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and Lowell Wood

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THE OUTLOOK FOR DIGITAL COMPUTING AND ITS
APPLICATIONS, 1976-1995*

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Abstract

The current status of digital computing technology and its applications are briefly reviewed. A surprise-free (invention-precluding) scenario for predicting the advance of this technology and its applications for the next two decades is developed, and employed to set lower bounds on the performance of digital computing systems and their potential applications. Progress-pacing features are identified, and are seen to be primarily of hardware origin in the near term, and due to software limitations in the longer term.

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INTRODUCTION

The automatic, stored program electronic digital computer has existed for slightly more than two decades as a commercially available entity, over which period the maximum processing power of the most powerful available system has doubled every 18 months, on the average. Over the past decade, digital computing applications have permeated the American way of life so deeply and across so broad a spectrum that both the civilian and military components of present U. S. civilization could not survive without digital computers. The benefits in overall per capita productivity conferred by the computerization of the United States may perhaps be most cogently epitomized by recent statements of both Soviet officials and Russian dissidents to the effect that the Soviet Union must substantially eliminate the huge present gap between American and Soviet computer technologies by the early 1980s, or else be doomed to permanent second-class superpower status. Future innovation will, of course, be necessary to maintain America's position at the forefront of computer technology.

In this paper we briefly review the development of digital computing technology to its present level, to create a means for projecting the technology's development over the next two decades. We consider first the conceptual base of the field and then its technological frontiers, seen from the current vantage point. We then proceed to employ a surprise-free scenario for extrapolating over the next 20 years the presently existing features of digital computing hardware and software technologies, excluding from the forecast the inventions and qualitative advances that will quite inevitably occur in these areas, in order to develop a set of lower bounds on the basis for applications of digital computing. We then sketch very briefly some of

the major near-term digital computing applications areas, with emphasis on those which are not obvious from past developments. We conclude by noting what the progress-pacing items in the development and applications of digital computing will most likely be over the period 1976-1995, suggesting areas where major development effort may be most cost-effectively expended.

THE CONCEPTUAL BASE OF DIGITAL COMPUTER TECHNOLOGY: DEVELOPMENT TO DATE
AND OUTLOOK

During the last 20 years, digital computing has emerged from its former, severely limited arithmetical calculational role to become a widely applied tool. Two decades ago, even computer manufacturers saw digital computers as toys of the scientific elite, and computers were conceived of as large, expensive, and relatively isolated devices, operated virtually stand-alone, with only those peripheral equipments needed to promote the required data flow. More recently, however, the digital computing concept has expanded explosively into new domains of users, hardware/software configurations, and applications. It is no longer easy to tell what should be called a computer, what is merely dedicated digital logic hardware, and what is a number of digital machines acting like a single computing system.

So, if any definition needs to be made, digital computation should be considered as the relevant technology, rather than associated with the vague word "computers." There is an underlying logic to this distinction, one which embodies one of the key concepts originated in the 20th century: Digital computing is merely the use of components to precisely execute, in a quantized, digital fashion, an internally stored sequence of instructions. This simple concept--a predictable, finite state machine that executes a program internal to it--has turned out to be one of the most powerful and versatile human inventions, for such a machine can adequately represent and manipulate the representations of important problems from the real world, with a speed and precision impossible for Man.

The stunning implications of this conception can be realized only for those problems for which one knows how to obtain suitable digital computing

hardware which then may be programmed to produce relevant information about the problem so modeled. Thus, there are two necessary aspects to any digital computing endeavor: the Physical Operation and the Logical Operation. If either of these elements is missing, then relevant digital computations on that problem will not be possible. Physical operations must be performed by some actual device with discrete (digital) behavior. Logical operations are those problems, expressed in a form that can be executed by the physical device, which transform data into solutions.

Using these clarifications, we can enumerate the possible avenues of development in digital computation. The Physical device technology--that which executes programs--can develop by increasing the speed at which programs are executed, increasing the number of programs being executed at once, improving the structure of the device to allow added instruction power, or by increasing the size or repertoire of programs that it can execute. The Logical programming technology can develop along the lines of new methods to solve specific problems, better structures to express those methods in (languages, environments), better tools with which to manipulate programs (operating systems), and better understanding of the nature of computing, so that ever more astute choices of methods, structures and tools can be made.

As digital computing continues to advance on all of these avenues the scope of configurations and applications grows. Digital computation techniques have expanded from simple number-crunching to engulf signal processing, process control, archive maintenance, drafting and clerical functions, and even resource management. The expensive, room-filling, work-alone, calculational computer of the early 1960's has given birth to descendents as small as matchboxes, as applications-adapted as light bulbs,

capable of riding satellites, interpreting radar returns, and interfacing with humans far more adroitly (in some cases) than humans do themselves. Few digital computing systems possess a large fraction of these attributes, but the vastly broader scope of applications that digital computing now addresses is quite evident. The unqualified title, "general purpose," once applied to computers, has quietly vanished, as increased understanding of the potentials of digital computing has prompted the specialization of the underlying technology for enhanced performance in specific applications.

Two major notions characterize the expanding applications of digital computing. These are both new perceptions of the roles that digital computing can play. One the physical side, with the decreasing price of digital computation came the notion of considering the computer as a component of a larger system. On the logical side, with increasingly compatible programming techniques and ever-larger numbers of computers and users per computer, the notion of the computer as a data-processing utility was born. These are bold new ideas, which certainly will characterize many of the presently unforeseen applications of digital computing that will appear as such machines become cheaper, more powerful, and more numerous.

The configurations in which digital computing devices are built will become much more numerous, as will their applications across the next 20 years. Within the last few years, the unswerving, almost dogmatic, implementation of the "one machine-one data stream-one instruction stream" philosophy has been abandoned, producing timesharing, pipelining, multi-processing, and parallel-processing. Each of these powerful concepts stems from a different technique of violating the one machine-one data stream-one instruction scheme philosophy. Timesharing involves using one machine to run several logical program streams, pipelining involves dividing complex

operations into sequences of simpler operations and performing the simpler operations in parallel on different data, multi-processing uses several instruction streams on different processing elements in addressing one problem, and parallel processing uses one instruction stream on different processing elements in addressing one problem.

As the next 20 years pass, other sorts of violations of the original philosophy will doubtless arise as the economy, power, and number of digital computing devices increase. With hundreds of distinguishable digital computers available, a user is not restricted to a single instruction stream or a single processor. With the steadily decreasing price and decreasing limitations of small digital computers, the user is able to consider computers merely as components to be included in a larger system. Decreasing costs allow human-oriented interfaces which no longer force users to interact with the computer through cumbersome and energy-wasting devices which are merely well-matched to the computing system being used.

In the past, the digital computer was a luxury. It added versatility and accuracy to quantitative problem-solving, and it allowed new methods to be applied to tasks that were previously performed by analog techniques and human manipulations, but the older picture of the digital computer technology was nevertheless one of an expensive, single machine dedicated to calculation. That is not the way of the present, let alone the wave of the future. Already digital computation capability is a commodity, comparatively well-understood and generally applied. No bank, airline, or trading business would be nearly as economical in the absence of this technology. Computing resources are increasingly shared, and problems spread among machines. The machine-independence this trend generates will

mean that the ability to run a program will look ever more like a utility: bought, sold, loaned, shared, and pooled on ever larger complexes of computing hardware.

The digital computing technology has been, is, and will be promoted by a profit-motivated industry whose only long-term product of value is progress. The hardware and software being produced could remain functional for well over 20 years, but typically becomes obsolete in 5. This is not a planned obsolescence, but is rather due to the steady march of technological progress. It is prudent to expect that this trend will continue indefinitely.

Given these conceptual trends and the industries that promote developments in all areas of digital computing, what can be said that will characterize the 20-year future? Material progress is almost guaranteed, and will be discussed shortly in detail. The conceptual progress that allows one to use this material progress is this section's central theme. The conceptual trends that have been outlined above indicate increasing acceptance that the digital computer is a versatile and necessary resource. As material progress further cheapens, compacts, empowers, and advances digital computation, conceptual progress will follow. Applications will expand as such devices are treated as system components, and as widely compatible computation power becomes ever more available to function as a utility. Configurations will continue to expand from the single expensive calculating machine to harness the potential of multiple machines.

So, the scenario of the next 20 years is one of increasing utilization of digital computation techniques in all data processing applications and a greater understanding of how to use them. Digital processing will appear inside a wider variety of machines, control systems, and communications

gear, allowing many new types of self-controlled semi-intelligent devices. Digital computation will be increasingly used (or abused) to collect, enhance, categorize, store, and represent all manner of data. Functions that could be called interfacing will be more often performed via digital computation, as will those which will show a reliance on the traditional role of digital computation: problem-solving. Users, machines, and networks of machines will display more interaction, as computation becomes a utility for both men and their more intelligent machines to buy, rent, borrow, steal, or share. All in all, in the next 20 years, the art of digital computing is destined to become more available, more mundane, and more often applied to non-calculational endeavors. For instance, it will become increasingly reasonable for homeowners to consider personal computers as appliances, to be shopped for and purchased much like televisions or radios are today.

TECHNOLOGICAL FRONTIERS OF DIGITAL COMPUTING TECHNOLOGY

In the next 20 years, substantial developments will be made in the art of digital computation. These developments will complete the work started on present frontiers and open up new ones. We will classify the possible forefronts of the digital computation technology according to the guidelines laid out in the last section, and discuss the nature of the problems and possible outcomes on each horizon. The fundamental classification is along the issues first discussed: the physical (hardware) and logical (software) natures of a digital computing system.

As previously described, the physical components of a computation scheme--the hardware--can develop in speed, number, structure, and size. The speed frontier is addressed along a wide front that extends all the way from solid-state physics to computer architecture. Getting an instruction to run faster is a matter of how one arranges the circuits, how one builds the circuits, and what they are built out of. This is the concern of computer architects, digital designers, circuit designer, solid-state engineers, and industrial process engineers, and physicists.

Along this frontier, digital computing has absorbed the resources and techniques of the semiconductor industry, which is continuing to undergo explosively rapid development. The entire "computer revolution" is largely based on the expanding capabilities of solid-state electronics. It is encouraging to notice that due to the phenomenal competition and progress in this industry, semiconductor manufacturers have absorbed significant inventive talent from allied engineering disciplines. New techniques for building solid-state digital devices are appearing approximately every two years, and almost all of the new ideas currently being discussed and phototyped (VMOS, I^2L , CCD, advanced ECL, etc.) appear to have long futures,

during which they will be further refined. The device technology has branched off in numerous directions from the original saturating bipolar design for digital logic, and seems likely to continue proliferating fruitful avenues of development even as digital logic designers reach the limitations of the old designs.

There is no valid model for inventive progress of this kind, except for its historical certainty. It seems to be advancing at a steady rate, just as do the more readily documentable improvements. Circuit speed increases seem to be somewhat stalled at present by commercial production technology and by silicon usage, but neither of those obstacles will endure for any large fraction of the next 20 years. Electron beam lithography is currently being discussed and ventured upon, while gallium arsenide technology is setting new speed records, well into the sub-nanosecond gate delay range. Low and low price technologies are also benefitting substantially from the steady stream of solid-state inventions since new device concepts often show promise on only one or two of the four primary device frontiers--speed, power, cost, and density.

Substantial inventiveness is also at work on the next level of the speed frontier: circuit design. Five years ago it took twice the number of devices (usually transistors) to make a digital memory cell as it does today; device count in circuits continues to drop, enhancing yield and reliability. Power supply requirements have also been dropping, both in number and in level required to drive newer circuits. The circuit design frontier does not seem capable of delivering more than a factor of 2 improvement for any given logic family conception, but the knowledge gained in circuit design often translates into new device inventions.

This same progressive increase in the state of the art is also seen on the highest level of the speed frontier: architecture. Digital design was once performed by any circuit designer, but today it is a large specialized field of its own. Much expertise in the computer architecture/digital design area has evolved within the recent past, and this should continue to snowball. Ultimately, this sophistication is embodied in later generations of digital integrated circuits, as the older developments in architecture become implemented on denser new generations of device technology.

The outlook is bright on the speed frontier, not only because the semiconductor industry will continue to feverishly pursue progress, but because the users of their technology are continually improving specification of the product, and conceiving of new technologies as well. Speed will be increasing ever faster, because advances in number and structure allow many machines to share jobs, via pipelining, multiprocessing, and parallel processing.

The frontiers in number and structure are just beginning to be thrown wide open to large numbers of alternatives. Only recently have efforts to simultaneously use several computers on one job been demonstrated. Only in the last decade have several isolatable machines been connected to sequentially perform an instruction (pipelining). The system of interconnections and protocols necessary to form large computer networks is quite immature and will go through several evolutionary stages. As the next 20 years elapse, the numerical frontier should burst wide open while the structure frontier should become at least an order of magnitude more complex. If we are fortunate, these 20 years will add understanding as well as familiarity to the pursuit of multiple-instruction-stream machines.

Such an understanding is of paramount importance to future digital processing technology because it is the only presently discerned way to pass beyond the theoretical barriers in device speed, economy, and size. The present size frontier, regulating the number of instructions/programs one can store and execute, is quite similar to the speed frontier in its make-up and critical bottlenecks. However, program size is not increased by only an increase in memory capability--an increase in executable program size is also needed. In many problems that must run in real time (weather prediction, radar data processing, satellite telemetry interpretation, etc.), the availability of more memory does not bring larger size programs into use. Any time-dependent application (i.e., most military ones) must have improved knowhow in the numbers of structure frontier, if it is to escape from the limitations of the component (memory and logic) technologies that are presently available.

Just as physical computation technology will learn to exceed the limitations of hardware in the next 20 years, the logical technology will learn to exceed the limitations of software. Software must be written and debugged to run on any digital computing machine. Logical technology expressed in terms of available methods, structures, tools, and understanding can be machine-independent. This is an extremely important step in the development of computation technology, because it greatly reduces the (increasingly limiting) software effort needed to develop new applications.

Calculational methods have already achieved a "machine-independent" status with the advent of compatible software tools (known as computer languages) to express them in. Input, output, throughput, and memory-management methods are not so fortunate, since they are often only

expressible in the instructions of the machines on which they run. This frontier is also opening up with the advent of firmware and system-programming languages, and in the near future it should be possible to conserve programmer effort in these methods as well. The actual creation of new methods is governed by the creativity of programmers, a rate-limiting commodity that continues to be in short supply even among the expanding legions of software professionals and computer scientists.

The structural frontier, that which covers languages in which to express logical programs, has seen steady but slow advances over the last 20 years, and should continue to do so over the next 20. This frontier poses no particular limit to computation, in that a program that could be written in one language (instruction set) could as well be written in another, so long as both are complete. But the difference between a language that is suited for a given problem and one that is not makes a vast difference in the amount of effort required to create a program for a given purpose. Language development is therefore of paramount importance to economize software costs, so that they do not dominate the cost of computation in new applications. Such developments seem to occur routinely, but are largely ignored by the community of computer users.

Likewise, software tools are vital to get around logical technology limitations imposed by economics and manpower. In the early days of computation, it was possible to create and run a program without an operating system. This mean that the user had to know all about the behavior of the machine and its other users (man or machine, if any). Presently, it is much preferable to employ system software that not only saves the effort required to program peripherals, but also allows multiple users (logical programs) to employ the machine without impairing each other's function. As the next 20 years pass,

and computation becomes even more common, uses more numerous machines, and adopts the characteristics of a utility (shared, bought, pooled, etc.), these system software tools will be forced to improve to allow multiple users, and to economize programmer time required to use multiple machines.

All of these frontiers are as critical to the progress of digital computation, as were the physical frontiers. Software costs already dominate the cost of computation at most installations. The strength of computing technology is the strength of both the physical and logical technologies; if either is lacking then the application is not feasible. Software technology and machine-independence become critical elements that limit the potential of digital computation through the maximum resources available to program an application. New capabilities and applications require advances on both the logical and physical sides of this technology.

On the other hand, the last frontier on the logical side, understanding, is not essential but rather expresses how well an attainable goal can be reached. If one doesn't understand the how and why of system design, the system one builds to tackle an application will waste time, money, and effort. If one doesn't have the knowledge to pick and choose among instruction sets, languages, logic families, etc., the end product of any labor entered upon in this field will be somewhat inefficient and uneconomical. Yet tasks can be done, new applications performed, with partial understanding. Our present understanding seems quite adequate to tackle all of the envisioned horizons, but progress in understanding can and will (if the past is any indicator) be made. This progress may not be absolutely necessary, but is bound to be useful, unexpected, and change the fact of computation (as we

know it) substantially over the next 20 years. It is among the reasons that our projections are necessarily lower bounds on what will actually occur over the next 2 decades.

CONTROL

MACHINES

The next 20 years will see increasing numbers of new machines built with primary computer control, with extensive internal computation for the direction of machine activities, and with their human-directed controls buffered by computation for a more versatile set of responses.

VEHICLES

Vehicles will be driven to increasing extents by computers, will contain built-in computers to avoid obstacles and optimize maneuvering, and will have their human-oriented control panels buffered by computation for more convenient and powerful control.

PROCESSES

Industrial processes (chemical, mechanical, etc.) will be monitored and adjusted to much greater extents than at present by the ever-vigilant and always-consistent actions of a controlling digital computer (with key sections repeated and netted together as required for reliability).

WEAPON SYSTEMS

Weapons systems, especially high value ones, will be directed by or with the aid of performance-enhancing computation, for in cases where use of a weapon system is necessary, every round should be targeted with accuracy levels that can be attained only through the use of semi-intelligent automatic systems.

AUTOMATIC PROGRAMMING

ROBOTS

Robots will become capable of creating detailed programs to control their actions and their data collection mechanisms on the basis of complex external conditions, proceeding on the basis of only general and incompletely specified human instructions.

CONTROL SYSTEMS

Control systems are presently so well understood that it will become possible to virtually eliminate all associated software costs by essentially completely automatic programming of control computers, specifying only control task that they must perform.

PROTOCOL SYSTEMS

Protocol systems can also be so specified that the software that implements them on process control and managerial computers will become automatically programmed to an ever increasing extent.

PATTERN MATCHING/ANALYSIS

SPEECH RECOGNITION

Speech recognition allowing computing devices to accept verbal commands, identify the speaker, and interpret his speech into machine-processable communications will become commonplace over the next two decades. Rudimentary, user-specialized systems of this type already are in use.

VISUAL RECOGNITION

Visual recognition includes the ability to interpret visual data as one of a possible set of known objects, to classify such data into most probable type classes for counting objects, and to match changes in this data with a known list of observable phenomena. Relatively highly developed systems of this type (e.g. fingerprint-recognizing, computer-based systems) are already commercially available, and will become much more prevalent.

SATELLITE DATA

Satellites in Earth orbit, both citizen and military, generate flows of information, most of which may be irrelevant to any particular user. Such data streams must be processed, indexed and stored in real time in flexible fashions to allow features of interest to be localized routinely. Considerable progress has been made in this area to date, largely by the remote Earth sensing user communities, and the rate of advance seems likely to accelerate sharply as more such satellites, with greatly increased data rates, go into service.

ACOUSTIC ASW DATA

Ocean acoustic data contains relatively specific weak sonic signals which must be recognized, classified, and localized in the presence of much stronger signals from many more sound sources of other kinds, both natural and man-made. Successful filtering of the signals of interest will necessarily involve very massive digital computing systems, intelligently employed.

CRYPTOGRAPHY

Relatively complex codes continue to be broken without an exhaustive (and generally totally impractical) searching of successful association of patterns in coded output with patterns

known or suggested to be present in the code-generating source data with extensive use of digital computing systems to conduct the required searching. Such applications will continue to provide great impetus for the development of even more powerful digital computers.

COMMUNICATIONS

ENCRYPT/DECRYPT

More messages will be routinely encrypted and decrypted using ever more sophisticated, digitally computed codes, so that personal, proprietary, secure, military communications can be performed free from the fear of effective interception by any other than those possessing the most powerful digital code-breaking systems.

COMPRESSION OF DATA

Data blocks will be compressed into the statistically shortest expression scheme before transmission to increasingly great extents, so that communication is not wasted transmitting relatively redundant data, and so that there is minimal redundancy in the message which might aid unauthorized decryption.

SOURCE CODING

Data channels can have their reliability greatly enhanced by selectively adding redundant information to their data streams in such a fashion that the resulting stream has a much larger probability of being received correctly. Such procedures are already routinely employed within digital computing systems, and their extension to other data channels will create large, sustained demand for specialized digital processors.

DIGITAL VIDEO

The processing of video image information is turning to digital techniques as the need to rectify selectively, enhance, and recognize portions of such images grows. This trend will continue into the foreseeable future.

AUTOMATIC ERROR RECOVERY

Digital coding techniques can be applied to messages that allow errors to be corrected as well as detected. Already common in advanced digital computing systems such techniques will be extended by specialized digital processors to create effectively noise-free data channels at very slight overheads relative to existing ones.

MULTI-USER MAIL

Mail systems attempt to make best use of available communications networks to tie their many users together in as rapid a fashion as possible without interference, and with of access. Specialized digital processors are crucial to the advance of this strongly demanded technology.

MANAGEMENT

DECISION EVALUATION

Every decision made by management or administrative personnel should be checked and evaluated for its complications for the managed system. Digital computation speeds up such verification and effects simulation, allowing a manager to implement more and more reliable decisions in a fixed period.

SECURITY

Data security is enhanced by digital data-manipulation which can withhold their information from undesirable users as well as search for possible penetration attempts, by search and pattern-recognition watchdog activities. The demand for such capabilities continues to escalate.

COMMAND STRUCTURE

Digital computing systems can act to feasibly implement and rapidly after a command/control/communication structure by obeying established rules concerning the routing of information to/from subordinate individuals or installations. Such capabilities are increasingly preferred to hard-wire C³ structures, for reasons of flexibility and relativity.

INSTRUCTION GENERATION

Not all human-originated commands need to be expressed by the exertion of human command functions, since a digital computer is capable of issuing many flexibly configurable commands to arbitrarily many subordinates, as the result of single human commands. The capability and response time-enhancement generated by this technology suggests an impressive future for this aspect of C³ system.

RESOURCE SCHEDULING AND ALLOCATION

Scheduling the use of installations and other resources is being totally computerized to allow reasonable and generally-accessible decisions to be made according to cost-effectiveness - maximizing procedures. This trend will continue into the indefinite future - humans seldom make complex resource - allocation decisions optimally without a great deal of expensive and time-consuming practice.

DATA ENHANCEMENT

ESTIMATION

Estimation continues to extend its preview beyond statistical averaging of data streams and forms to get the best guess of some desired property of a complicated data set about which there is interest and relevant information.

FILTERING STOCHASTIC SIGNALS

Stochastic signals are signals corrupted (possibly purposefully) by noise. These signals are increasingly often filtered by sophisticated digital algorithms to remove much of the noise from the signal, utilizing an increasingly often prior information about the structure of either the noise or signal.

3-D RECONSTRUCTION

At present, essentially all data that can be gathered from physical sensors is at best two dimensional, but several two-dimensional data streams can be used to infer the three-dimensional geometry of the sensor's source. This is an increasingly popular application of digital data processing.

IMAGE ENHANCEMENT

Image enhancement allows images of often greatly improved quality to be generated from poorer ones available through telescopes, photographs, slow detectors, infrared imagers, etc., by restoring focus, eliminating motion blurring, and otherwise sharpening indefinite features, using information about the data gathering process that produced one degraded image. Digital processors will apparently continue to enjoy a virtual monopoly in such applications, due to its uniquely flexible non-linearity of data processing.

SIMULATION

WEATHER PREDICTION

Weather prediction is a stratingly successful application of maximally powerful digital computing (of the "number-crunching" variety) and, as it is more thoroughly integrated with remote Earth sensing satellite systems, promises to favorably impact human welfare on a very fundamental plane.

ENERGY SYSTEMS

Controlled nuclear fusion is an example of a large-scale energy system being developed with very heavy reliance on computer simulation of the complex physical systems comprising it. These physical simulations will grow in complexity to allow more complete and accurate modeling of thermonuclear and other advanced energy systems (e.g. wind, energy conversion technologies) phenomenology.

AERODYNAMICS

Aerodynamics systems are digitally simulated in detail for increasing extents to verify complex sonic and supersonic aerospace designs, the more so do representative wind-tunnel simulation is more often explained to the point of impracticality and the "diagnostics" of digital simulation can access physical data of interest that cannot be effectively obtained by alternate means.

SEMICONDUCTORS

Semiconductor behavior is being simulated to even greater extents to allow the design of more compact devices that make the best use of their available volume, while responding as rapidly as possible to signals.

ECONOMIC SYSTEMS

Economic systems are already digitally simulated to guide individual profitable enterprises, as well as government management of nation-scale economics. Such capability will grow to treat with more complicated systems that have a better chance of modeling the interactions in a real economy, as well as formulating macro-economic problems with verifiable microeconomic data.

BALLISTICS

Ballistics (including accurate, complex aerodynamic interactions) continue to be digitally simulated to increasingly complex extents, for criminological needs as well as for rest-time correction of both offensive and counter-fire directly munitions systems.

ELASTOPLASTIC MECHANICS

Problems dealing with the elastic deformation and plastic failure of solid 3-dimension shapes under load are of extremely great practical importance. Advancing digital computing simulation and control capabilities will permit the adequately realistic simulation of the performance of complex machinery (possibly designed with computer aid) and its semi-automated construction.

DATA BASES

ARCHIVAL STORAGE

Large volumes of data may be computer-concentrated in a single location (archives) to allow for ready and comprehensive searching, as well as allow effective pooling of knowledge from as many sources as possible.

REFERENCING

Data bases are being structured to ever-greater extents so that their users may readily pursue references from file to file within them, allowing the user to locate all data relating to a given topic without having to execute a search of all conceivable relevant data elements. As the human information base continues to exponentiate, such computer-originated capability will become ever more crucial.

OPTIMIZATION

RESOURCE ALLOCATION

Resource allocation involving the disposition of food, people, machinery, productive capability, raw materials, fuel, etc., should be optimized whenever possible; when complex considerations are involved, extensive digital computer utilization is a vital necessity.

PLATFORM ARRANGEMENT

Platform arrangement is the solution for the best placement of objects of known functions, limitations, and liabilities, such as factories, busses, computer installations, warehouses, paint sprayer nozzels, etc., and is likewise subject to optimization in real time, interacting with the objects' environments.

COMMUNICATION PROTOCOLS

Communication protocols are the sequences of priorities and formal messages required to guarantee communication according to established procedures and priorities between interacting installations. These rules for transmission and reception may in many circumstances (e.g. battle management) have to be optimized rather continually, so that priorities and preliminaries of communication may be modified in response to the tasks facing a communication system and the constraints placed upon it. The unique power and flexibility of digital controls is at a high premium in most applications.

DESIGN OF HARDWARE

Mechanical, electrical, chemical, nuclear, etc., hardware should employ configurations and components optimized at their design time, so that expenditure of materials, weight, expense and other key value items are minimized.

DESIGN AIDS

MECHANICAL LAYOUT (CAD)

Computer Aided Design technology allows the mechanical designer to vary the layout and shape of the assemblies being designed and evaluate the results in simulation, all from a computer terminal without having to build or test models and prototypes. This very powerful capability will be employed exclusively before the end of the century.

ELECTRONIC DIAGNOSTICS

Electronic digital simulation diagnostics even now allow the electronic circuit designer to very quickly evaluate various circuit designs from a computer and to accurately predict the actual behavior of such traisl designs. Such capability will become even more generally employed, and then extended by computer-controlled design implementation.

OPTICS

Optics systems may also be designed with try it-and-see computer simulation requiring nor physical prototyping, via use of digitally simulated characterization of the optical system being designed at a computer terminal. Such capability strongly augments the set of technologies which, next to digital technology itself, most strongly extends human conceptual abilities.

AUTOMATED DRAFTING

Computer-automated drafting already allows the engineer to produce draftsman-quality prints of all or part of a design he has only generally (but sufficiently) specified, and to do it almost instantly at a computer-controlled plotter unit.

ANALYSIS

RADIATION

Radiation data is already routinely analyzed to determine possible sources, transmission features, and effects in real-time; medical x-ray tomography is an outstanding example which is very rapidly advancing at present and it crucially dependent on digital computing technology.

CHEMICAL

Chemical data from complex analysis equipment are analyzed to identify or quantify both anticipated and unexpected chemicals, their probable origins, and the possible hazard they may represent by specialized digital computing gear at present; the general technological intensification of modern society will demand even more of such capabilities to safeguard human welfare.

MEDICAL

Biomedical data analyzed continually or periodically at present monitor inpatients and outpatients, to diagnose, and to administer drugs without requiring a trained human in experimental chemical situations with the aid of specialized digital processors. Such applications will become increasingly routine.

STRUCTURAL DEFECT

Defects in complex structures can be located, monitored, and quantified by the analysis of structural loading and deformation data at present, by computer-integrated sensors. Such applications will become increasingly common in the future, as their cost-effectiveness becomes more widely appreciated.

CLERICAL

DOCUMENT RETRIEVAL

Documents will cease to be resident in physically vast archives as computer-automated secretarial systems locate them nearly instantaneously and offer them up on a TV screen or on paper, as desired.

UPDATING

Documents so stored will be updated in all of their extent locations by suitable changes in digital memory, rather than by issuing more paper to effect and propagate modifications.

MEMOS

Memos will be among the interpersonal communication generated, issued, stored, updated, and retrieved by such automated secretarial systems.

MAIL

Mail will be increasingly computer-sorted, -routed, and -redirected, to speed written communication, while flexibly allowing for changes in the various statuses of the receiver(s), by such computer-centered communications systems.

FILING

Filing will be done by such automated systems on both archival and smaller memories, to uniformize and allow originator-specified access for other users to filed information.

EDUCATION

COMPLEX TEST CORRECTION

Examination is a vital part of the instruction process, and is an element of considerable drudgery for all but computerized test-correction methods. Low level computing machinery is routinely employed for correcting simple types of tests now, and application to even more complex examinations in the future is assured by the very low cost of microprocessors.

COMPUTERIZED TEACHING

Digital computers are used presently to implement flexible programs of individual instruction that allow pupils to learn at their own paces and afford maximum interaction with the student on all of his/her questions and problems. Extension of this trend to include most pupils through the secondary school level awaits only another factor-of-two reduction in per capita costs, and will be the dominant new development in education over the next two decades.

PROGRAMMING OF LEARNING

As with managerial scheduling, computers may be used to judge the requirements of a group of students and to schedule a locally optimized sequence of their coursework, classrooms, problems and examinations to best use existing resources and time. Such techniques will be among those employed to drop unit costs of computerized education and hasten its large-scale advent.

INTERFACING

VIDEO

Digital computing devices serve as excellent means for generating, modifying, and presenting video data on TV screens for easy human interaction, and are very rapidly coming into widespread use for such purposes, as microprocessor and memory costs continue to decline exponentially.

MUSIC

Music is readily processed by digital means, can provide highly variable ambience control, and is a relatively convenient means by which computer systems may optimize its working relationship with their sets of users.

POWER SYSTEMS

Power systems, though very complex, can be controlled and instrumented by digital computers, allowing their internal states to optimally reflect calculated and predicted needs, in real time.

MACHINES

Machines of all sorts may serve as the physical effectors of digital computers, and permit digital computer output to effect physical reality. Real time optimal control of complex machinery is a very rapidly developing area at present, and will continue to be so until production means are fully automated. Soviet and Japanese emphasis in this area is particularly great.

CONTROL PANELS

Control panels are widely recognized as ideal targets for improving man-machine interactions with the versatility and responsiveness of computer control.

TYPED INPUT/OUTPUT

Typing is unconditionally better, more repeatable, and more available when performed by the computer, which is capable of very rapidly generating universally readable text after complex editing tasks. "Word processors" with digital control systems area already a major feature.

CHARACTER RECOGNITION

Character recognition allows digital computers to read the varied scrawlings and type fonts used by humans to communicate documented information. Computer-centered character recognition systems are already in widespread use, even in post offices.

(Continued)

INTERFACING (Continued)

SPEECH GENERATION

Speech generation allows the computer to answer and instruct, as well as claim the attention of human listeners. Originally developed for military systems, quite credible computer-controlled speech synthesizers are now commercially available.

GRAPHICS

Graphics is the art of presenting computer-generated images so that human beings can more rapidly assimilate computational results. Some of the most demonstrable examples of creativity in computing systems hardware and software presently originate in the graphics area.

COMPUTER TECHNOLOGY FORECAST

The projections involve technical characteristics and capabilities of data processing systems, subsystems, and components. This conservative forecast does not depend upon future technological breakthroughs but merely assumes that research and development in digital computing-supporting technologies will continue at their present rates (i.e., constant slopes of existing learning curves). While some basic technologies will doubtless saturate over the next two decades, the rise of new ones will much more than compensate, according to the experience of the last two decades.

Computer technology is paced by developments in hardware, software, and architectural design innovations. Since the introduction of integrated circuits, semiconductor device technology has drastically increased both the speed and reliability of logic circuits and memory components, the key components of computer hardware. Both software and architectural advances have been slower-paced, comparatively speaking, though each field has developed vigorously.

Hardware

Semiconductor device technology may be expected to improve steadily over the next 20 years, until fundamental physical laws governing device characteristics of manufacturing process preclude further improvements in speed and density. Other characteristics of advancing integrated circuit technology are exponentially decreasing gate speed-power products and decreasing cost/gate, as per-chip costs of \$3-\$5 may be expected to remain constant while gate areal densities continue to increase exponentially from their present values of 10^2 (fastest bipolar) to 10^4 (MOS) per cm^2 . See Table I and Figures 1 and 2.

Plummeting hardware costs and other hardware advances in speed and packaging density will continue to make computers with exotic architecture and more CPU processing power economically feasible, relative to contemporary standards over the next two decades.

Memory technology, long dominated by magnetic core and continuous magnetic medium storage, is certain to be strongly advanced by newly developed technologies such as magnetic domain-wall motion devices, charge-coupled assemblies, and electro-optical techniques, all of which have already given strong indications of greatly superior effectiveness. The introduction of solid-state mass memories, already underway, will continue to extend both the speed and capabilities of the memory hierarchy, and will contribute further to high processor speeds through creation of optimized hierarchies of memory and varying speed and capacity, each of which is user-transparent. See Table II.

Architectural innovations such as pipelining, mapping, networking, and multiple processor system configurations have been responsible for increasing computational power by several orders-of-magnitude over the past two decades, and all seem certain to continue to contribute strongly to the creation of exponentially greater computing system power and cost effectiveness.

The architectural design of a computer has had tremendous influence on the balance between hardware and software complexity. Initially, high hardware costs forced designs which used minimal hardware, and instruction implementation was software-intensive. The rapid decline in hardware costs and accompanying increases in logic circuit speed led to hardwired designs which were faster but inflexible. The most recent trend in architecture has been microprogrammable logic (firmware), which utilizes the

full capabilities of both hardware and software in adapting digital computing systems to widely varying user requirements.

Figures 3 and 4 indicate how data processing rates and the cost effectiveness of general-application computers continue to steadily increase, due to advances in all areas of computer technology. This trend will continue through 1995 as the power of general-application computer systems continues to exponentially increase and unit production costs decline with the extension of modern mass production automated assembly line techniques into all areas of digital computing manufacture.

With semiconductor device technology nearing its theoretical limits in raw speed (in a logarithmic sense, to be sure), it is unlikely that more than a two order-of-magnitude increase in computational speed will be generated by efforts in that direction. These limitations on logic circuit speed in turn forebode diminishing returns for uni- or superprocessor architectures, which rely largely upon hardware speed advances for increases in their computational power. In addition, superprocessor systems will not be as cost-effective as multiple-processor configurations, which are relatively hardware speed-independent, and may attain very high effective speeds through exploitation of parallel processing techniques, and their implicit economics of scale. Uni- and multiple-processor configurations will apparently compete across virtually the entire spectrum of applications for relatively powerful digital computers. There are very few such applications which are intrinsically so highly iterative that multiple-instruction-stream, multiple-data-stream computing systems are at a substantial disadvantage in addressing their requirements, relative to single-instruction-stream, single-data-stream processors.

However, introduction of integrated optical digital circuitry (projected for the early 1980s) will greatly increase the computing power of superprocessors, and thereby extend the useful life of this digital computing concept well beyond 1995. The subsequent extension of optical technology to multiprocessor systems as learning curve considerations drop unit prices (as has occurred with semiconductor technology) will continue to keep multiprocessor systems well ahead of uniprocessor ones in both total power and cost-effectiveness, though.

Software

Early computer system costs were dominated by hardware, rather than software, costs. This trend has been sharply reversed due to the rapid expansion of general-purpose computer usage, which has resulted in the need for specialized programs and languages to suit specific needs. In addition, growth in data-processing power has been matched by the need for more effective and sophisticated operating systems to take full advantage of system capabilities. Multi-tasking, timesharing, virtual memory utilization, and parallel processing are among the innovations which have been made to meet this need. Even more extensive program sharing, as well as (computer-) automated program writing and validation ("proof" of correctness of form and function), are among the recent innovations in software which seem destined to palliate the software dislocations which have been growing of late.

PROGRESS-PACING CONSIDERATIONS FOR DIGITAL COMPUTING THROUGH 1995

Hardware

Maintenance of present rates of progress in most of the application areas mentioned above will require the development of computing systems having orders of magnitude more processing capability and storage capacity than current "supercomputers" (e.g., the CRAY-1), as forward motion in most present computing applications is limited most stringently by the computing power and memory capacity of available systems (in contrast to the cost or number of available systems). Advances in semiconductor hardware technologies cannot be expected to contribute greatly to computer processing power enhancement in the next 20 years, as noted above. Therefore, long-term maintenance of the average trends of the past two decades will depend on

- the emergence of radically different processor technologies (e.g., cryogenic or optical), and
- basic architectural innovations (e.g., the effective inter-connection of 10^2 or more individual processors).

Virtually all of the applications noted above are well-suited for multi-processor application. Therefore, to supplement obvious effort to develop exotic component technologies, it is crucial that a strong effort be made to develop large multi-processor systems. It is important to realize that cost-effective multi-processor systems will exhibit the following characteristics:

- Processing elements will be high performance units, with nearly the state-of-the-art uni-processor performance levels;
- Processing elements will have the capability to uniformly address a very large shared memory;
- Local cache memories will buffer processor requests to shared memory;
- Each processing element will execute its own instruction stream.

These multi-processor system characteristics necessitate the following trends in component technology:

- The availability of custom LSI circuits at low cost to facilitate the design of optimally cost effective processing elements. Processing element design should not be constrained by either the cost of custom LSI development or by the functions available in standard LSI.
- The inclusion of more high performance features such as floating point and pipelining in standard chip sets (e.g., in the bit-sliced microprocessor chip sets).
- The availability of faster and larger cache memories. The speed and size of these memories become limiting factors as the number of processors in a multi-processor is increased.
- The development of 3D lithography to allow the fabrication of parts with complex interconnection patterns (e.g., the connection pattern of the bitonic 16 sorter used to build very large, fast processor interconnection networks).
- More reliable packaging technology and more effective chip-testing procedures to increase the mean-time-between-failures of systems containing as many as 10^6 chips.

The development of multi-processor systems will also require advances in software technology as follows:

- User-level parallel programming languages.
- Efficient multi-processor operating systems.
- Reliability enhancement of large software systems.

The very rapid recent decline in semiconductor and magnetic disc storage costs occasioned by the accelerating maturation of MOS and moving head disc technologies appears likely to rapidly alleviate the dislocations in many digital computing applications caused by full maturation of the magnetic ferrite core technology. See Table II.

Software

As advances in hardware processing rates, architecture and memory sizes remove existing hardware bottlenecks to digital computing applications

over the next few years, present software shortcomings will become ever more apparent, and will remain the pacing limitation in most digital computing applications through 1995. The origin of this limitation is indicated in Fig. 5, which shows that the amount of software needed to fully exploit the power potentially available in a given computing system increases approximately with the processing power of that system; the power of the largest available computing system has of course increased exponentially with time.

Unfortunately, only humans generate computer software through the present time, and at rates which are very nearly date-invariant. Demands for software have consequently (super-) saturated the skilled programmer market for the past decade, resulting in substantially lower per capita software productivity, which would be much more striking if relative stagnation of processor speed and memory development had not paced the field for the last half decade. The elimination of the hardware bottleneck projected to occur over the upcoming half-decade, together with the advent of microprocessors, will accentuate the currently latent software bottleneck.

More effective utilization of existing programmer talent and the more rapid development of more talent will require:

- the more efficient and widespread sharing of information resource, both within and between large, multi-user systems, via data base swapping, common language linkage and calling conventions of subroutines, and enhanced message facilities;
- improvements in process specification means and associated programs, particularly those for specifying multiple tasks and the efficient utilization of multi-processor hardware systems, and those for handling asynchronous parallel processes by interrupt systems;
- more highly integrated and responsive user-customized man-machine interfaces, including facilities for rapidly creating and retaining those features which maximize individual user efficiency in computing system interactions, over a wide user population.

CONCLUSIONS

The ongoing integration of digital computing systems into human affairs is widely appreciated as being the mental analog of all the physical toolmaking and using in which man has engaged over the last few thousand millenia: digital computers extend the power of human thought in the same way tools and sensory aids extend human muscular and sensory operations. Though this enormous expansion in human capability is still in its earliest stages, it has already had both broad and profound impact.

We have reviewed the bases of digital computing technology, and have noted that conservative, surprise-free projections suggest its advance at rates at least comparable to the historic one for the next two decades, with continuation of its time-exponentially greater cost-effectiveness. We have therefore suggested the likely utilization of this technology in ever more areas of human interest and endeavor, at an exponentiating pace. We believe that only the exact magnitudes of the e-folding times are in question, and have noted the factors which will determine them.

FIGURE CAPTIONS

- Figure 1. The number of functional elements which can be synthesized on a chip which can be commercially marketed in a cost-competitive fashion is indicated for both memory- and logic-intensive chips, as a function of time.
- Figure 2. The component density on particular types of commercially available chips is indicated as a function of time. The optical diffraction limit is expected to pose no insuperable limit to component generation via contemporary optical photolithography, as far uv photo- and electron beam- lithographic processes already demonstrated are substituted, and even-larger semiconductor wafers are employed. The indicated limit corresponds to 25 μm elements uniformly distributed over a 2" wafer.
- Figure 3. A composite history and forecast of the largest general application digital computing systems is given for the 1955-1995 period. All but the ILLIAC IV have been commercially available as of the date indicated. The processing rate indicated is only for those instructions which materially advance the computation being performed for general scientific/technical programs (e.g., adds, conditional branches, logical ORs, tec.), and does not include preparative-type instructions (e.g., address computations, data fetches/stores, register-register transfers, etc.). Relative stagnation in hardware processing power over the past half decade is evident. The bars on the ILLIAC IV, CDC STAR 100, TI ASC and CRAY-1 systems range over the processing powers available for programs well and poorly matched to the specialized capabilities of each of these systems; the indicated point for each of these systems is the typical scientific program-averaged value. Multiple processor systems are projected to rapidly outdistance single processor ones in total power over the next decade, in spite of new hardware technologies always being introduced into single processors (e.g., optical digital circuits in the early 1980s) several years before they become cost-effective for multi-processor systems.
- Figure 4. The cost of a computing system per unit processing speed (here, a million instructions of the type of Figure 3 performed per second) through the present time, and projected through 1995. The relative hardware stagnation over the past half decade is even more apparent than in Figure 3, due to the high one-time development cost of the ILLIAC IV, which was ~ 3 times the typical \$107 cost of any supercomputer. The cost effectiveness "action" in computing hardware over the past half-decade has been quite exclusively in the areas of mini- and micro-processors, the equivalent values for which would lie very nearly on a straight line connecting the 1969 point for the CDC 7600 and the mid-1978 point for the first large multi-processor system.

FIGURE CAPTIONS (Continued)

Figure 5. The software requirements for large computer systems for the period 1954-1970, in lines of code. Code-compatible families of computers (e.g., the IBM 360 family) have connected points. More recently introduced computer systems (e.g., the CDC 6400-6600-7600 family) have incomplete, but trend-conforming software histories. Industry estimates are those the average programmer generates a net (after corrections and modifications) of 5-10 lines of code per day, at an average cost of ~\$10/line.

FIGURE 1

FIGURE 2

COMPOSITE PERFORMANCE FORECAST OF GENERAL- APPLICATION COMPUTER SYSTEMS.

FIGURE 3

COST PROJECTIONS FOR HIGH-PERFORMANCE GENERAL-APPLICATION COMPUTERS

FIGURE 4

GROWTH IN SOFTWARE REQUIREMENTS
FIGURE 5

TABLE CAPTIONS

Table I. Present and projected characteristics of the highest speed silicon bipolar gate LSI assemblies are given for the period 1975-1995. Gate areal and volume densities are totally circumscribed by power dissipation limitations. Heat generated by gate operation is taken to be sunk into a thin, high conductivity (e.g., sapphire) substance, from which it is removed by forced liquid convection. Values given are those projected to be technologically attainable, and are not suggested as necessarily being maximally cost-effective. Gate volume densities comparable to that of the human brain (though operating at 10^8 times greater rate and 10^7 times greater power dissipation) are projected for 1995. Lower speed silicon gates may be expected to have 2-3 orders of magnitude greater areal and volume densities, at any time.

Table II. Salient characteristics of projected read-write digital computer memory systems and components are given for the 1975-1995 period. Integrated optical memory units (and processor logic assemblies) are expected to become cost-effective in above the same epoch that advancing semiconductor and disc technologies finally render magnetic cores non-cost-effective for all applications. "Fast" and "slow" are of course purely relative terms, as applied to the aggregated semiconductor memory technologies; "fast" referred to those technologies characterized in Table I.

TABLE I. PROJECTED CHARACTERISTICS OF HIGHEST SPEED SILICON BIPOLAR LSI ASSEMBLIES.

Year	Gate Delay t_p (ns)	Gate Power Dissipation (mW)	Gate Areal Density (gates/cm)	Silicon-Substrate- Coolant Thickness (cm)	Effective Gate Density (cm^{-3}) ^a	Effective Gate Weight ^b (gm)
1975	0.4-0.55	55-35	200	0.1	2×10^3	5×10^{-3}
1980	0.2-0.35	35-18	10^3	0.03	3×10^4	3×10^{-4}
1985	0.1-0.2	25-7	10^4	0.02	5×10^5	2×10^{-5}
1990	0.06-0.15	20-5	10^5	0.01	10^7	10^{-6}
1995	0.03-0.1	15-3	10^6	0.01	10^8	10^{-7}

^aBased on indicated total package thickness and areal density of gates.

^bBased on a factor-of-three packaging weight penalty.

TABLE II. CHARACTERISTICS OF PROJECTED READ/WRITE MEMORY SYSTEMS.

	Year	Cost/Bit (Cents)	Capacity (Bits)	Average Access (μ sec)
Magnetic Cores	1975	.5	32×10^6	.35
	1980	.4	32×10^6	.3
	1985	-	-	-
Semiconductor (Slow)	1975	.2	2×10^7	.1
	1980	.05	8×10^7	3×10^{-2}
	1985	.02	3×10^8	1×10^{-2}
	1990	.01	1×10^9	3×10^{-3}
	1995	.005	3×10^9	2×10^{-3}
Semiconductor (Fast)	1975	1	2×10^5	2×10^{-2}
	1980	0.5	8×10^5	8×10^{-3}
	1985	0.25	3×10^6	3×10^{-3}
	1990	0.1	2×10^7	1×10^{-3}
	1995	0.05	1×10^8	8×10^{-4}
Magnetic Disk (Fixed Head)	1975	.025	2×10^8	8×10^3
	1980	.018	4×10^8	5×10^3
	1985	-	-	-
(Movable Head)	1975	.002	10^{11}	3×10^4
	1980	.0005	2×10^{11}	1.5×10^4
	1985	.0002	5×10^{11}	1×10^4
	1990	.0001	10^{12}	8×10^3
	1995	.00005	2×10^{12}	
Magnetic Bubble	1975	.1	10^7	1500
	1980	.02	10^8	750
	1985	.004	10^9	450
	1990	.001	10^{10}	200
	1995	.0003	10^{11}	100
Charged-Coupled Devices	1975	.1	10^8	128
	1980	.02	10^8	25
	1985	.006	10^9	6
	1990	.002	10^9	1
	1995	.0008	3×10^9	0.3
Electron Beam	1975	.1	18×10^6	5
	1980	.02	4×10^7	4
	1985	.005	10^8	3
	1990	.001	2×10^8	2
	1995	.0003	5×10^8	
Optical (Integrated)	1985	0.3	2×10^5	3×10^{-3}
	1990	0.2	2×10^6	3×10^{-4}
	1995	0.05	2×10^7	3×10^{-5}

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