistor is equal to $\rho_0 L/W$, where ρ_0 is equal to the sheet resistance of the resistor diffusion (often the base diffusion), L is equal to the length, and W is equal to the width. A 5% variation in any of these parameters will cause a 5% variation in the resistance R. In monolithic fabrication, there is a minimum dimension that can be held to a specified tolerance. The optimum value of resistance (least area = lowest cost) then tends to be about equal to the sheet resistance ρ_0 with L and W at the minimum dimensions that result in the desired tolerance. For any other case, the area of the resistor would be increased, and with it its cost.

In the fabrication of diffused resistors, the value of the resistance is determined by the control of the epitaxial material, the control of the diffusion process, and the control in masking technology. The combination of these parameters rules out the use of 1% resistors and tends to place readily achievable resistor values in the 10% to 20% absolute tolerance range [5].

A key requirement in a successful monolithic circuit is the ability to utilize components that may have poor absolute tolerances but that have good ratio tolerances. Many of the process variations that occur tend to affect similar components in the same manner. It is, therefore, possible to achieve relatively good tracking of components on the same chip. Ratios of resistors can be held to 5% or less. Forward characteristics of diodes can be matched to within a relatively few number of millivolts. Transistors fabricated adjacent to each other will have similar current gains and diode characteristics.

Transistors and diodes are among the smallest components in a monolithic circuit. Hence, the previous desire to minimize their usage has substantially disappeared. Capacitors and inductors are, for most practical purposes, unavailable to today's monolithic circuit designer, as are special types of components such as tunnel diodes and precision reference diodes.

3.4. *Design techniques*

The maturing of semiconductor technology has been accompanied by major changes in circuit design techniques. Much circuit work is still done starting with device specifications, designing a circuit by writing the dc equations, and doing transient testing on a bench setup.

However, much more powerful computer-aided design techniques are becoming available to the device and circuit designer. The development of these techniques, and the computer simulation and optimization of designs prior to build, represent a major technical advance in circuit design [6].

Fig. 7 shows a flow chart of a design procedure, utilizing computer programs, that might be followed in designing a new circuit family. These programs eliminate much of the guesswork in design. They permit a quantitative comparison of various design alternatives and greatly reduce the number of hardware iterations required for design optimization. The diffusion parameters that will be used in the fabrication of the planar devices represent a starting point in this design cycle. This starting point determines the vertical profile of the device. Using the model for the impurity profile, the dc and ac characteristics of the device can be predicted for a wide range of voltages and current levels. At this point, the statistical distribution of device parameters, based on the variation of processing parameters, can be determined via a Monte Carlo approach. Determining the current density limitations assists in determining the horizontal geometry for the device. From this point, the designer proceeds with the dc design of the circuit.

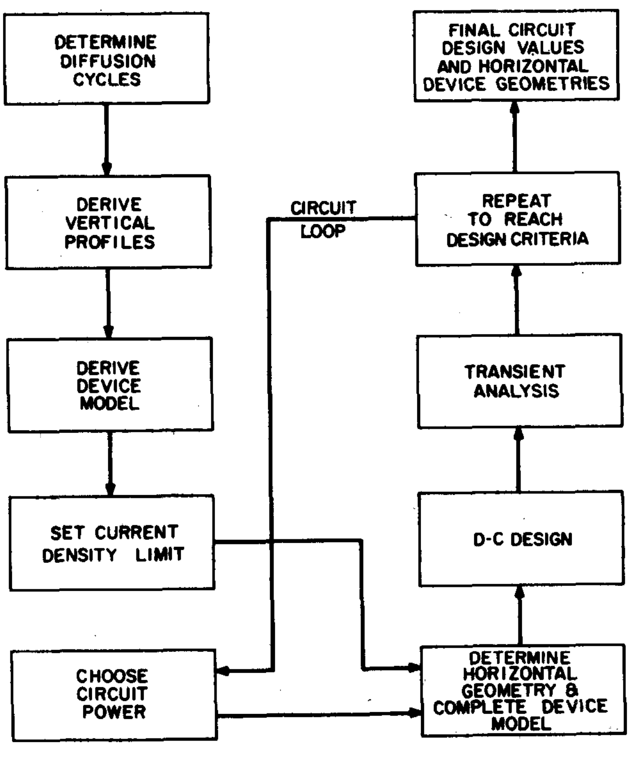

Fig. 7. Design procedure.

A common technique in the past has been to investigate the performance of the circuit under certain worst-case extremes of component values, or one can settle for a somewhat more realistic design approach and utilize, as input to the analysis, the expected statistical distribution of the components. Statistical designs are, for the most part, achieved on a computer and may involve ten thousand or more trials.

Relatively sophisticated transient-analysis techniques and programs [7] that avoid actual measurement of the transient response of a large number of circuits have been developed within the past few years.

The ability to accurately predict the electrical characteristics of a device from its vertical and horizontal geometry, and the transient response of a circuit prior to its fabrication, result in a significant saving in engineering time and cost.

As shown in fig. 7, several iterations of this design procedure may be undertaken prior to the fabrication of any device or circuit. The circuit and device designers must work together in attempting to optimize the overall characteristics of the process and the circuit.

3.5. *Testing*

After a monolithic circuit has been fabricated, the designer can measure its characteristics only by means of its terminal properties. With simple circuit configurations, it is still possible to check, within a reasonable degree of accuracy, the characteristics of the internal components. However, the more complex the circuit becomes, the greater the difficulty in characterizing the circuit. Techniques have been utilized, e.g., fabricating test components in the kerf between chips on a wafer. These test components are destroyed when the wafer is cut into individual chips, but are available during wafer test. However, in the final analysis, the terminal properties of the integrated circuit must be utilized to determine how well the circuit will perform its prescribed function.

Testing of a highly integrated chip has become a difficult, complex, costly problem. Chips having 50 to 100 circuits may have similar number of I/O terminals. The chip often contains internal storage cells that place it in the category of a sequential circuit. To date, little has been published on testing techniques for chips of this type. Some of the more complex chips may never be completely tested before they are utilized in a computer. The problem is, in many ways, similar to that of testing a small computer that may run for months before a combination of circumstances causes a design fault or a marginal condition to give an incorrect output. The cost of testing is a significant portion of the total component cost.

4. CIRCUITS AND IMPLEMENTATION

4.1. *Circuit types*

The evolution of transistor circuit design has seen a proliferation of transistor circuit types. Early transistor circuits used summing resistors for logic because resistors were the lowest cost components available. However, these circuit types were slow. Where greater speed, and fan-in and fan-out capabilities were required, resistors were replaced with diodes. But the speeds of diode circuits were also limited. In addition, diode logic required relatively large voltage swings, which, when coupled with high speed, demanded that the circuits operate at high current and power levels. To overcome this difficulty, an all-transistor logic scheme consisting of emitter-coupled transistors was developed. This scheme is presently called either a current switching circuit or an emitter-coupled logic circuit.

With the advent of monolithic integrated circuits, a form of logic known as TTL (transistor-transistor logic) has been developed; this approach is an evolution of diode logic, but utilizes a multiple-emitter structure suitable for monolithic fabrication. In the interim, many other circuit types have been developed and utilized. These included direct-coupled transistor logic, tunnel-diode logic circuits, complementary transistor logic circuits, etc.

Today the transistor circuit types that appear to be of the greatest commercial importance are diode transistor logic, transistor-transistor logic, and current switching logic [8]. It is possible that transistor-transistor logic may eventually replace diode logic, leaving only two basic circuit types in wide use. Fig. 8 shows these circuits in relatively elementary form. Many variations of these three circuit types are in use today. For the most part, these variations have two purposes: to increase speed and drive capability of the circuit, or to increase its logical power.

The logical power of a circuit has never been quantified but can be stated roughly as follows: The fewer circuits required to implement a system function, the greater the logical power of each circuit. Logical power of a circuit is en-

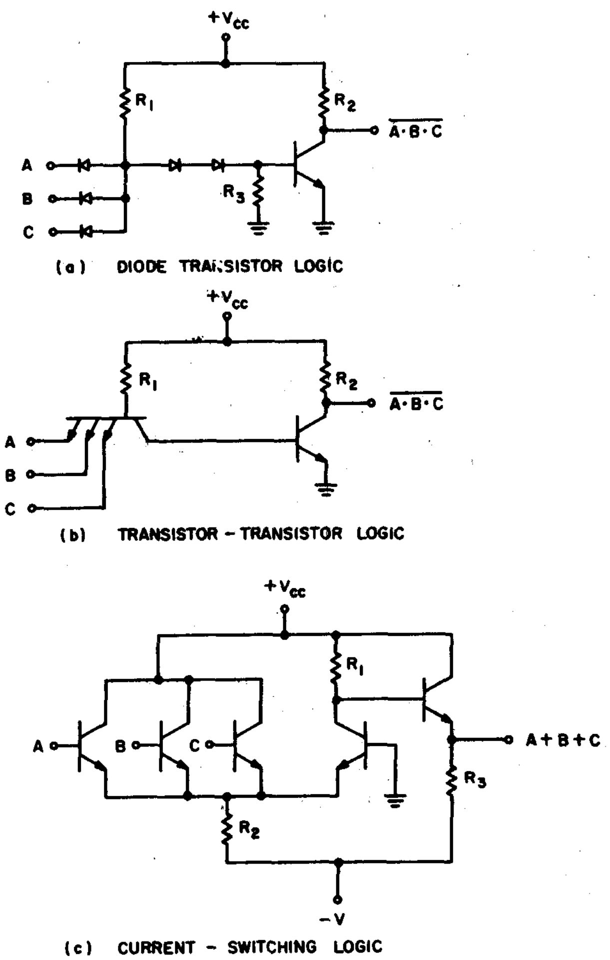

Fig. 8. Circuit topology.

hanced by the circuit's ability to do wired logic, i.e., in certain types of circuits, it is possible to achieve AND or OR operations by wiring outputs together. The emitter-follower output of a current switching circuit can be combined to provide an output OR. The availability of both true and complemented outputs also reduces the number of circuits required. The objective of most circuit development has been to develop circuits with good logical power and that can be manufactured at low cost.

Power dissipation of circuits has become of increasing concern because of the greatly increased packing density made possible by hybrid and monolithic technologies. This is discussed more fully in the section on Packaging.

The primary advances in circuits have been:

a. Achievement of high performance designs in fully monolithic structures.
b. Increased recognition and use of wired logic.
c. Increased recognition of the effects of wiring

on circuit performance and the development of transmission line techniques compatible with high performance, low power, monolithic circuits.

4.2. *Isolation methods*

The monolithic fabrication process can fabricate many components closely spaced on a common silicon surface. The elements in discrete or hybrid circuits were physically isolated by space. Negligible coupling occurred between components. In monolithic components, electrical isolation is obtained by separating components by back-biased *P-N* junctions. These junctions provide some capacitive coupling between the isolated components. Several methods of reducing this interaction have been proposed, such as replacement of the *P-N* junctions with a low-dielectric insulator or complete air isolation as is achieved in the beam lead process [9,10]. All alternatives to *P-N* junction isolation disclosed to date involve more complex processing. In practice, the effects of junction isolation can be made so small that subnanosecond circuits appear possible with its use.

MOS devices do not require the use of isolation diffusions to achieve electrical isolation [11]. The single diffusion used in the fabrication of the devices forms a junction with the substrate; the junction is biased in its high-resistance region over the normal-device-operating region. This characteristic of MOS devices enables them to be fabricated with generally higher density than is achievable with bipolar transistors.

4.3. *Levels of integration*

The industry has moved from one circuit per chip to 2-4 circuits per chip now in computers, with 10-40 circuits a proven reality and in preparation for use in systems on the drawing board. Serious work is progressing towards the 100 or more circuits per chip area. This latter development has been given the qualitative name of Large Scale Integration (LSI), where "Large" is a rapidly moving target (see fig. 9). The statistics are even more impressive when expressed in actual components per chip for logic, memory, and advanced development (see fig. 10). Regardless of where the degree of integration will wind up (if it has a limit), integration offers the possibility of reducing circuit costs to a few cents a circuit, of improving reliability, and of offering the ultimate in high-speed performance. While LSI might be capable of meeting all these goals, it is not obvious at this time how to reach the millennium. Several conflicting requirements must

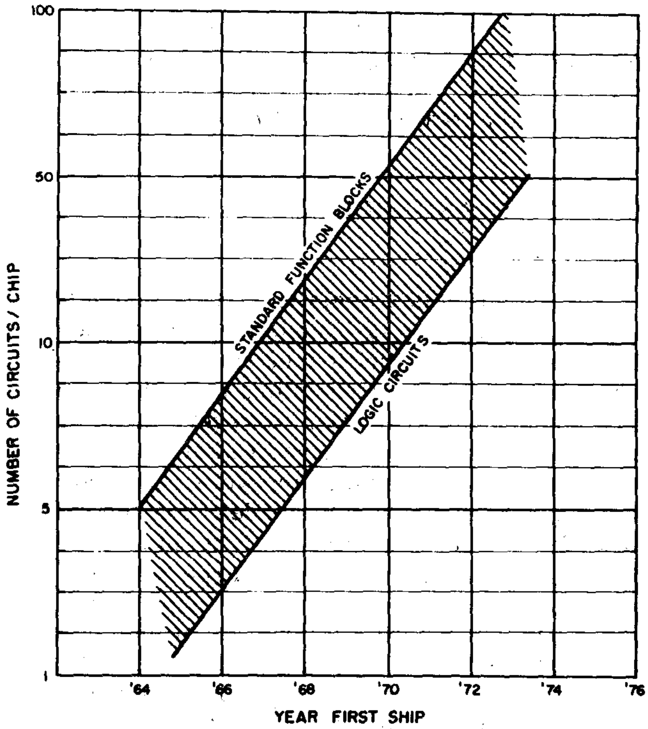

Fig. 9. Logic circuit density.

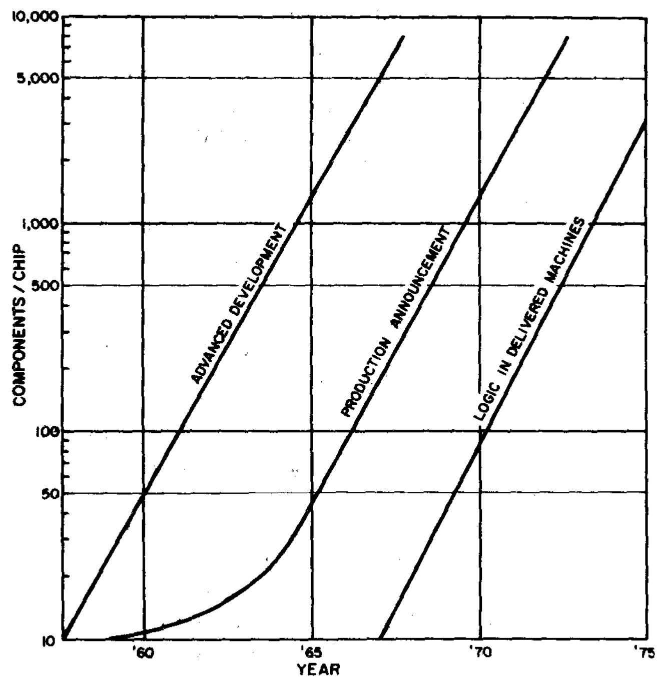

Fig. 10. Component density.

be resolved before LSI can achieve its full potential: