"chemical effect" and "state effect" have even approximate validity, they will be useful to an increasing number of individuals who wish to chromatograph species too nonvolatile for conventional gas chromatography.

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Computer-Assisted Instruction

R. C. Atkinson and H. A. Wilson

Ten years ago the use of computers as instructional devices was only an idea that was being considered by a handful of scientists and educators. Today that idea has become a reality. Computer-assisted instruction, like other aspects of electronic data processing, has undergone an amazingly rapid development. This rate of growth is partly attributable to the rich and intriguing potential of computer-assisted instruction for answering today's most pressing need in education—the individualization of instruction. Many useful ideas, however, have not achieved realization as quickly as computer-assisted instruction. The favored growth pattern of this method of instruction then must involve causes other than just a rich potential for meeting an educational need.

At least three other factors may be cited as contributing heavily to the growth of computer-assisted instruction. One of the most important was the development of programmed instruction. The surge of interest in programmed instruction during the 1950's, stemming primarily from the work of Skinner (*1*), focused the interest of educators on the problem of individualized instruction. Even though the actual results of programmed learning fell somewhat short of the glowing predictions of its early prophets, it left educators in a state of "rising expectations." The feeling remained that somehow through the use of science and technology the instructional process might eventually be tailored in a meaningful way to match the already known differences in motives and abilities among students.

The second factor contributing to the growth of computer-assisted instruction has been the mushrooming of electronic data processing in general. More specifically, however, the introduction of time-sharing systems and the design and production of third-generation computers has provided a major impetus to computer-assisted instruction. The early pioneering work at the University of Illinois on the Plato I system, which could handle only one student terminal at a time, furnished the foundation for further development. With the advent of time-sharing and the capability of the central processor to maintain more than one student terminal simultaneously, the wedding of programmed learning and electronic data processing got under way.

A third factor, and one of no less importance than those previously mentioned, has been the increasing aid to education by the federal government. In particular, the National Science Foundation and the various funding agencies which came into being under the Elementary and Secondary Education Act of 1965 have contributed substantially to the growth of computer-assisted instruction. Experimentation and development in the area of electronic data processing, particularly in the third-generation systems, has been an expensive process. Without supporting funds from the various government agencies and private philanthropic foundations (Carnegie, Ford, and others) the notion of applying electronic data processing capabilities to the problems of instruction might still be an idea discussed abstractly in a few technical journals.

Due to the interaction of the above factors, computer-assisted instruction has grown in less than 10 years to a point where during the school year of 1967–68 several thousand students ranging from elementary school to university level received a significant portion of their instruction in at least one subject area under computer control. In the Stanford projects alone approximately 3000 students were processed daily. Serious applications of computer-assisted instruction are now in progress in many universities throughout the United States: a list of those that have had major programs under way for two or more years includes Stanford University, University of California at Irvine, University of Texas, Florida State University, University of Illinois, Pennsylvania State University, University of Pittsburgh, State University of New

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Fig. 1. Student terminal used for tutorial instruction in initial reading.

York at Stony Brook, and Harvard University. The University of California at Irvine, which is a relatively new university, has made a serious attempt from its earliest planning stages to integrate computer-assisted instruction into its total instructional program (*2*).

Computer-assisted instruction has been used in university centers and is now moving into the public schools. Philadelphia's was the first major school system to implement computer-assisted instruction independent of university development or sponsorship. Philadelphia was followed closely by New York City where a significant project in computer-assisted instruction began its initial phase of operation during 1967–68 and will be in full operation during the school year 1968–69. Projects in several other school districts are in the planning stages and will be in an initial implementation phase during 1968–69.

Industry has also become deeply involved in the field of computer-assisted instruction, particularly in the design and production of totally integrated hardware-software systems. IBM was a pioneer in this area with the production of the 1500 System which will be in operation in over a dozen installations throughout the country during the 1968–69 school year. Philco-Ford was next, entering the market with the system currently in use in the Philadelphia public schools. More recently, Instructional Systems was organized as a division of RCA. The RCA Instructional 70 System is now in its debugging phase in the New York public schools and will commence full-scale operation at the beginning of the 1968–69 school year. Applications of these commercial systems have covered a wide range of content and method, from relatively simple drill and practice in elementary arithmetic to sophisticated simulation exercises in college level science courses.

Of equal importance to the development of hardware and time-sharing systems is the development of instructional programs, the curriculúms to be used with the system. Several major publishers are entering this vital area of computer-assisted instruction either alone or in collaboration with one of the hardware manufacturers. Harcourt, Brace and World, L. W. Singer, Harper and Row, and Science Research Associates all have programs in preparation. The heavy, long-range financial commitment of both publishers and hardware manufacturers is an index of the present reality and future development.

The Stanford Project

The growth of the computer-assisted instruction project at the Institute for Mathematical Studies in the Social Sciences at Stanford University is illustrative of the development of the field over the past several years. Beginning in 1963 with a grant from the Carnegie Foundation, we set about to develop a small tutorial system. Since there were no integrated computer-assisted instruction systems available at that time, we assembled a system from components produced by several manufacturers. The central processor of that first Stanford system was a PDP-1 computer produced by Digital Equipment Corporation, working from a disk on an IBM 7090. The system used an IBM film-chip projector and a Philco cathode-ray tube, both equipped with light pens, as visual presentation and student response devices; also included in the system was a Westinghouse "random access" audio device. The technical difficulties of forging a unified system out of such diverse components were enormous. However, most of the difficulties were overcome, and the system went into operation. Six student stations functioned simultaneously, providing instruction mainly in elementary mathematics and language arts. Elementary school students were brought to the Stanford laboratory by bus and received instruction on a more or less regular daily basis.

Encouraged by our initial success on the first Stanford system a sizable grant was obtained from the U.S. Office of Education under Title IV of the Elementary and Secondary Education Act for the development and implementation of a computer-assisted instruction program in initial reading and mathematics for culturally disadvantaged children. At this point IBM, in collaboration with the Stanford group, undertook the design and development work on the IBM 1500 System and an author source language known as Coursewriter II. After major developmental efforts by both IBM and Stanford, the 1500 System was installed at the Brentwood Elementary School in the Ravenswood City school district in East Palo Alto and went into operation in the fall of 1967.

The 1500 System consists of an IBM 1800 Central Processing Unit with bulk storage maintained on tape and interchangeable disks, a station controller, and peripheral devices including a card reader and line printer. The student terminal interface consists of a cathode-ray tube, a typewriter keyboard, a light pen by means of which touch probe responses may be made on the face of the cathode-ray tube, an image projector with a capacity of 1000 frames which may be randomly accessed under computer control, and a set of earphones and a microphone (Fig. 1). Audio messages may be played to the student from a bank of audio-tape playing and recording devices. One hundred and eighty minutes of audio messages may be stored on each of the three-track tapes and may be randomly accessed under computer control.

By the end of the second year of operation of this system (June 1968), approximately 400 students had received a major part of their daily instruction in either reading or mathematics under computer control. The 1500 System has been classified as a tutorial system in the sense that a very rich branching structure allows real-time instructional decisions to be made on what material is to be presented next based on the student's last response or upon an evaluation of some subset of his total response history. The Stanford-Brentwood laboratory was the first installation of its kind in an ongoing school environment, and it has therefore received considerable national attention from professional journals and the popular press and from television coverage. In addition, over 3000 visitors a year have observed students at work on the system. More importantly, significant gains in student achievement have been observed in each of the 2 years of operation (*3*).

Parallel to the development of the 1500 System, a second computer-assisted instruction system based on a considerably different design has been developed by the Stanford group (*4*). The system, known as the Stanford Drill and Practice System, uses a Digital Equipment Corporation PDP-1 central processing unit with a high-speed drum for bulk storage and model 33 teletype units at the student interface.

Although the hardware configuration on the drill and practice system is much simpler than that of the 1500 tutorial system, an even greater difference is found in the data management and branching structures. The drill-and-practice system does not have the real-time branching capability of the tutorial system. Individualization is accomplished through an off-line update where the performance of each student on day t is examined overnight and the appropriate lesson material is selected, based upon that performance record, for presentation to the student on day $t + 1$. The basic assumption in the drill-and-practice mode is that concepts are presented and developed by the teacher in the classroom, and the computer system furnishes intensified drill and practice on those previously developed concepts at a level of difficulty appropriate to each student.

During the first year of operation of the system (1965), 41 fourth-grade students received drill in elementary arithmetic computational skills at remote terminals in Grant School (Cupertino Union school district, near San Jose, California). In the 1967–68 school year approximately 3000 students received daily lessons in arithmetic, spelling, logic, and elementary Russian in seven nearby schools and in locations as far distant as McComb, Mississippi, and Morehead, Kentucky, all under control of one central computer located at Stanford. With the addition of the logic and Russian programs, the distinction between drill-and-practice and tutorial programs becomes extremely blurred.

The Stanford project of computer-assisted instruction has expanded rapidly from its rather modest beginnings, and throughout its period of growth, the project has had an important influence on the development of computer-assisted instruction. Let us turn our attention now to other modes of development as exemplified by a few selected projects.

Current Modes of Computer-Assisted Instruction

The tutorial and drill-and-practice procedures described above in the context of the Stanford project are by far the most prevalent modes of computer-assisted instruction. However, they are both essentially simulations of normal teacher-student interactions and homework assignments. Their value lies in the degree of individualization of those activities and the increase in efficiency which can be brought about through the unique capabilities of electronic data management. Another mode of application of computers to the instructional process has been pursued by Systems Development Corporation (SDC). A college-level statistics course developed by SDC and implemented at University of California at Los Angeles uses a source language called *PLANIT* which provides the student with a powerful computational tool. By means of this system the student can manipulate large and complex data bases. This introduces an important element of realism, particularly in a course in statistics, and gives the student practice in handling realistic data. The SDC program is also illustrative of the general use of the computer as a laboratory tool in mathematics and science courses.

The use of games and simulations is being explored in a number of projects. An economics simulation has been developed by the Board of Cooperative Educational Services in Westchester County, New York, called the Sumerian Game, in which the student rules a mythical empire through his actions at critical decision points. The results of his decisions on the allocation of manpower and resources are extrapolated by the computer and the interactions of economic factors in complex situations are graphically illustrated to the student through his manipulation of the relevant parameters.

A computer simulation program involving laboratory experiments in chemistry has been developed by Bunderson (*5*) at the University of Texas. This program, which is an important component of a developing computer-assisted course in chemistry, frees the student from the time-consuming task of handling complex and sometimes dangerous equipment and allows him to concentrate on observation and the logical dynamics of analysis.

The ultimate computer-based instructional system is one in which the student could input free-form questions and statements which would be analyzed by the system and understood in the sense that the system would then compose and display appropriate replies (*6*). We are some distance from that goal at the present. However, the logic program developed by Suppes (*4*) at Stanford University is a step in that direction. In this program the student is required to carry out logical derivations and algebraic proofs. The system will accept any line in the proof or derivation that does not violate the rules of logic. Thus, the student and the system can achieve a kind of free interaction, at least within the confines of the very restricted language of elementary logic.

The above is but a brief sampling of the variety of applications of computers to education that are currently available. Let us turn our attention now to some of the problems that confront workers in the field of computer-assisted instruction.

Current Problems

A variety of technical problems concerning both hardware and software design remain unsolved. The cathode-ray tube is the most flexible device for displaying graphic information, but at present, it has serious limitations. The resolution is not adequate for many purposes, and tubes must be placed usually at a distance of not more than 180 meters from the computer because of broadband transmission problems. By their very nature, cathode-ray tubes require continuous regeneration of the image. This requirement presents problems both of cost and limitations on the number of terminals that can be maintained on a given system. A plasma display tube is under development by Bitzer (*7*) at the University of Illinois, however, which may solve at least some of the problems encountered with the video display devices currently available. The plasma tube does not require image regeneration since the decay interval is extremely long. This will greatly decrease the cost of maintaining the image on the tube and increase the number of terminals that can be handled simultaneously.

Random-access audio tape units are plagued by a host of mechanical and physical problems, not the least of which is the trade-off between message capacity and search time. Work being carried on at Stanford and at other centers on audio problems points to the efficient use of digitized audio in the near future. The major problem in storing audio in digital form is the cost of both bulk and rapid access storage components. Partial relief on that problem is anticipated within the next 2 years in view of recent developments in the area of data storage.

Costs are a recurring problem in almost all aspects of computer-assisted instruction. Costs per terminal hour are relatively high even with the simplest systems available, and they increase with the addition of sophisticated audio and graphic display components. The major costs in this respect, however, are associated with the terminal hardware itself. Considerable reduction in these costs can be anticipated in the next few years as equipment design becomes more standardized and efficient

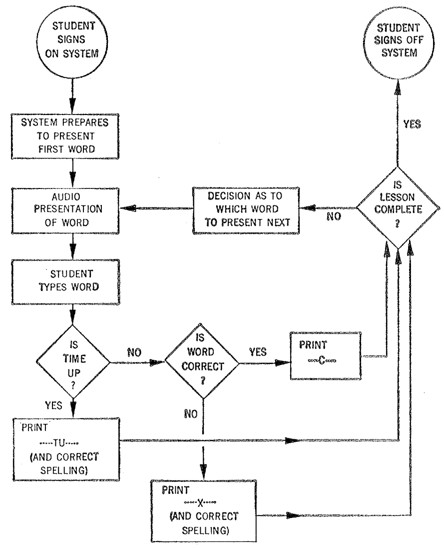

Fig. 2. Flow chart for one type of spelling lesson used in the drill-and-practice program at Stanford.

production methods are brought into play. Telephone line charges also play an important role in the cost structure when maintaining terminals at remote locations.

In general, technical solutions to problems of hardware design can be expected to reduce the cost per terminal hour. Organizational solutions will also play a part in reducing costs by providing for maximum use of the system. Extension of the instructional day will have a desirable effect as will the prorating of the central processing unit's costs over tasks such as record keeping, budget planning, course scheduling, and others (*8*).

Of a much more serious nature than technical improvements or reduction of hardware costs is the problem of premature evaluation or of evaluation questions stated in the wrong terms. Attempts at a general evaluation of computer-assisted instruction in terms of cost and effectiveness are premature in two respects. The costs, as has been suggested above, are unrealistic in even the short-term sense. Hardware manufacturers are only beginning the transition from development to production. As the transition continues over the immediate future, the per unit costs will be reduced accordingly. Second, measurements of effectiveness are difficult to achieve given the current lack of a sound theoretical basis for describing levels of learning and achievement. What is needed is a definition of some standard unit, some "erg" of learning and forgetting. Definition of such a unit is far from realization.

At a more intuitive level it must be clearly understood that evaluation of a computer-assisted instruction program is only partially an evaluation of the system and equipment. Primarily it is an evaluation of the instructional program and as such is basically an evaluation of the program designer who is the real teacher in a computer-assisted instruction system.

The evaluation question then becomes, "To what extent did the curriculum designer provide the computer with an appropriate set of instructional materials and an adequate decision structure for branching among them?" Unfortunately, curriculum design is still more of an art than a science. However, computers are a unique instructional tool in that we can embody in their programs what scientific knowledge we currently possess about human learning; at the same time they hold the promise of increasing that knowledge at an astounding rate if proper use is made of the response data which they can collect. For example, Grubb (*9*) at IBM is developing a qualitatively new approach to computer-assisted instruction, and at the same time is investigating important differences in cognitive style through a learner-controlled statistics course. Similarly, analysis of data from the Stanford-Brentwood project will help us to better understand how young children acquire reading skills (*3*). As a further example, data from the drill-and-practice program in mathematics have been used to develop performance models that predict a variety of response statistics generated by arithmetic tasks (*4*).

One of the primary aims of computer-assisted instruction is to optimize the learning process. This is implicit in the concept of individualized instruction. A major focus of the research effort at Stanford is the development and testing of instructional strategies expressed as mathematical models. An important class of such models may be called optimization models since they prescribe the sequence of instructional events which will produce optimum learning within certain boundary conditions. Such optimization models are generally extremely difficult to investigate in a rigorous way for complex learning procedures. The problem can be attacked, however, at the level of fairly simple learning tasks; to be sure, these simple tasks do not encompass all of the instructional processes of interest even at the elementary-school level, but they include enough to warrant careful investigation. Analyses of these tasks will, it is hoped, provide guidelines for the investigation of the more cognitively oriented instructional precedures.

An example of an optimization procedure is provided by one type of spelling lesson used in the drill-and-practice program at Stanford (*10*). A list of N words are to be learned. The instruction essentially involves a series of discrete trials: on each trial the computer selects a word to be pronounced by the audio system, the student then responds by typing the word, and the computer evaluates the student's answer. If the response is correct the computer types –C–; if incorrect, –X– followed by the correct spelling. A flow chart summarizing this procedure is given in Fig. 2. If n trials are allocated for teaching the list (where n is much larger than N), then the problem becomes one of finding a decision rule that will maximize the amount of learning. In general, such decision rules can be classified into two types: those that make use of the student's response history on a moment-to-moment basis to modify the flow of instructional materials, and those that do not. The resulting strategies have been termed response sensitive and response insensitive (*11*). The response-insensitive strategies are usually less complicated and can be specified completely in advance so that they do not require a system capable of branching during an instructional session. The programs developed by Skinner (*1*) and his associates are examples of response-insensitive strategies.

In order to illustrate a response-sensitive strategy, let us assume that the learning process for the spelling task described above is adequately described by the one-element model of stimulus sampling theory (*12*); in essence, this is a mathematical model which postulates that the learning of a given item occurs on an all-or-none basis. Under the assumptions of the model the optimum strategy is initiated by presenting the N items in any order on the first N trials, and a continuation of this strategy is optimal over the remaining $n - N$ trials if, and only if, it conforms to the following rules. (i) For each item set up two counters; one (designated the P-counter) to keep track of the number of times the item has been presented, and the other (the R-counter) to count the length of the most recent run of correct responses to the item. At the end of trial N set all the P-counters to 1, and all the R-counters to 0. (ii) On any trial, present an item if its R-count is least among the R-counts for all items. If several items are eligible, select from these the item that has the smallest P-count for presentation. If several items are still eligible under this condition, then select from this subset the item that had the slowest reaction time on its last presentation. (iii) Following a trial, increase the P-counter for the item presented by 1. Also, increase the R-counter for the presented item by 1 if the subject's response was correct, but reset it to 0 if his response was incorrect. Leave all other counters unchanged.

Even though these decision rules are fairly simple, they would be difficult to implement without the aid of a computer. Data from our experiments indicate that the above strategy is far better than one that presents the items equally often in a predetermined order. Another potentially more useful model may also be derived that fixes the achievement criterion at some specified level, and produces a set of decision rules which minimize the number of trials required to reach criterion.

These are examples of extremely simple optimization strategies. Others under investigation (*3, 11, 13*) make use of more realistic assumptions regarding the learning process and use more powerful mathematical techniques to derive optimum strategies. Of greater importance, they attempt to optimize performance not only within a given day's session, but from one unit of the curriculum to the next. The development and testing of viable models for optimizing instruction have just begun but show great promise for the future. These problems have received little attention in the past because optimization strategies that have been derived for even the simplest learning tasks are usually too complex to incorporate into an instructional setting without the data-managing capability of the computer.

Summary

We have briefly reviewed the rapid growth of computer-assisted instruction from its beginning some 10 years ago to its present realization in many schools and universities. We have also characterized several different modes of application and discussed some current problems. The use of computers as educational tools is still extremely limited when one considers their potential for improving the instructional process. Many problems remain to be solved; the obvious problems of hardware and costs as well as the deeper problems of understanding the learning process more fully and applying that knowledge in both curriculum development and evaluation.

Because of the shortage of funds for research on learning, only a small segment of the scientific community is involved in work on computer-assisted instruction. However, the theoretical and practical problems to be solved in this area are exciting and engrossing for the scientist who wants to apply his skills to the pressing problems of society. There is every reason to expect that the area will be able to attract top-rank scientific talent and, in the not too distant future, make a direct impact on education.

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