Int. J. Man–Machine Studies (1974) **6**, 137–154

Heuristic Strategies for using Computers to Enrich Education

T. A. DWYER
Department of Computer Science, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, U.S.A.

(*Received 19 March 1973*)

Computers differ from other technology in an important way—they are part and parcel of a growing body of insights about human problem-solvers. The accomplishments of young students, in particular, suggest that certain aspects of computing are directly related to a deep view of education. This paper examines the basis for such a relationship, and proposes a heuristic methodology for bringing it about. The methodology is derived from the view that the primary function of education is to liberate human potential. Four heuristic strategies for using student-controlled computing to support this view are given. The relation of such a use of technology to the role of human teachers, and to the technology of CAI are also discussed. An example of how the heuristic methodology has been used to design a new approach to math education (Soloworks) is described.

Introduction

Recent advances in technology, especially those related to the ideas of computer science and human problem-solving, offer fascinating potential as agents for implementing a rich and quite deep view of education. Yet many educational programs involved with computer technology studiously avoid entanglement in such issues, preferring instead to accept the safe but shallow waters of drill and practice, frame-oriented tutoring, computer-aided testing, and other traditional management-of-student applications. There has undoubtedly been a tendency to associate technology with some of the more mechanistic aspects of instruction.

The purpose of this paper is to describe an educational viewpoint—both a philosophy and a methodology—based on the assumption that the complexity inherent in human nature should "drive" the relationship between technology and education; that deep technology is of little value without a deep view of education. It will also be argued (paradoxically perhaps), that the workability of this philosophy in the real school world is very much dependent on advanced technology.

This viewpoint is derived from three years of experimentation at the secondary school level in Pittsburgh (Project Solo), and a study of similar work in several other cities (Critchfield, Dwyer, Fennell & Taulbee, 1973). Some excerpts from interviews conducted during this study are given in Appendix A. Earlier examples of student work at the secondary school level are given in Dwyer (1971); additional examples are shown in the film *My Computer Understands Me* (1972), and in the multi-media report *Midnight to Midnight* (1973). An example of how the viewpoint described here is being applied to a new math education program (Soloworks) will be described at the end of the present paper.

The Goals of Education

Defining the goals of education is a basically ungrateful task; the results will seldom meet with concurrence. Yet it is an essential task if one is to make progress in applying technology at a non-superficial level; at a level which focuses on more than instruction in facts or skills. I will therefore first attempt such a definition, trying to be time-independent, that is, as independent as possible of the strengths, weaknesses, attitudes, or politics of a particular point in history. I shall then describe a heuristic methodology for applying this definition to the real world of education and I shall also try to do this in a fairly time-independent manner. In this case, time independence will mean developing a methodology that is independent of the technology of a particular era. However, I will also argue—and this will be my principal point—that the computer-related technologies and concepts of the '70s have the unique distinction of being the first to match the requirements of the methodology being proposed.

First, let me attempt to define education and its goals. I will base my definition on ideas from a wide range of educational theorists, including Aristotle, Aquinas, Whitehead, Dewey, and Piaget, on the writings of psychologists like Rogers and Maslow, and on some of the contemporary insights of people like Illich and Papert. I think that the common thread one can find in these writers is the view that education should be linked to the ideas of liberty, and fulfillment of human potential. The following shall be used as my definition: *Education is that which liberates human potential, and thus the person.*

The first step in translating this definition into more practical terms is to note that it implies helping people achieve certain kinds of control over their lives. We could thus characterize education as that which shows people how to achieve "liberating control"—control over both their environment, and themselves. Control over environment would include control of social, physical, and economic factors. More important, education should teach internal control. After three decades of work with progressive education, Dewey (1938) could still write "The ideal aim of education should be self-control".

When addressing the question of control, a deep view of education recognizes the importance of understanding "the human condition"; it recognizes that one more often deals with failure (or partial failure) than with success. It is thus important for the educational process to work at equipping people to deal with partial failures, and to suggest ways of doing something about this—to try alternatives, to "debug" the procedure that resulted in failure, to find challenge and satisfaction in working out a personal "can do/can't do" mix. Such a view can have a very positive long-term value, as has been described quite directly by Maslow (1970): "I'm hopeless with numbers; I've always had trouble with numbers. I can't remember them; I'm not interested in them. It's something constitutional or genetic, from my earliest days. So what? I forgive myself for it. I learned the minimum I had to. I did not become a mathematician; I'm a poor statistician. But I'm good at something else, and I've built on my own capabilities rather than trying to overcome defects."

It should be noted that the general definition of education proposed here passes the test of specializing to more specific definitions. For example, control over one's economic environment yields the idea of career education for a decent job. Control over physical environment suggests education in science and engineering. Control over self includes education toward social responsibility through acceptance of limits on one's own behavior in respect of the rights of others. Control over self also implies that it is in the domain of education to address the problems of self-knowledge and self-determination, somewhat along the lines advocated by Carl Rogers (1969). It also endorses educational goals concerned with fostering life-long artistic, intellectual, and emotional growth; with developing the satisfactions found in an active "life of the mind".

Translating Goals into Practice

The preceding adds up to an admittedly theoretical, and perhaps somewhat utopian, view of education. Let me now try to relate it to the real world of schools, teachers, and students.

The insights of other disciplines (including, in particular, those of computer science) suggest that there are two systematic approaches for translating educational theory into large-scale practice.

The first might be called an algorithmic approach. This approach is oriented toward defining predetermined sequences of activities for achieving predetermined measurable goals. The method suggests starting out by specifying output (often in the form of what educators call "behavioral objectives"), and then designing a procedure for producing this output from a wildly varying, quite mysterious input made up of children and "curricula". This approach is associated with what is sometimes called educational technology (as distinguished from computer technology); educational technology, in turn, draws many of its ideas from the field of "systems analysis" (Hinst, 1971).

The algorithmic approach has the merit of giving structure and precision to what might otherwise be a fuzzy process, and of encapsulating that precision in a reproducible form. Furthermore, the reproducible form theoretically possesses the logic and detail needed if it is desirable that people (or computers) can be trained (or programmed) to replicate the system exactly.

This last characteristic of the algorithmic approach explains one of the reasons it is also invoked in educational circles. Much educational research is predicated on a "pipeline" model, where the end product of that research is shipped out to users after development. This model views the teacher as a transmitter of these products; it must therefore package the products in reproducible form. From an intellectual viewpoint, the teacher has little prestige in such a system. As Piaget (1970) notes, "What the schoolteacher lacks, in contrast to all these (professionals), is a comparable intellectual prestige. And the reason for this lack is an extraordinary and rather disturbing combination of circumstances. The general reason is, for the most part, that the schoolteacher is not thought of, either by others or, what is worse, by himself, as a specialist from the double point of view of techniques and scientific creativeness, but rather as the mere transmitter of a kind of knowledge that is within everyone's grasp."

The second method, which I find much more attractive and very powerful in both theory and practice, is to employ open-ended procedures, by which I mean that neither output nor algorithm are completely specified. Direction and control are achieved instead by applying "heuristic strategies". I'll use the phrase "heuristic strategy" to mean a local procedure for pointing to global goals; a principle or guideline that helps one make both decisions and discoveries, but leaves open the question of the universe in which they are to operate. A heuristic strategy assumes that there are many procedures available; its function is sometimes to suggest new directions, sometimes to suggest backtracking. Its real power, however, lies in suggesting ways of redefining the present state of the procedure being used as the initial state of a new one. This second method is related to the theory of Dynamic Programming (Bellman, 1961); it also bears some resemblance to the goal-oriented strategies employed in artificial intelligence (Newell & Simon, 1961).

Further insight into the heuristic approach is given by associating it with the word "learn". Heuristic devices do not tell one what to do; they tell one how to learn what to do. Thus a heuristic system takes a very different view of the teacher. It insists that the teacher become more and more proficient, eventually arriving at an expertise that transcends that of the original designer of the heuristic system. This is in contrast to a teacher functioning in an algorithmic system where the instructor is often viewed as a technician for implementing predetermined aspects of the system. When critics of educational innovation say that it will not work because teachers will reject it, they are really talking about innovation implemented under an algorithmic, not a heuristic system.

I shall give examples of four such heuristic strategies, and simultaneously say something about how computer-related technology can make it possible to employ them in a manner that is unprecedented in both its workability and its profundity.

The Authoritarian View vs. Respect for the Learner

The first strategy is a principle for dealing with the problem of "authoritarian" vs. "liberal" views of education. An authoritarian view of education is not an evil one. It is, in fact, valid and essential, since it holds that each civilization presents its young with a large history of accomplishment, that there is always a significant heritage worth examining, that there is invaluable information about theories that did and did not work, and that these can (in fact must) be passed on for the profit of succeeding generations.

The difficulty with this view lies not in stressing the value of accumulated know-how. The problem is with the tendency of human teachers (and even more so, authors of CAI) to embed the information they transmit within their own personal and unalterable interpretations (models) of how to use this information. Piaget (1970) tells us that, indeed, the "lesson is always bound to conform to the tendencies of the teacher, since that is by far the easiest solution."

My first heuristic device would be to insist on educational procedures that continually reassess how well they recognize (and do something about) the distinction between transmitting accumulated experience, and transmitting models of that experience which are not valid for the new learner.

Let me give a simple example (which also explains our use of the word "solo"). It has to do with flight instruction where a distinction is made between dual and solo mode training. Dual mode involves an instructor, and much of it is authoritarian. The student must use a certificated aircraft, he must obey air traffic control, he must use the right airspeed to optimize climb, and so on. Yet he knows that he is moving to a solo flight, where he can only succeed if he develops his own models of how to use all this "past" heritage. The student alone can build the "right" model for solving a given problem, say, making a landing. The instructor knows how to land an airplane in the sense that he can do it; he can also theorize about how he does it. But he will never know much about the student's internalization of this information. So the instructor's primary task is really not to tell the student how to land the aircraft, but to help the student build his own model of the process.

The importance of helping students build their own models of the world comes home in a striking way when one observes experienced teachers of blind children at work. These teachers know that the manner in which these children "see" the world will forever be a mystery to the instructor. Such instructors become educators only when they respect this mystery, and organize their instruction accordingly. As one teacher put it, "you don't help them do it—you help them do it for themselves." I submit that adding the sense of sight does not change the essential rightness of education based on this important distinction.

What has technology to do with these ideas? I think the answer is that we are at a point in history where we have an unprecedented technology upon which to build educational systems that distinguish between the transmission of past heritage, and the eliciting of new understanding. It is called student-controlled computing. Student-controlled computing is to solo mode, as CAI* is to dual mode. Student-controlled computing means that the student uses technology to develop and test his own models; that the student learns to deal with failures; that it is in his power to debug the procedures that caused these failures. He also develops a powerful store of ideas ("ways of thinking"), from his contact with real computer science (Minsky, 1970). The user of CAI is, as Arthur Luehrmann (1972) points out, denied all of these riches.

Expectation of the Unexpected

The second heuristic strategy I would propose hinges around words like "trust", "expectation", and "recognition". The words assume that a human

*Computer-assisted Instruction, used in the sense of computer-managed drill, tutoring, and testing.

teacher and human relationships are an indispensable part of education. A human teacher is important for clarifying, inspiring, guiding, and propelling. Formal educational systems do not build habits of lasting self-propulsion. But trust, and expectation of the unexpected, are grade A propellants in any setting. They are especially valuable if they initiate a history of success. This means that expectation should match student capabilities.

The role of technology in supporting this heuristic device is quite direct. When a teacher hands over control of the sophisticated tools of computing to a student (including the bells and whistles of real hardware), this is an act of trust and expectation. It does not need to be verbalized, and it does not require a teacher with a Ph.D. in psychology to be effective. Moreover, the general nature of computing, and the natural way in which it invites problem segmentation, allows for success on many levels. We have seen numerous examples in our work that verify the power of technology in this role.

There are some words of caution that should be added at this point. Teachers who encourage solo mode learning in the manner I have advocated must face up to a problem that is not found in dual mode instruction. They will have to develop an approach to handling that aspect of maturation in students we sometimes call "moral judgment". They will have to anticipate that at times it will seem as though their trust has been betrayed. This can be a devastating experience; the experience can be even more traumatic when the teacher must also face the wrath of those who feel obliged to fix blame on one person. I should also warn that even when there are no "failures", solo mode can be rougher on the instructor than the student; airport tower operators have learned to spot a solo flight more by the apprehensive nail-biting figure of the instructor on the ground than by the performance of a student flying in their traffic pattern.

Lest these remarks seem overly pessimistic, I should hasten to add that "betrayals" of trust are exceptions, not the rule, in a student-controlled computing environment. Even when they do occur, they are usually traceable to a combination of "unthinkingness" about the consequences of certain actions, and a desire to do things (often of a quite advanced technical nature) which had been declared off-limits for students. Thus one is sometimes faced with the strange dilemma of having to classify a desire to learn as an offence. I think the solution to this dilemma lies in the idea of "control over self" that was part of my original statement of purpose for education; in stressing the development of a "can do/can't do" mix; in the pursuit of legitimate ways of changing (debugging) the system that produced the dilemma in the first place.

Many other things can be said on this subject. Some interesting work in the area of developing responsibility through control of "dangerous" technology is going on in other areas. The film *Choosing to Learn* (1971) describes one such project for very young children. Such experiments are interesting because the problem of teaching "moral judgment" has usually been skirted in public education. The reason is the traditional association of moral education with religious beliefs. Strange as it may seem, technology (in the form of student-controlled computing) may provide the beginnings of an answer to this impasse.

Environmental Learning

The third heuristic strategy is based on the principle that education, in the sense defined earlier, takes place best in a rich and joyful environment. Learning and play go hand in hand. Artifacts, both simple and sophisticated, when used correctly, can make complex ideas transparent. The work of Seymour Papert (1971) at MIT in teaching young children advanced mathematical ideas (through the use of sophisticated artifacts) illustrates this idea. The success of certain community learning centers (e.g. the People's Computer Company), and imaginative museum settings (e.g. Frank Oppenheimer's "Exploratorium") is greatly attributable to the spirit of fun environment they have developed.*

One *caveat* should be given: environmental learning, devoid of purpose and guidance, can be inefficient, and at times harmful. A person who lives in the wrong part of France can learn bad French; South American babies who learn to swim by falling off their family house-raft don't always survive. Like most good ideas, environmental solo learning needs to be coupled with other factors—with a supporting structure—before it reaches its full potential. A study of the factors which support solo mode flight instruction (which is an excellent example of environmental learning) gives particularly good insights into the role of supporting structures. Some of these factors are discussed in Dwyer (1970).

The relation to computing is this: if the student learns to make a computer (and related technology) sit up and do tricks [to be a "symbiotic partner" in the sense described by John Kemeny (1972)], this student is working in one of the richest intellectual environments yet devised by man—and it is fun. A proof of this last statement is not needed by any teacher who has tried it—the stories about students staying very late after school or getting up at 5 a.m. to be the first "on-line" are legion.

*Artifacts need not always be expensive. For example, the Nuffield math materials contain a rich store of ideas for constructing low-cost devices.

The richness of computer environments is presently limited by student–machine interface technology. I suspect that we will see fundamental growth in our understanding of the potential of environmental learning as these limits are gradually removed. Some of our own work that is moving in this direction will be described later in this paper.

There are two pitfalls to be avoided in building technology-based environments. The first is an administrative one that comes about when local control of equipment is sacrificed to the god of centralized efficiency. The folly of such an approach can be seen even in the use of simple technology. For example, a teacher who has exclusive control of a projector and suitable screening room is a much more effective user of films than one who must share a central resource. Central resources look great on paper, but they can lead to the reversal of important educational priorities in practice.*

The second pitfall is to develop environments that are too rigid or too simple. The prepackaged lab experiment that is built around a cookbook-type curriculum commits exactly the same kind of educational error as the instructor who insists that there is only one way to attack a problem. The environment that is simplified to ensure foolproof operation assumes (literally) that students are fools. The first heuristic device, with its insistence on the importance of learning to debug unsuccessful procedures, tells us that this is wrong. Educational environments need to have a complexity which invites alternate explorations, and (possibly) alternate solutions.

The Teacher Rediscovered

The final heuristic strategy I will suggest is to organize educational change around a system that encourages teachers to become expert in, and enthusiastic about, an area that students admire. I think it is no secret that schools of education do not in general produce the kind of expertise that is regarded highly by students, or even by the teachers themselves. Yet it becomes clear in dealing with young people, that despite an apparently cynical attitude toward authority, they are still very much influenced by qualities of expertise in teachers. They are even more impressed by such qualities as a zest for learning, and enthusiasm for discovering new answers.

What has technology to do with supporting such a principle? The answer is simple, and circularly (recursively?) ingenious. The way to apply this fourth heuristic strategy is to reshape a good segment of teacher education

*There are notable exceptions to this rule; the Dartmouth computer center and our own experience with a commercial time-sharing service (Com-Share, Inc.) come to mind as examples of educationally superior systems that are partly centralized.

along the lines suggested by the first three heuristic strategies. I have used the phrase teacher education rather than teacher training, to emphasize (using my original definition) that I am really proposing a liberation of the human potential of those who will work at liberating the human potential of others.

Actually, the role of technology in supporting teachers goes well beyond teacher education. One of the most difficult things for any teacher to handle is a prudent student–teacher relationship; one that recognizes that such relationships are essential, but also that they can be taken advantage of. The "objects" of technology can serve as intermediaries for resolving this conflict. They do this by acting as the common ground to which both students and teachers can relate (usually in quite different ways). They can thus serve as the link for establishing such relationships, as the buffer for safeguarding them, and as later-life reminders of the values discovered through them.

The Role of CAI

The preceding discussion has emphasized the value of student-controlled computing as a technology for implementing heuristic strategies derived from a humanistically-oriented view of education. This does not imply that CAI, used in the sense of author-controlled technology, cannot make important contributions to an educational system based on this same view. On the contrary; CAI can be an important subsystem for the "transmission of past heritage" (just as student-controlled computing is an important subsystem for eliciting new understanding of, and contributions to that heritage).

More precisely, I view CAI as having unique value as a subsystem of dual-mode instruction, especially when it frees the human instructor for the global aspects of teaching. A good instructor learns that many things are best left unsaid, and that his primary function is to focus the student's attention on the forest, not the trees. But without trees, there are no forests. CAI can be an excellent tool for planting and nurturing educational trees.

CAI becomes especially valuable when dual and solo modes build on each other, and when there is planned transition between modes. Some of the technical consequences of insisting on transitional ease between CAI and student-controlled computing are discussed in Dwyer (1972).

An Illustrative Example

An application of the preceding ideas to a math education project for beginning secondary school students (aged 13–17) is presently in progress at the University of Pittsburgh.* Extensive use of technology is involved, but the role of this technology has been primarily determined by the heuristic educational principles just described. The math curriculum developed will in fact be deliberately structured so that its replication elsewhere will be dependent on the conscientious application of these same principles. This is a weakness of the curriculum in the sense that it assumes teachers and administrators who understand and agree with the heuristic approach. It is a strength in the sense that it gives the curriculum the ability "to learn and adapt". In the

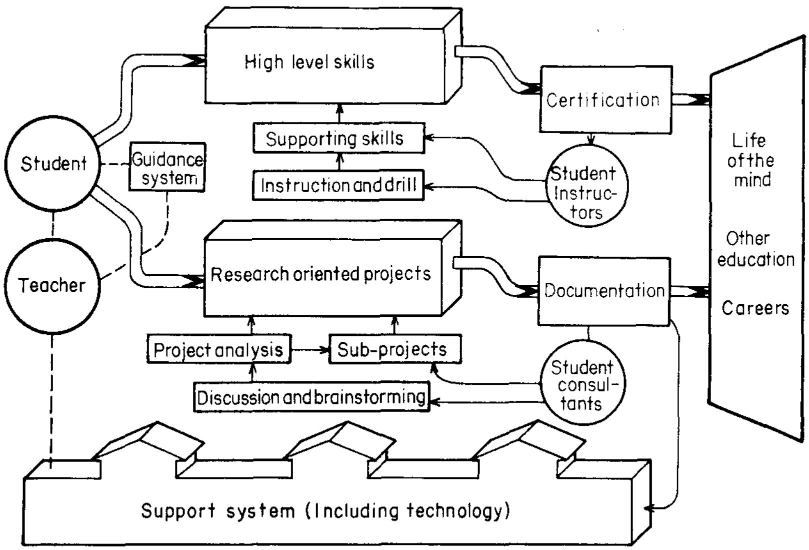

FIG. 1. Organization of the Soloworks Labs.

description that follows, square brackets will be used to point out the heuristic strategies being applied.

The Soloworks math program will be organized around four labs called Computer Lab, Dynamics Lab, Synthesis Lab, and Modelling/Simulation Lab. Each lab will focus on both the achievement of major skills, and on the pursuit of research projects. A research project is defined as any endeavour in which the outcomes are not completely predetermined [expecting the unexpected, trust]. The instructional plan behind the labs is shown in Fig. 1.

The role of the teacher might be described as one of "knowledgeable facilitator". This means that our teacher-training program must focus on

*Sponsored in part by NSF grant EC-38063. The informal name of the project is "Soloworks".

having teachers live with, experience, and become good at some (not all) of the skills connected with the labs [encourage teachers to become expert in areas that students admire]. The supporting structure box for each lab consists of both curriculum material and exciting technology [a rich and joyful environment].

(1) The Computer Lab will focus on those aspects of mathematics that are well described by algorithms, and encourage student access of a local computer and terminals. A major skill students will achieve in this lab is that of computer programmer. Examples of some projects that have already been done by students in this lab are developing programs to do accounting and inventory for a small store, programs to manage computer dating, generation of random ballet dances, programs to plot all kinds of mathematical curves, programs to predict and plot their intersections, etc. The significance of the project approach is that although students have made available to them past "heritage" appropriate to attacking the project, they are also expected to develop new and unique extensions of that heritage [respect for the learner's need to develop his own models]. We have found that this is difficult for students at first; most of them exhibit a high reliance on an instructor's explicit orders. But we have also found that patience is rewarded; students can and do make the transition.

(2) The Dynamics Lab focuses on mathematics that describes processes that take place in time. One form of technology being used in this lab is a flight simulator [rich environment]. The skill acquired in using this particular equipment is that of making a full instrument landing, or becoming good at instructing a fellow student to do the same [trust, recognition]. An example of a project would be to sample analogue readings of heading, time, and speed from the flight simulator, translate these into digital data, and then write a program that plots the path of the flight simulator. Another type of artifact being used in the Dynamics Lab is the "Rube Goldberg" machine, a gadget designed by the student to do nothing useful, but to be a mind-stretching exercise in imagination.

(3) The Synthesis Lab is concerned with mathematical methods that make use of the principle of superimposition, producing complex effects by adding together simple ones. Two special pieces of technology we will use are the "Music Monster" (a kind of programmable band-organ), and a multi-media programmer together with suitable projection equipment. The obvious skills associated with these devices are composer and media-designer. Projects will focus on the design, debugging, and performing of original works.

(4) The Modelling/Simulation Lab uses mathematics as a tool for creating new models of reality that can be studied and manipulated [new models vs.

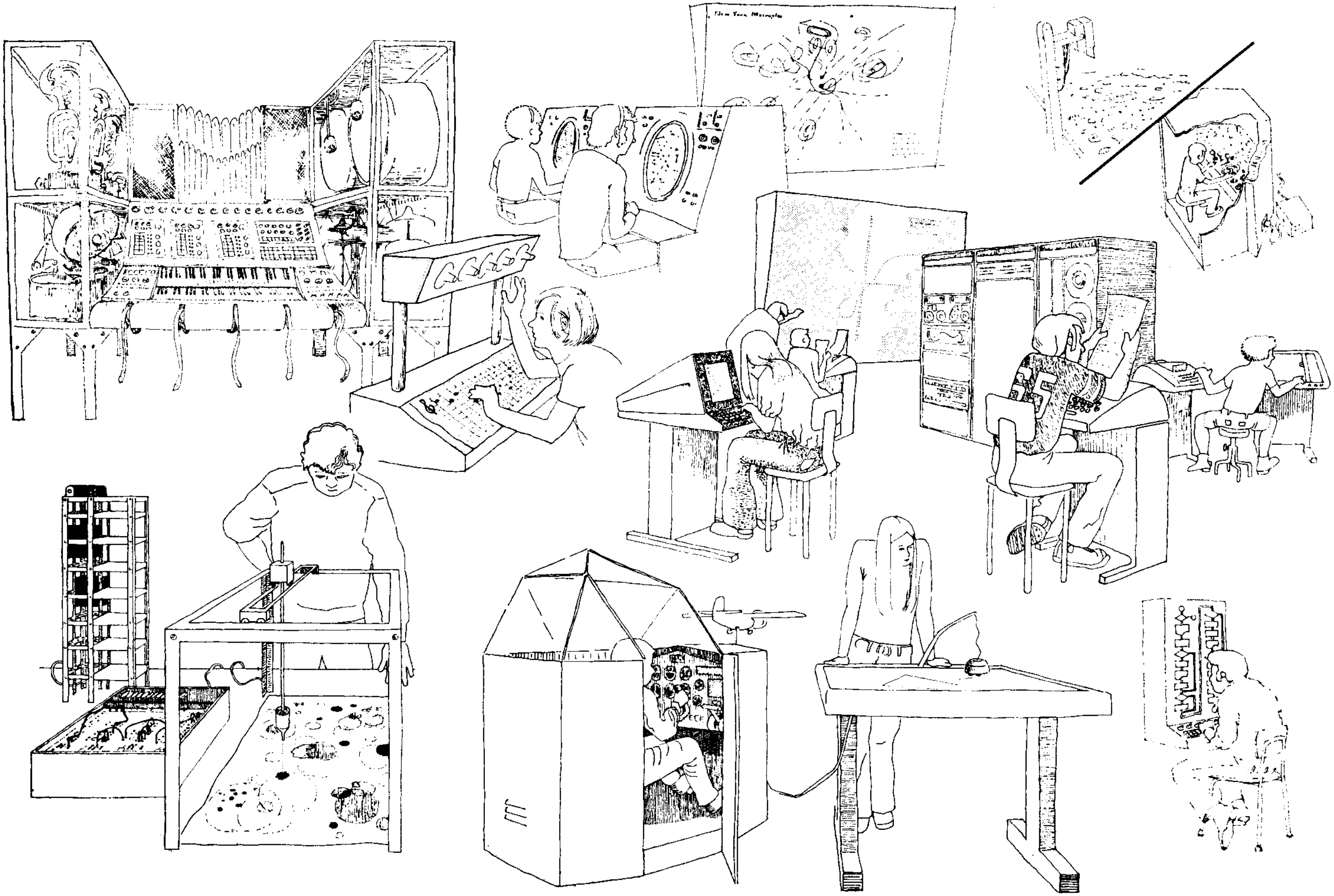

FIG. 2. Some examples of the Soloworks Lab components.

old heritage]. Some of the models are physical (e.g. bridges, elevators, lunar landing modules, etc.), some are abstract (e.g. an ecology). The skill developed here is really that of applied mathematician, while the gamut of possible projects is open-ended. This is because the computer available to students is general purpose, allowing them to simulate systems not heretofore dealt with [expecting the unexpected].

The sketches in Fig. 2 give some idea of the form of the technology we are or will be using [fun environment!]. We are just concluding our first year of what will be a three-year program to develop and test these ideas.*

Conclusion

The methodology I have proposed has difficulties of course. The source of these difficulties is pinpointed in the words of Piaget: "The heart-breaking difficulty in pedagogy, as indeed in medicine and in many other branches of knowledge that partake at the same time of art and science, is in fact, that the best methods are also the most difficult ones." I would argue that this is precisely the challenge that those engaged in developing technological innovation for education ought to embrace as their own. Just as the complexities of technology cannot balance out inadequate educational philosophy, thoughtful philosophy cannot survive without a methodology attuned to the complexities of human nature. This is the primary standard against which technological innovation in education, present or future, ought to be judged.

The work on Project Solo was supported in part by NSF grant GJ-1077. A study of similar work was supported in part by NSF grant GJ-33221.

References

BEGLE, E. (1973). Some lessons learned by SMSG. *The Mathematics Teacher*, **66**, 207.

BELLMAN, R. (1961). *Adaptive Control Processes*. Princeton: Princeton University Press.

Choosing to Learn (1971). A film distributed by Educational Development Center, Newton, MA (02160).

CRITCHFIELD, M., DWYER, T., FENNELL, J. & TAULBEE, O. (1973). Final report: *A Case Study of Courseware for Student-controlled Computing*. National Science Foundation.

DEWEY, J. (1938). *Experience and Education*. New York: Macmillan Co.

DWYER, T. (1971). Some principles for the human use of computers in education. *Internatl. J. Man–Machine Studies*, **3**, 219.

*Progress reports in the form of a newsletter are available by writing to the author.

DWYER, T. (1970). Project Solo: a statement of position regarding CAI and creativity. *Interface*, **4**, 13.
DWYER, T. (1972). Teacher/student authored CAI using the NEWBASIC system. *Comm. ACM*, **15**, 21.
HINST, K. (1971). Educational technology—its scope and impact. *Educational Technology*, **11**, (7), 39.
KEMENY, J, (1972). *Man and the Computer*. New York: Charles Scribner's Sons.
LUEHRMANN, A. (1972). Should the computer teach the student, or *vice versa*? *AFIPS Conference Proceedings*, **40**, 40.
MASLOW, A. H. (1970). What is a taoistic teacher? In *Facts and Feelings in the Classroom*. Ed. R. J. Rubin, 1973. New York: Walker & Co.
Midnight to Midnight (1973). A multi-media report prepared by Project Solo, Pittsburgh, PA (15260).
MINSKY, M. (1970). Form and Computer Science. *Comm. ACM*, **17**, 197.
My Computer Understands Me (1972). A film produced by Project Solo, and distributed by the Film Library, Digital Equipment Corporation, Maynard, MA (01754).
NEWELL, A. & SIMON, H. (1961). GPS, a program that simulates human thought. *Lernende Automaten*, Munich: R. Oldenbourg KG (Reprinted in *Computers* and *Thought*, New York: McGraw-Hill, 1963).
PAPERT, S. (1971). Teaching children to be mathematicians vs. teaching about mathematics. *MIT Artificial Intelligence Memo 249.*
PIAGET, J. (1970). *Science of Education and the Psychology of the Child.* New York: Orion Press.
ROGERS, C. (1969). *Freedom to Learn.* Columbus: Merrill Publishing Co.

Appendix A

A problem that sometimes confronts an educational system based on student-controlled technology is the request to "prove" its worth through evaluation based on standardized tests. Using such evaluation can be a misleading exercise, since standardized tests (and the test-makers who devise them) favor the outcomes of dual mode instruction; both questions and answers are influenced by the models of the test-makers. Papert suggests that using such tests to evaluate an innovative instructional system concerned with eliciting new models, is like evaluating the potential of a precision electric motor by measuring its ability to drive a cart meant to be drawn by horses.

There are several kinds of useful evaluation that can be applied to education based on a dual/solo model. One is based on an analysis of new student output and the structure of the models that the student built to produce such output. Such evaluation is very impressive when done well; some work along these lines is currently in progress as part of the Soloworks project.

Another kind of valid evaluation is based on the argument that it is more important to fill in glaring gaps in a system, than to effect small percentage gains in areas that have already accomplished the goals for which they were designed. An illustration of one such gap is given by Begle (1973) in an article that discusses the experience of the SMSG "new" math program:

> . . . student attitudes towards mathematics seem to be rather favorable at the beginning of fourth grade and improve slightly during the remainder of elementary school. However, at the beginning of junior high school, student attitudes towards mathematics begin a slow but steady drop that continues to the end of high school. These attitude changes seem not to be affected by the nature of the curriculum to which the student has been exposed.

The ability of student-controlled computing to fill this kind of gap appears to be one of its strong points. The following excerpts from some interviews* with administrators, teachers, and students who have used student-controlled computing for a few years will give some insight into the nature of this phenomenon.

> "In a computer math course you have the freedom to allow students to become very expert, which a lot of students want to do, while in a regular course you don't have that freedom." (Teacher)

> " . . . it's exciting to use computing in other classes. That portion of the class becomes quite exciting." (Teacher)

> " . . . Every time I wrote a program I always wondered what I could add to make it better; the only thing wrong with that approach is I would still be working on my first program." (Student)

> "I came running out [after seeing my plotter program work]. I found [I had discovered] a very important principle in calculus." (Student)

> "It's really amazing how [students] will go ahead on their own; they go beyond my scope. My best students are much better than I am." (Teacher)

> "I am completely bewildered at times by our big computer. . . . I haven't learned it all. But I have students who are very interested and I have *them* present that part of the program. . . ." (Teacher)

> "I have absolute confidence that, in the sphere of high school math, these kids can write algorithms in whatever areas you wish." (Teacher)

> "We hope that next semester we'll be able to expand. Right now we're operating in what may be termed a converted broom closet. We need more space, . . . we're trying to get it, and I think we will." (Principal)

> "They found that . . . students seemed to not only learn the subject taught, but were using the generalizations produced with the computers to enhance their skills in related subjects." (Teacher)

*Conducted at George Washington High School in Denver, and Fox Chapel High School in Pittsburgh.

"Finally, when we finished the survey, the job of analyzing the [social studies] data was given to another group of people, of which I happened to be a part. We decided that the only obvious solution would be to use the computer." (Student)

"My private study project is . . . travel in space involving relative time conversion using the Lorentz transformation equations developed by Einstein . . . I have taken all the physics courses offered at G.W. . . . the way I increased my knowledge in physics was through the computer math course." (Student)

"They've written programs for the language classes. . . . And then they've written programs for refresher arithmetic." (Teacher)

"They also solve problems for other teachers . . . a girl modelled the political growth of a city." (Teacher)

"[Steve] has been writing practice programs for basic math students . . . games with the computer so that they have to add and subtract and give the right answer." (Teacher)

"I see a teacher in there for whom we just can't get enough money and terminals and computer time. . . . In my case I've found all I have to do is get out of the way and let her [the teacher] run." (Administrator)

"We immediately rushed down to the principal's office and showed [the project] to him. He was very interested in it, and he encouraged us to [go ahead]." (Student)

"We couldn't be more excited about the program. . . . We've had very, very favorable community reaction and continue to have." (Principal)

"It was challenging [to introduce computing], but I always liked a challenge . . . I'm more enthusiastic about this than about any other area I have ever taught. . . ." (Teacher)

"I see young people in there till five o'clock in the evening . . . not only do they understand the computers but they seem to understand the why of the mathematics behind it. . . ." (Administrator),

" . . . . This is the hard part in senior high school, trying to get the kids the least bit interested in learning math . . . I heard one little girl who was really animated about describing what had happened . . . she was talking . . . in a quite sophisticated way, yet she never had a history of achievement in mathematics before." (Administrator)

"They go out and try [new things]—we have several projects going on right now . . . such as modelling where they actually construct mathematical models." (Teacher)

"We've even had trouble because they were staying after school was closed. . . . They would hide . . . until everybody disappeared and then they would come here [computer room]. . . . They found them at 8.00 at night sometimes. . . . They want to be on these machines from midnight to midnight. We have to throw them out at night. It's really fantastic." (Teacher)

" . . . I became so engrossed in computer programming that I would work on programs at night by flashlight or wake up at 5.30 to get to the computer lab when it opened. I would work all weekend on various programs to do my homework, or to solve problems in chemistry, math, and even carpentry. After a while I realized that there is more to life than computers and I slowed down a bit." (Student)