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ABSTRACT

A revolution that will transform learning in our society, altering both the methods and the content of education, has been made possible by harnessing tomorrow's powerful computer technology to serve as intelligent instructional systems. The unique quality of the computer that makes a revolution possible is that it can serve not only as a cognitive tool but as an active agent, in a way that books and television cannot. In this context, a new paradigm is emerging that will provide computers with an ability to understand the learner by representing problem-solving expertise within the computer, building models of the learner's skills, and communicating in English rather than programing languages. Three prototypes are discussed which manifest some of the capabilities that could be realized in tomorrow's learning environment. The first explores a potential transformation of technical education through the computer acting as consultant; the second explores the potential for a fundamental change in educational evaluation through the computer acting as assistant; and the third explores the potential for a renaissance of education in the home through the computer acting as coach. (VT)

COMPUTERS IN A LEARNING SOCIETY

TESTIMONY FOR THE HOUSE SCIENCE AND TECHNOLOGY SUBCOMMITTEE ON DOMESTIC AND INTERNATIONAL PLANNING, ANALYSIS, AND COOPERATION

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COMPUTERS IN A LEARNING SOCIETY

We Are At the Beginning of an Information Revolution

We believe that a revolution is possible over the next decade that will transform learning in our society, altering both the methods and the content of education. This revolution can occur by harnessing tomorrow's powerful computer technology to serve as Intelligent Instructional Systems.

It is clear to those who follow the cost projections that powerful personal computers will become widespread over the next decade. However, it is beyond the vision of many that these personal computers can serve as intelligent, sensitive tutors.

No one would debate that computers can be page turners or rote drill and practice monitors. But it may seem impossible that they can be insightful tutors, responding appropriately to a wide range of unanticipated situations.

A new paradigm, however, is now emerging. In our laboratories at Bolt Beranek and Newman and at MIT, we have focussed on providing computers with an ability to understand the learner -- that is, understand his strengths and weaknesses as well as his style of learning. This enterprise, the design of Intelligent Instructional Systems, treats as central -- first, representing problem-solving expertise within the computer, thereby escaping the limitations of traditional, frame-based CAI; second, building models of the learner's skills, thereby being responsive to the needs of the individual; and third, communicating in English, thereby escaping the straightjacket of computer jargon. (A historical perspective on this new paradigm is provided in Note 1.)

These are difficult problems that raise deep questions about the very nature of learning. But they are problems that we can approach through an interdisciplinary effort of psychologists, educators, and computer scientists.

From this effort is arising a theory for bridging the gap between a learner's needs and the machine's capabilities -- a theory that will make the computer a truly personal tool.

Since 1970 we have been exploring the computer as an intelligent instructional agent. We embarked on this endeavor because we saw the 1970's as prelude to a massive dissemination of computer technology with truly incredible capabilities. We believed that while others were successfully nurturing the growth of this technology, there remained a pressing need to understand the cognitive issues involved in its use.

Prototypes of the Future Must Be Created Today

We will now discuss three prototypes which manifest some of the capabilities that could be realized in tomorrow's learning environments. The first prototype explores a potential transformation of *technical education* through the computer acting as <u>consultant</u>; the second explores the potential for a fundamental change in *educational evaluation* through the computer acting as <u>assistant</u>; and the third explores the potential for a renaissance of *education in the home* through the computer acting as <u>coach</u>.

Computers Can Serve As Consultants

The first prototype explores the impact Intelligent Instructional Systems can have on *technical* education. Training competent technicians to repair the everchanging number of devices and technologies on which our society depends is an important educational goal. The mass dissemination of tomorrow's powerful computers makes possible the widespread use of simulations in technical training. Just as flight simulators have long been important in training pilots, we believe that electronic simulations, for example, will be equally basic to technical training. These simulations provide inexpensive and safe opportunities for students to explore the complexities of a device.

The critical contribution of the Intelligent Instructional System is to monitor and critique simulated tests and repairs made by the student. We have designed a prototype of such a system called SOPHIE for a limited part of the electronics domain. SOPHIE presents the user with a simulated circuit to be fixed. The user can make any measurements he wishes, replace any parts. SOPHIE observes these measurements and employs a deep understanding of electronics to decide whether a given measurement is needed or a given part replacement justified. Its tutorial function is to discuss these observations with the novice technician. In essence, it is a troubleshooting consultant. The student can explore the device with no possibility of harm, in a private setting.

There is another role such consultants can play. We believe citizens themselves can employ computer consultants to reduce the alienation engendered by modern technology. SOPHIE-like environments are fun: it is quite enjoyable to take apart a simulated TV set to see how it works. The embedded computer consultant can provide a guided tour of the device by embodying a deep theory of the domain along with a cognitive theory of what constitutes common sense understanding. While citizens will probably never actually repair their TV sets, they have gained a sense of command, of personal power through a better understanding of the devices which they employ.

Indeed our vision extends beyond consultants for technical repair, to simulations and coaches for a vast number of activities in our culture including flying a plane, sailing a boat, building a bridge, and even piloting a moon shuttle. Moreover we are designing a consultant for the task of programming itself, to avoid the computer becoming a source of mystery and alienation.

Our culture has grown so complex that many feel it is beyond their understanding. Through the simulated world of the computer, with the advice and aid of an embedded consultant, a dramatic and beneficial improvement can occur in our understanding of the world around us.

Computers Can Serve As Assistants

The second prototype is an Intelligent Instructional System capable of diagnosing the underlying cause of errors in a student's basic arithmetic skills.

Below is a set of problems a young student, Johnny, was given in a screening test. All of the answers are wrong. Not surprisingly, the teacher concluded that Johnny could not add.

87	365	679	923	27,493	797
+93	+574	+794	+481	+1,509	+48,632
11	819	111	114	28,991	48,119

But the teacher was not correct. For Johnny had a perfectly reasonable procedure for addition; it just had one small bug. (See Note 2.) Johnny was only one small step away from a correct procedure, a fact that the teacher failed to observe for most of the entire school year. The failing grade produced by traditional evaluation neither diagnosed the nature of Johnny's misunderstanding nor helped him to debug it.

Recently we have designed a prototype *diagnostic* assistant called BUGGY that can construct a deep procedural model of a student's arithmetic skills. BUGGY examines a student's answers and automatically grows a *diagnostic model* that best explains the observed errors. In a recent experiment, BUGGY analyzed over 10,000 problems done by 1300 students. The results were procedural models for each student which identified the bugs in that student's arithmetic skills. In the case of our young student Johnny, BUGGY would have inferred "why Johnny can't add."

The consequences for standardized tests of the 1980's are enormous. It is entirely reasonable to conceive of the current national tests being replaced by single most popular use of the home computer. Hence, they provide a crucial point of educational leverage.

The idea is this: Some TV games provide a challenging and active educational environment. However, as with any game, the player can reach a skill plateau. Good coaching is then required to move the student off the plateau. This is the function of the Intelligent Instructional System. It provides this coaching by embodying expertise of the game, modelling players' skills, diagnosing their plateaus, and supplying appropriate advice to help them surmount their current difficulties.

A representative TV game for which we have constructed a Basic Skills coach is a modern day version of Theseus and the Minotaur. Play occurs in a maze of caves, in which various dangers reside. To play well, one must employ knowledge of logic, probability, and geometry to determine the best move. Thus, the game is designed to exercise basic reasoning skills.

It is important that these games provide an active environment that captivates children and adults, and that exercises important intellectual skills. But their revolutionary impact derives from our ability to add a cognitive component to these systems, a personal coach or kibitzer serving to advise the players about what is intellectually significant about their current game situations.

To illustrate our prototype coach, suppose Mary, a young player, has reached a skill plateau. For example, she is not understanding the common sense heuristic that multiple evidence carries more weight than single evidence for competing hypotheses. Our prototype coach can observe whether Mary is consistently failing to apply this heuristic in her play. If so, the coach waits for an appropriate situation and offers advice. For instance, the coach might say:

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Mary, it isn't necessary to take such large risks with the Minotaur. You have multiple evidence that the Minotaur is in cave 14 (where you want to go) which makes it quite likely that the beast is there. It is less likely that cave 0 contains the Minotaur. Hence, Mary, we might want to explore cave 0 instead.

In the absence of such advice, Mary might be long delayed in acquiring this heuristic and the other basic skills exercised by the game. In a natural way, the computer coach marries education to recreation.

Of course, a human coach could also perform this function. But this is not practical when one realizes that these games will be [illegible] the home, played as recreation by any member of the family at any time.

Naturally, there are many subtleties in creating a successful computer coach: the coach must not interrupt too often, it must not give explanations that are too lengthy, and it must retain a rapport with the student. To this end, we are constructing a *procedural theory of the teacher* that takes account of such considerations. It is a difficult enterprise and much work remains to be done. But it offers the possibility of making the computer the ultimate in congenial tools, one that is sensitive and responsive to its user.

MINOTAUR is only one game among many that we could have discussed. For example, we have constructed computer coaches for the PLATO project's arithmetic game "How the West was Won" and the math educator's game of "Attribute Blocks". Rather than relying on canned responses, all of these coaches embody an ability to construct diagnostic models of the strengths and weaknesses of the student's play, and techniques for generating explanations for any situation that may arise in the game.

The potential here is enormous. Imagine, for a moment, ten thousand computer activities -- all intellectually challenging, all different. Now imagine tens of millions of citizens engaging in these activities as recreation. And finally, add to this vision the availability of the coaches. Explicitly, the coaches provide advice to improve play; they serve a recreational purpose. But, implicitly, an educational purpose of the most profound kind is being served. In essence, we are creating a new environment for learning, centered in the home and equipped with personal tutors available on demand. This hands-on environment is useful for all citizens and may be ideal for reaching that segment of the population for which the classical schoolroom situation has failed. We believe that such personal computers will have a major impact in the <u>sociology of learning</u> by enabling the *home* to assume a new importance as a center of education.

A New Science of Learning Is Emerging

Let us now step back from these examples of Intelligent Instructional Systems. We have organized our discussion around them to give a concrete feel for the future we envision. But such an organization conveys only implicitly the most important characteristic of this enterprise, which is that we believe a new science of learning and of teaching is emerging from this research. It goes beyond traditional psychology in its pervasive use of the procedural metaphor, beyond traditional education in its employment of new learning environments, and beyond traditional computer science in its focus on personal computing. Already it holds the promise of transforming educational evaluation, of reformulating technical curricula, and of diminishing the difference between recreation and education.

Its fundamental contribution is to develop the concept of building a procedural model of the skills of the learner. It is this model that guided the repair advice of our technical consultant, the diagnoses of BUGGY, and the choice of explanations made by our computer game coach. The form and structure of procedural models of the learning process can have impact as much on the content of education as on the development of a new computer-based methodology. Thus, the deepest significance of Intelligent Instructional Systems in a learning society is that the cognitive component underlying these systems not only revolutionizes the methods of education, but its very content.

Places of Excellence to Explore This Future Must Be Created

Now we will turn to the question of the issues of public policy raised by this coming explosion of computing power. Considering the potential impact of the computer revolution on the student, the schools, and the family itself, we believe it is urgent that a major program for research into the theory and technology of computers in a learning society be established.

Currently, the major source of support for this research is the Department of Defense (see Note 3) where it has been correctly perceived that powerful computing can serve a critical function in *military* manpower training and augmentation. But if we are to consider this imminent revolution from the perspective of its impact on the schools and on the family, a new *civilian* program must be established.

Small projects have been funded by NSF and NIE, but they are below critical mass. We believe centers of excellence should be established where the full possibilities of 1980's technology can be explored today. (See Note 4.)

Such centers will be expensive, for they will require the most advanced technology. Less expensive, but less powerful prototypes are pointless, for they will not reflect the resources available to the average home within even five years from today.

To some, this might suggest that we wait until the 1980's to pursue this research, when the technology is inexpensive. But while hardware is getting cheaper, the basic breakthroughs in cognitive understanding are not being made.

We can wait, and risk a vast wasteland of home computing. Or we can begin to understand the issues now. The cost is insignificant compared to the national investment soon to be made in these home computers. The cost is also insignificant compared to the change that will occur in the educational, recreational, and professional lives of our citizens.

A Frontier of the Mind is Being Opened

In closing, we wish to stress that the revolutionary transformation of learning in our society that is possible for the 1980's is not simply a consequence of the incredible computer technology that will be available then. It would not revolutionize education, for example, to place the Encyclopedia Britannica within the memory banks of every home computer. While this may be worthwhile, it would not be qualitatively different from placing the books themselves in the home.

The unique quality of the computer that does make possible a revolution is that it can serve as a cognitive tool. It can be an active agent -- a servant, assistant, consultant or coach -- in a way that books and television cannot. With vision, with planning, with dedicated research, our citizens can be employing this tool to open a new frontier of the mind within a decade.

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Notes

Note 1: The History of Intelligent Instructional Systems

Intelligent Instructional Systems represent a new generation of *learner-based computer aided instruction*, preceded in time by the original *frame-based systems* and an intervening generation of *expert-based CAI*. The following table characterizes the history of CAI in terms of these three generations.

FRAME-BASED CAI	EXPERT-BASED CAI		LEARNER-BASED CAI
			WEST
	ABLOCKS-I	--->	ABLOCKS-II
	SCHOLAR	--->	WHY
PLATO	SOPHIE	--->	SOPHIE-III
TICCIT	EXCHECK		
	WUMPUS	--->	MINOTAUR
	BIP	--->	BIP-II

The *Frame-based Period* occupied most of the sixties and even today remains the dominant paradigm outside the research environment. Programs developed within this era were typically organized as a decision tree of multiple choice questions, with the student's responses determining which path in the tree is taken. These CAI programs were the first explorations of the computer as an educational tool. They were in some cases able to provide interesting learning environments, for example the fruit fly simulation of PLATO [Bitzer *et al.* 1972], but were ultimately limited by an inadequate understanding of the problem domain being taught, and inadequate models of the teaching and learning processes. The paradigm of this period was to develop tutor languages to facilitate the design of scripts by teachers for their domains. Such an approach to CAI remains useful in certain contexts, but to achieve a new plateau of performance, a new design philosophy is necessary.

The *Expert-based Period* represents the shift to a new paradigm in which the goal is to embed genuine domain expertise in the CAI program. Three benchmark efforts in this category, each concerned with a very different kind of expertise, are the Logic and Set Theory tutors constructed by Suppes *et al.*; the geography tutor of Carbonell and Collins; and the electronics troubleshooting tutor of Brown and Burton.

Suppes has been involved with CAI since its inception, and hence his work spans all three generations. One of his long standing goals has been the development of a proof checker capable of understanding the validity of a student's proof. With the gradual evolution of machine intelligence techniques, he and his colleagues have been able to evolve successively more powerful proof checkers [Goldberg and Suppes 1972, Smith *et al.* 1975]. Thus, in this case, the research represents an evolutionary rather than revolutionary transition from frame-based to expert-based CAI.

Carbonell designed Scholar around 1970 as a CAI system for geography that could answer as well as ask questions. The basic theoretical improvement was the use of a semantic net to represent domain knowledge. Since that time, Scholar has evolved as a result of the later work by Carbonell, Collins and others [Carbonell & Collins 1973; Collins *et al.* 1975].

Brown and Burton's SOPHIE system for tutoring electronic troubleshooting is impressive in terms of its level of domain expertise [Brown *et al.* 1975]. The program is capable of simulating the internal behavior of a power supply, and hence can answer most student questions regarding the state of the device.

These programs made possible a new level of performance. Such CAI tutors are not limited to comprehension of a highly restricted set of student responses; rather, through an embedded domain Expert, they are able to comprehend a much wider set of interactions.

Recently, a third phase in CAI research has begun, characterized by the inclusion of expertise in the tutor regarding *the student's learning behavior and possible tutorial strategies*. In the above table, this generation is referred to as *Learner-based CAI* to emphasize the use of AI techniques in the modelling and tutoring components as well as in the Expert module. Within this context, Collins [1976] has investigated computational models for Socratic tutoring strategies. Burton and Brown [1976] in a tutoring program called WEST have introduced issue-oriented models of the student's knowledge, techniques for automatically inferring such models from a student's behavior, and strategies for using this model to control the tutoring component. Atkinson and others at the Institute for Mathematical Studies in the Social Sciences have examined the representation of domain expertise as a network in which tasks and their requisite skills are represented [Barr, Beard & Atkinson 1975]. In this research, the BIP system for tutoring the computer language BASIC, a model is maintained of the student's familiarity with various skills, and the next task posed to the student is done on the basis of which skills are currently known.

The Intelligent Instructional Systems described in these notes are examples of this new generation and represent an integrated investigation into tutoring and modelling.

Note 2:

When adding two digits with a carry, the student wrote down the carry and threw away the units digit.

Note 3:

Defense department agencies that have funded research on embedding a cognitive capability in computers to serve as tutor or consultant are: the Advanced Research Projects Agency, the Office of Naval Research, the Air Force Human Resources Laboratory, the Army Research Institute for Behavioral and Social Sciences, and the Navy Personnel Research and Development Center.

Note 4:

NIE has recently established a center for cognitive studies related to reading comprehension. Although its mandate is not to explore the marriage of advanced technology and Intelligent Instructional Systems, it is producing theoretical studies that will be of use in this endeavor.

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