Computers and Research

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Overview

The revolution of the research process itself by "computers"—foreseeable for 20 years, discernible for 10 (*1*)—is now well advanced. Computers have been adopted, adapted, and absorbed into every aspect of the research process, with aggregate consequences that are pervasive and profound.

Twenty years ago, Bell Labs Research had acquired its first modest (IBM 650) computer. A mere handful of mathematical enthusiasts, privy to the arcana of transforming equations into effective sequences of machine code, were stimulating applications throughout the research area. But "computing" was, figuratively and literally, only a minor annex of mathematics research. Today, large modern computer centers provide efficient, scientist-oriented batch and time-shared services. And throughout the research areas are scores of dedicated minicomputers and hundreds of interactive terminals—an average of one mini and five terminals per 15 professionals. First-hand experience in computer use is the norm, and at least minimal literacy in "computerese" is nearly universal. Computer pervasion of the research process is virtually complete.

Idea generation, the crux of the creative process (Fig. 1), is influenced in fundamental ways, such as the kinds of ideas, what they are about, the terms in which they are conceived, and the stimuli to which they are a response.

Broadly, these are now more complex ideas about more complex matters. But a complicated idea is worthless unless something can be done about it. What has changed is the usable level of idea complexity. Computers have significantly expanded the domain of tractable complexity. The exploration processes through which ideas must be validated and refined into science have been augmented and expedited.

Computer models involving many elements, interrelated in specific but analytically opaque ways, can now be evaluated, manipulated, and explored in pursuit of confirmations, insights, and narrowings of uncertainties. Thus the development of computers has made possible extensive explorations, validations, and refinements that in some cases would have been literally impossible, and in others would have been addressable only through very extensive, expensive and time-consuming programs of experimentation, data collection and analysis.

Thus, in many instances, computer studies afford quick, cheap alternatives to older exploratory methods. But they are also used to facilitate, expedite, and enhance field and laboratory experimentation and demonstration by prior targeting of critical parameter combinations for exploration and of decisive variables for measurement. The productivity and effectiveness of laboratory experimentation has been further enhanced by the exploitation of computers in order to achieve "nicer" and more elaborate control, as well as quick, reliable data collection, analysis, summary, and display.

Not all potentially useful data can be acquired under tidy, controlled laboratory conditions—notably in fields such as ecology, psychology, and economics. New computational-graphical techniques now enable the profitable probing and exploration of previously intractable masses of imperfect, inadequately structured data to find useful new patterns, segmentations, correlations, trends and visualizations. Accordingly new clues to understanding, inferences of structure, and model conceptions are derived.

The permeation of the exploration phases of the research process by computer techniques feeds back upon the antecedent phases of cerebration and inspiration in significant ways. The new motivations and stimulations encourage idea conception more often in terms of specific logical, quantifiable relationships and processes, thus enhancing sharpness and coherence of thought in all sciences.

A further phenomenon is the symbiosis between the overall research process and computing science itself. Stimulated by their personal activities in the exploration phases, scientists of all kinds conceive ideas about computer use that are applicable beyond their own fields, and thus contribute directly to computing science. Furthermore, the questions and complaints of the diverse community of sophisticated scientist users provide invaluable motivation, direction, and focus for the computing research activity per se in evolving new techniques and methodologies of ever greater real utility to the research community.

In this article, we elaborate on the foregoing general observations by examples drawn from four different research sectors. First, however, we discuss important additional contributions of computers to the flow of information nurturing the research process.

Getting Information In, About, and Out

The effectiveness of the research process depends critically on scientific and technical communication, a process that is deeply and increasingly intertwined with the continuing electronic revolution. Researchers must communicate among themselves to maintain an awareness of related fields, and with others to ensure that their work will be relevant and that their results will be applied.

Perhaps the most important instrument for scientific and technical communication is the telephone, which is supported by the international telecommunications network. A trend is now evident toward providing scientists with computer terminals so that they have become able to exchange written messages with speed and convenience, and to share in the development and use of an evolving store of programs and data. Nevertheless, a research effort cannot have maximal impact until its results are formally documented, published, abstracted, indexed, and used.

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Once written information exists, scientists depend heavily on libraries to help them find it, and libraries are using computers in a growing number of ways to become more efficient and effective. For example, the Bell Laboratories Library Network (*2*) consists of 25 libraries serving more than 10,000 technical and managerial employees in nine states. To help these libraries work together as a single entity, the BELLREL system maintains an on-line file of the entire book and journal collection. The complete union catalog is published annually in book form with monthly cumulative supplements, and copies are available to provide ready access for all employees.

At Bell Labs the library's MERCURY system uses a computer to route, on the basis of subject matter and other criteria, internal technical reports to interested employees. The library also publishes a dozen current awareness bulletins, prepared in whole or in part by computer from external magnetic tapes or locally entered data, or both. For information retrieval, the library provides literature searching of commercial and governmental data bases, and often publishes the results as specialized bibliographies.

Until recently, nearly every journal article was typed several times at the author's institution, and then retyped or typeset by the publisher. Later its title, abstract, and bibliography would be retyped again and again for abstracting, indexing, reviewing, and searching. Typically each retyping would correct some errors and introduce others. Fortunately, an article can now be typed once into a computer, and edited as often as the author, the referees, and the editors require. When the article is in final form, a computer-driven phototypesetter can produce camera-ready copy that is essentially indistinguishable from the best manual typesetting. Special programs are available for mathematical equations and complex tables. Citations can be obtained from an online data base, and numbered automatically. Computers can also help in locating spelling errors, making notational changes, and constructing indexes. Even page layout can be accomplished by computer, thus eliminating the need for galley proofs.

As is usually the case with automation, the most important benefit of computer-aided document preparation is that it not only does previously expensive work more cheaply, but it also creates wholly new possibilities. For authors, the results of scientific computations can be fed directly into a paper, while programs, equations, and tables from the paper can be fed back to compilers, formula manipulators, and other programs for verification and further research. For publishers, the economies of total automation may at last transform the MERCURY-like personalized journal envisioned by Brown, Pierce, and Traub (*3*) into a profitable reality.

We are witnessing the birth of a new system (Fig. 2) for scientific and technical communication. As an author conducts his research, often largely inside a computer, his report will evolve with it. When the report is finished, the myriad of activities that follow—from printing and distribution to storing, searching, and retrieving—will be based on computer processing of successive versions and subsets of the original document.

Speech

Speech research provides an excellent example of the impact of computing on a research area. In the mid-1950's, computers rescued speech research from interminable instrumentation work that slowed progress to a snail's pace. As the power of computation increased, computer-aided research dominated the field so that by the late 1960's almost everything was done by program writing. In the 1970's digital processing became so powerful and cheap that computerlike devices were incorporated into speech communication systems, replacing analog devices. The research tool itself became the product of the research.

Speech processing in 1977 makes an interesting contrast to speech processing in 1957 when, at Bell Labs, the first digital speech material was stored in 30,000 computer cards, which represented all of 2 minutes of speech. The cards were processed with an IBM 650 computer. A single study of a simple encoding often required 24 hours. Extremal coding was invented in this way (*4*). The computer had only to locate successive maxima and minima of the speech waveform. Although the computer was slow, any other way of doing the task would have required a year of equipment building.

In 1977, by contrast, one of the fastest and most sophisticated speech synthesizers speaks in real time by dint of its ability to multiply and add in 250 nanoseconds and take square roots and divide in 2 microseconds. The machine is called a linear predictive synthesizer and is constructed from 700 integrated circuits. It is digital, but is no longer a stored program machine since it was built to perform one specific function. However, it was carefully simulated on a stored program machine before being constructed.

Speech research introduced a kind of simulation that provided a new way for people to interact with computers. Computers previously had been used to analyze data or to evaluate long complex expressions. To evaluate speech transmission systems, a human listener must hear the transmitted sound. No formula can adequately predict the

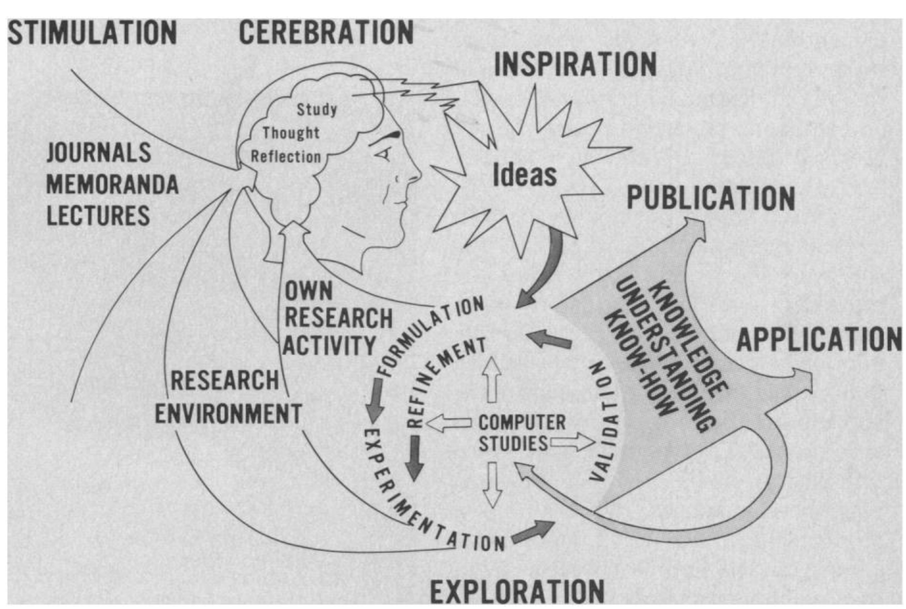

Fig. 1. The research process—in 1027 words.

quality of the transmission. In order to simulate a system on a computer, input speech must be converted into numbers, which then are processed by a computer. The computer calculates numbers representing output speech and these are ultimately converted to a sound wave. Thus, analog-to-digital and digital-to-analog converters were developed along with speech systems. During the development, the size of the converters shrank from hundreds of pounds of vacuum tubes costing thousands of dollars to single integrated circuits costing tens of dollars.

Thousands of numbers per second are necessary to represent high frequency signals—56,000 bits per second is the current standard for telephone speech. Processing and storing these numbers pushed the development of computers in important directions. Magnetic core memory plus digital magnetic tape data storage were the necessary ingredients. The IBM 704 and its transistorized successor, the 7094, were the workhorses of our speech simulation to the mid-1960's. After that time, big computer development turned toward satisfying multiple users with time-sharing programs. The shared machines were not appropriate for the heavy computations and real time demands of speech. Consequently, speech researchers turned to minicomputers as their principal tool. This encouraged the development (i) of cheap, small, powerful central processors, (ii) of the direct connection of computers with laboratory equipment, and (iii) of visual displays on scopes. The development of many of the features of today's minicomputers was strongly influenced by these computing demands (*5*). Eventually, networks of minicomputers emerged and pointed the way to distributed but interconnected computing power which may be the principal pattern for the next generation of computers.

Figure 3 shows a computer at which a researcher is synthesizing speech. As she hears the speech, she watches the movements of the articulators on a scope. She can record speech directly into the computer memory by speaking into a microphone. She can control the operation of the computer with buttons and knobs. The computer has much information on its disk files including past speech samples and a complete pronouncing dictionary. Long computations can be sent to a special high-speed central processor.

With such computing equipment,

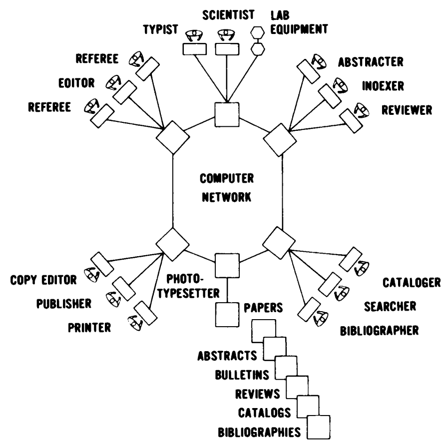

Fig. 2. Evolving system for scientific communication.

new ideas can be tried quickly and be improved or rejected according to their merit. Efficient speech encodings, excellent quality speech synthesis, limited automatic speech recognition, verification of a talker's identity, and progress toward a deeper understanding of the nature of speech have been achieved (*6*). The results of this research can now be directly applied, embodied in today's integrated circuits and microcomputers.

Atmospherics

Atmospheric chemistry exemplifies the power of new computer-dependent exploratory methodologies in modeling many-component, dynamic, interactive processes, and in statistically discerning useful forms and patterns in great masses of data.

Early in the revolution, modeling studies were decisive in unraveling the

Fig. 3. Computer speech synthesis from text.

mysteries of the exotic phenomena observed in hypersonic reentry of space vehicles. Here the computer, being given chemical reactions, generated internally differential equations and solution schemata. Another example is the priority study of fluorocarbon reaction dynamics in the upper atmosphere.

As to the lower atmosphere, a timely and exciting example is afforded by the first comprehensive study of the urban air (*7*). This study has demanded and strained the capability of the computer to handle simultaneously a complex chemical model of reactions in mathematical form, a large data base of atmospheric measurements, an extensive library of robust methods of data analysis, and a variety of graphical displays. The results have demonstrated the power of the use of chemistry, mathematics, and statistics together with the computer to provide incisive contributions to the solution of controversial and difficult problems.

The aim is to understand the scientific basis for contamination of the urban atmosphere. Thus the first requirement is to represent to sufficient accuracy the chemical kinetics of the lower atmosphere. The associated differential equations are stiff, but recent mathematical developments have made them amenable to computation (*8*). The model contains 70 distinct chemical species and 130 reactions among these species, each with its own characteristic constants. Apart from the variety of individual reaction rates, other essential factors include the influence of sunlight, both through photochemical reactions and through the height of the mixed layer of the troposphere, air turbulence, and bulk air flow.

The essential novelty of the approach is not primarily in the size of the mathematical system—roughly twice the number of variables and equations in previous models—but especially in the successful modeling of sulfur and of aerosol reactions, and in the fact that the constants associated with each reaction were taken from previous theory or experiment rather than iterated for an overall best fit. The latter decision produced greatly increased confidence in the model at the expense of previously unmanageable computational complexity.

The data base contains more than three million observations from approximately 40 primary and 60 secondary locations in the band from Pennsylvania to Massachusetts. They include a great assortment of air quality

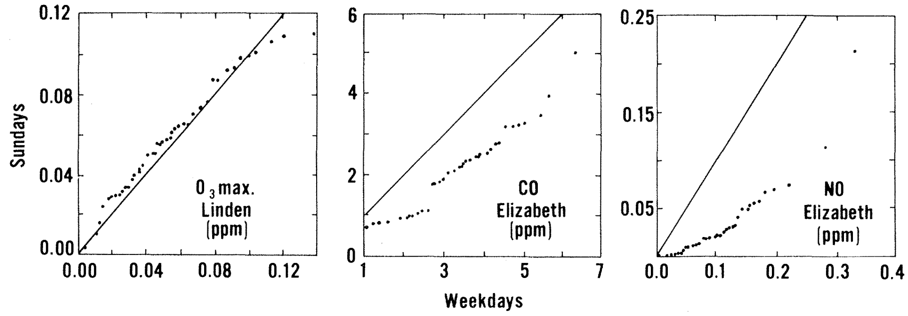

Fig. 4. Quantile-quantile plots for Sundays as compared to workdays.

measurements and meteorological observations. Differences in instrumentation and measurement techniques at the various stations, missing values, and occasional poor or extremely deviant observations affect 5 to 10 percent of the data, and make it vital that the statistical analyses be insensitive to such disturbances. These requirements made the project a critical but grateful customer for the developing arsenal of robust methods of data analysis.

Computer generated displays of results, at their best, give insights with an economy and power not easily obtained otherwise. They facilitated the accomplishment of the dual aims in this study of the urban atmosphere: to test the agreement of the complex chemical model with the observed facts, and to display the insights produced by the robust statistical analyses. Three recently developed tools of especial value are quantile probability plots, plots of moving statistics, and box plots. The quantile-quantile (Q-Q) plot displays quantiles of one distribution against those of another, and permits graphical comparison of two cumulative distribution functions without any prior assumptions regarding the nature of these distributions. It is especially useful in comparing workday with Sunday observations of various contaminants. Moving statistics superimposed onto a two-dimensional scatter plot provide local summaries of data whose structure is difficult to perceive otherwise. Such plots, for example, permit us to see characteristics of the distribution of contaminant concentrations as a function of wind direction. Thus the importance of the transport of pollutants by wind currents becomes evident. A box plot allows simultaneous presentation of extreme high and low values, upper and lower quantiles, and the median for an ordered series of distributions—such as monthly concentrations of various pollutants.

The study has produced an atmospheric chemical model of the New Jersey—New York area which shows good agreement between predicted atmospheric contaminant levels and those determined experimentally from field data. Two sample results from the study (*7*) are as follows.

1) Aldehydes, which themselves promote formation of other contaminants, are produced chemically in the atmosphere besides being emitted from motor vehicles.

2) While most primary emissions, such as carbon monoxide and nitric oxide, are noticeably lower during Sunday morning hours than on workdays, ozone levels are at least as high on Sundays as on workdays (see Fig. 4) (*9*).

Ozone is frequently considered a representative atmospheric contaminant, and tends to dominate air quality standards. The combined power of chemistry, statistics, and the computer has enabled us to understand that the actual ozone levels on any given day are the result of a delicate balance between several major atmospheric processes.

Psychology

In psychological research the computer revolution has influenced both method and theory. In perception research, for example, the computer generates and permits precise control over complex visual and auditory patterns; in psychophysiology it provides a rapid high-capacity storage medium for multichannel analog responses such as electrical brain waves; and in sensory and learning studies it increases experimental efficiency by introducing flexible real-time management of adaptive testing, in which prior responses guide the choice of new observations. Laboratory computers have accelerated research progress and encouraged exploration by facilitating changes in experimental conditions and reducing—sometimes dramatically—the delay between data collection and analysis. Without computers, some of the widely used methods of multivariate statistical analysis would be impractical because they require iterative operations on large numbers of observations. One such method is multidimensional scaling, which reveals patterns in complex psychological data by permitting diverse sets of stimuli to be represented as points in a space whose dimensions correspond to the attributes that determine how the stimuli are perceived or judged (*10*).

Computer science has also expanded and altered the kinds of questions psychologists ask and the nature of the acceptable answers (*11*). During the first half of this century, scientific psychology, dominated by behaviorism, focused mainly on the effects of repeated trials on the directly observable relations between stimuli and responses, and hardly dealt with describing the perception, memory, and thought processes that intervene. This stemmed at least partly from the lack of an adequate formal language for characterizing such processes; whereas the available mathematics was too restrictive, ordinary prose was too vague. Computer science, however, made new languages available and persuaded psychologists that programming concepts might be acceptable as precise descriptions of information processing in man as well as machine. Moreover, the hardware-software distinction supported the legitimacy of theories couched in terms of abstract information-processing operations in the mind rather than in terms of neurophysiological or chemical processes in the brain. A new field of cognitive psychology flourished as psychologists realized that concepts such as "feature extraction," "coding," "subroutine," "search," and "parallel processing" are ideally suited for theorizing about higher mental processes. In provocative new models, complex activities of thought and decision, whether conscious or unconscious, are conceptualized in terms of input, transformation, storage, retrieval, and comparison of internal representations—operations that are concatenated in systematic flow charts. Some investigators have gone even further, stating their models in actual programming languages and then testing them by comparing computer simulations with real data (*12*).

The new interest in the constituents

rather than merely the consequences of mental activity has led to a revival of reaction-time methods. In turn, these methods provide some of the strongest supporting data for a flow-chart concept of the mind by showing that the time between stimulus and response can be a *sum,* composed of the durations of a series of separate *stages* of processing (*13*). An example is the discovery that memory retrieval is sometimes accomplished by internal serial search processes analogous to ones that a computer might use. In Fig. 5, the bottom function shows the time to decide whether a test digit was present in a previously memorized list of randomly ordered digits. Although the decision seems automatic and instantaneous, the time it takes to make the decision increases linearly with the length of the list, indicating a serial search. The top function indicates a slower search to ascertain where in the list a test digit was located.

The increasing use of reaction-time measurements is one of many consequences of psychologists' new view of man as an active processor of information, characterized by speed and capacity limits.

Computing Science

Computing science both supports and stimulates the research process, by providing tools and techniques that make it ever easier for researchers to do what they find useful, and by probing and extending the boundaries of what is computationally possible.

Beginning as a subfield of applied mathematics, computing science now exerts a profound influence on almost all parts of its parent discipline. Computers have led to new kinds of attack on many classical numerical and statistical problems. Computing science itself has raised fundamental questions about computational complexity (how does the time required to solve a problem of size *n* by a given algorithm grow with *n*?)—questions that continue to occupy many first-class mathematicians (*14*). Complexity theory, whose contributions thus far range from the fast Fourier transform to proofs that a wide range of combinatorial problems are in some sense equally intractable ("NP-complete"), has changed the way people think about algorithms, and has led to new emphases on fast heuristic procedures for "finessing the impossible,"

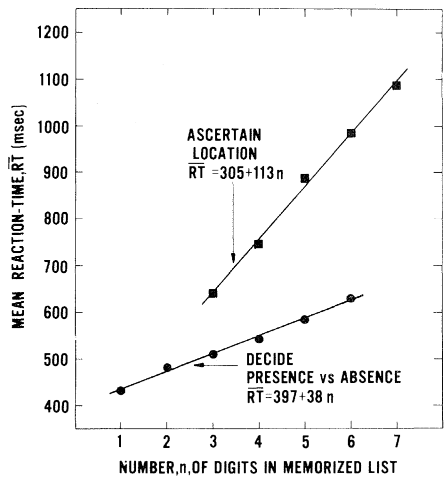

Fig. 5. Examples of experimental results suggesting that mental processes might be usefully regarded as concatenations of elementary information-processing operations.

that is, getting reasonable approximate solutions where exact solutions are known or conjectured to be unacceptably lengthy.

Computing science has also done much for people who merely want to use computers to "do their thing." Fortran is still the workhorse of scientific computation, but it has many disadvantages. The available control instructions in Fortran lead to complicated logical flows, often difficult to unravel a few months later. Furthermore programmers tend to use the special features of their local compiler, which plays hob with portability. Finally, Fortran is not adapted to systems programming if one wants to manipulate individual bits and bytes.

Many new tools have resulted from the theory of programming languages. Fortran preprocessors (*15*) have been designed, themselves written in Fortran, which provide additional control instructions leading to a much simpler, "top-down" logical organization for every program. Verifiers (*16*) exist that will take any program and automatically flag every instruction that does not conform to a standard subset of Fortran, thus essentially solving the portability problem.

The creation of new languages tailored to specific tasks has been facilitated by the development of practical compiler-compilers—programs that accept an abstract description of a language and generate a compiler for the language on a given computer. With a compiler-compiler it is possible to design a special-purpose language, refine it, and get an acceptable human-engineered final product within a matter of weeks.

Modern time-shared operating systems, such as Bell Labs UNIX (*17*), provide a well-designed file system for storing memorandums, programs, and data. The user enters alphabetical or numerical characters, typically via a keyboard terminal, and gives the file a name, and the system automatically stores it. To get the file back, one merely types in its name and the output device or program where it is wanted. The intended use does not have to be known when the file is created.

Under UNIX, numerical or textual data may flow through a whole sequence of programs without the user having to store intermediate results. This encourages people to produce small programs that perform a single intelligible function, and then hook them together in different ways. The building of such tools enables programmers "to stand on each other's shoulders rather than each other's feet."

A flexible file system and convenient facilities for entering, revising, concatenating, and running programs make a system like UNIX useful as a "workbench" for preparing and debugging programs, which are then run either on UNIX or on other computers via data links. Simultaneously UNIX keeps track of program documentation and of message traffic among its users. In such a research environment each person's contributions, if they meet a general need, rapidly get used by others. The result is a substantial cumulative and synergistic effect.

Scientific computing used to be mostly batch-oriented number-crunching. With the advent of simple, elegant operating systems and computer-communications networks, a user can now reach a whole federation of large and small computers, general-purpose and specialized, through a keyboard or display terminal. One can communicate and collaborate with other users, program in a variety of user-oriented languages, have jobs run on whatever machine one selects, and present the results in visible, audible, graphical, or printed form as desired. The interaction among computing scientists, mathematicians, and the rest of the research community has made an ever larger number of scientists effective users (and knowledgeable critics) of the increasingly powerful tools provided by computing, to the benefit of the whole research process.

Conclusion

Our discussion has of necessity been limited to the research process alone. However, we might have pursued the evolution of new science beyond research into the engineering and development processes, and cited counterparts of the same revolutionary trends and effects. Even within research, we haven't even alluded to whole broad areas of physics, biology, materials science, mathematics, economics and systems science from which could have been drawn other striking instances of revolutionary computer impact through enhanced mastery of complexity. Our case has been understated.

What of the future? The revolution, well begun, has by no means run its course. While no one can foretell its form, some of the propelling forces are clear. The hardware costs of computing power continue to drop by two orders of magnitude per decade. Great strides are being made in facilitating and automating the production of software for complex procedures. Methodology is evolving for the aggregation of numerous, specialized processing units into distributed, federated entities with new orders of capabilities. And, at a most fundamental level, new bridges of common technique, understanding and philosophy are abuilding between and among the diverse disciplines—deriving from a shared common language for discourse on complexity. Computerese is the new *lingua franca* for science.

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Tutored Videotape Instruction: A New Use of Electronics Media in Education

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In the early 1920's, shortly after radio broadcasting was proved to be economically feasible, Robert Hutchins is said to have predicted that this new technology would undoubtedly have a dramatic impact on education. Subsequent events have shown that his assessment of the educational potential of radio was probably correct but, for a variety of reasons, the potential did not materialize. In the early 1950's instructional television was introduced with a similar fanfare. However, with a few notable exceptions, its potential also failed to materialize. It seems that more recent innovations such as computer-aided instruction and satellite-based educational delivery may come to a similar fate. Why is it that these technological aids to education seldom seem to live up to their potential?

There is of course a different set of reasons in each case, though inconstant financing and the competition with commercial interests are surely among the most pervasive. However, important as these factors are, there seems to be a still more basic problem. The proponents of media-based education describe this problem as a failure of the educational establishment to involve itself seriously with instructional technology. As a result, they say, the changes in the design of the educational system that must be made before instructional technologies can be used effectively have not been forthcoming. This is a valid criticism. However, the educational establishment makes a counterargument that is also true: The devices of instructional technology are too inflexible. Effective classroom teachers regularly capitalize on unexpected, unplanned opportunities for the achievement of specific goals. As Jackson (*1*) says, "Stray thoughts, sudden insights, meandering digressions and other unpredicted events constantly ruffle the smoothness of the instructional dialogue. In most classrooms, as every teacher knows, the path of educational progress could be more easily traced by a butterfly than by a bullet." Jackson concludes from this that education is best served by tools that can be readily adapted to a wide variety of educational tasks with a minimum of advance planning. Compared to most electronics media, blackboards and books provide at low cost an impressive degree of flexibility. Furthermore, after honest efforts to use electronics media over an extended period of time, many teachers have been unable to see a clear improvement in learning. Hence, electronics media are generally judged by teachers to be inappropriate educational tools for most circumstances.

Tutored Videotape Instruction

If we accept these criticisms as valid, we are led to seek out ways of using those media that will have the desired flexibility without requiring a major change in teaching styles, and to apply them to situations where the changes in the educational system that are necessary to accommodate them can be easily

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