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Computers are classically viewed as amplifiers of cognition. An alternative conceptualization is offered of computer as reorganizer of mental functioning. Software analyses illuminate the advantages of the latter approach for new visions of the potential cognitive benefits of computers. A new result emerges: Because the cognitive technologies we invent serve as instruments of cultural redefinition (shaping who we are by changing, not just amplifying, what we do), defining educational values becomes a foreground issue. The demands of an information society make an explicit emphasis on general cognitive skills a priority. The urgency of updating education's goals and methods recommends an activist research paradigm: to simultaneously create and study changes in processes and outcomes of human learning with new cognitive and educational tools.

The computer, that symbolic workhorse and supreme number-cruncher, has lately become a central topic of thought and discussion for educators and psychologists. Brought by the advent of inexpensive and relatively powerful software for personal computers, now within the budgetary considerations of most if not all school systems, the uses of computers have raised many seminal questions about the future of education and for the research community in psychology and education. What exactly does this technology offer the processes of education? What is unique about its workings as a tool for the intellect? How does or should its uses in society influence what is done in schools with computers? How can our research inquiries contribute to the understanding and effective design of these major changes to the face of education? How might information technologies redefine the very possibilities of education?

In this paper, I analyze some of these issues, shaped by what has been learned and the emerging issues after 5 years of research at the Center for Children and Technology at Bank Street College in New York and related studies elsewhere. Among our research projects have been studies of the development of problem solving and planning skills in Logo programming (Kurland & Pea, 1985; Pea & Kurland, 1984; Pea, Kurland, & Hawkins, 1985), of the cognitive demands and consequences of learning programming (Clement, 1984; Kurland, 1984; Kurland, Clement, Mawby, & Pea, in press; Mawby, in press), of classroom uses of tool software such as data-base management systems and word processors (Freeman, Hawkins, & Char, 1984), of how teachers' interpretive frameworks for software are linked to how they reorganize classroom learning with new technologies (Hawkins, 1985; Hawkins & Sheingold, in press; Sheingold, Hawkins, & Char, 1984), and formative research for the cre-

Parts of this paper were presented at the annual meetings of the American Educational Research Association, Division C, Invited Symposium on "Computers as Tools of the Intellect: Lessons from the Past and an Agenda for the Future," April 1985, Chicago, IL. My colleagues at the Center for Children and Technology have contributed immeasurably to these arguments. Kurt VanLehn and Jim Kaput helped reveal to me the drastic changes in mathematical thinking and education arising with problem-solving software. Seth Chaiklin helped in thinking about the moral issues (and with editing). I also thank Jerome Bruner, Richard Shavelson, and Noreen Webb for their valuable suggestions. I would like to express appreciation to the Spencer Foundation, the National Institute of Education, the Alfred P. Sloan Foundation, Carnegie Corporation, Xerox Corporation, and IBM University Relations for their generous support of our research at the center and for providing opportunities to examine these issues throughout our research projects. The opinions expressed here do not necessarily reflect the policies of any of these institutions or individuals.

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ation of a multimedia instructional package (software, television, print) of an open-ended nature for student learning in mathematics, science, and technology (Char, Hawkins, Wootten, Sheingold, & Roberts, 1983).

This paper highlights the potential yield in thinking of roles for educational computing differently than we typically do. Computers are commonly believed to change how effectively we do traditional tasks, amplifying or extending our capabilities, with the assumption that these tasks stay fundamentally the same. The central point I wish to make is quite different, namely, that a primary role for computers is changing the tasks we do by reorganizing our mental functioning, not only by amplifying it. Therefore, although the predominant use of computers in education today is with software that aims to make more efficient long-familiar drill and practice activities in basic skills, especially in math and language arts, I plan to focus on more recently emerging trends and on future directions in using software as tools for supporting and reorganizing children's thinking.

This paper has four parts. The first sketches these two different conceptualizations of the transformational roles of noncomputer cognitive technologies (e.g., written language) in human intelligence and cognitive change, as amplifier and reorganizer of mind. From these conceptualizations, one is likely to draw different implications for how computer technologies may contribute to human thinking and to the processes of education. The second part analyzes several examples of software as cognitive technologies, and the findings illuminate the advantages of the reorganizer approach for conceptualizing potential benefits of computers in human thinking. The third major section traces deeper consequences of the reorganizer approach for educational uses of computer-based cognitive technologies. In particular, because the cognitive technologies we invent can serve as instruments of cultural redefinition (shaping who we are by changing what we do), selecting values for educational goals becomes a crucial issue. I argue that cognitive demands wrought by the information society make a curriculum explicitly emphasizing general cognitive skills an important priority. In the fourth part, I suggest that the urgency of updating educational aims and methods recommends an activist research paradigm for simultaneously creating and studying changes in processes and outcomes of human learning with new cognitive and educational technologies.

Historical Perspectives on Cognitive Technologies

Long before computers appeared, there were remarkable extensions of human intelligence through the use of technical instruments. I take as axiomatic that intelligence is not a quality of the mind alone, but a product of the relation between mental structures and the tools of the intellect provided by the culture (Bruner, 1966; Cole & Griffin, 1980; Luria, 1976, 1979; Olson, 1976, 1985; Olson & Bruner, 1974; Vygotsky, 1962, 1978). I call these tools *cognitive technologies*. A cognitive technology is provided by any medium that helps transcend the limitations of the mind, such as memory, in activities of thinking, learning, and problem solving. The technologies that have received perhaps the most attention in this respect are written language (Goody, 1977; Greenfield, 1972; Olson, 1977; Ong, 1982; Scribner & Cole, 1981) and systems of mathematical notation, such as algebra or calculus (Cassirer, 1910, 1957; Kline, 1972).

But consider computers as cognitive technologies. Computers are universal machines for storing and dynamically manipulating symbols, which appear to serve as the currency of human thought (Greeno & Simon, in press). Capable of real-time programmable interactions with human users, computers may provide the most extraordinary cognitive technologies thus devised. How can past research on noncomputer-based cognitive technologies guide our definition of priorities for future research with computers as cognitive technologies in education?

Cognitive technologies, such as written languages, are commonly thought of as "cultural amplifiers" of the intellect, to use Jerome Bruner's (1966, p. xii) influential phrase. They are viewed as cultural means for empowering human cognitive capacities. Greenfield and Bruner (1969) observed that cultures with technologies such as written language will "push cognitive growth better, earlier, and longer than others" (p. 654). We find similar upbeat predictions for computer technologies embodied in a widespread belief that they will inevitably and profoundly amplify human mental powers (Pea & Kurland, 1984).

This amplifier metaphor for cognitive technologies has led to many research programs, particularly on the cognitive consequences of literacy and schooling (e.g., on formal logical reasoning) in the several decades since Bruner and his colleagues published *Studies in Cognitive*

Growth (e.g., Greenfield, 1972; Olson, 1976; Scribner & Cole, 1981). The amplifier metaphor continues in contemporary work on electronic technologies by John Seeley Brown of Xerox PARC, who in a recent paper describes his prototype software systems for writing and doing mathematics as idea amplifiers (J. S. Brown, 1984a). For example, *AlgebraLand*, created by Brown and colleagues (J. S. Brown, 1984b), is a software program in which students are freed from hand calculations associated with executing different algebraic operations and focus on high level problem-solving strategies, which they select for the computer to perform. *Algebraland* is said to enable students "to explore the problem space faster," as they learn equation-solving skills. Although quantitative metrics such as the efficiency and speed of learning may truly describe changes that occur in problem solving with electronic tools, it can be shown that more profound changes—as I later describe for the *AlgebraLand* example (after some historical background)—may be missed if we confine ourselves to the amplification perspective. As Bruner has acknowledged (personal communication, November 10, 1985) cognitive tools can yield orders of magnitude and thereby qualitative changes in forms of thought.

There is a different tradition in the study of cognitive technologies that may be characterized as cultural-historical. Influenced by the writings of Vico, Spinoza, and Hegel, Marx and Engels developed a theory of society now described as historical or dialectical materialism. Human nature, on this view, rather than being a product of environmental forces, is of our own making and continually "becoming." Humankind is reshaped through a dialectic of reciprocal influences: Our productive activities change the world, thereby changing the ways in which the world can change us. By shaping nature and how our interactions with it are mediated, we change ourselves. As the biologist Stephen Jay Gould observes (1980b), such "cultural evolution," in contrast to Darwinian biological evolution, is defined by transmission of skills, knowledge, and behavior through learning across generations and has been our nature-transcendent innovation as a species.

On this cultural-historical perspective, labor is seen as the factor mediating humans and nature. By creating and using physical instruments (e.g., machinery) that mediate in less and less direct ways our interactions with nature, we come to reshape human nature. Note how a change in the instruments of work (e.g., a plow rather than the hand) changes the functional organization, or system characteristics, of humans' relation to work: What humans do as their tasks differs, not only do they accomplish the work faster.

In efforts to integrate accounts of individual and cultural changes, the Soviet theorists Vygotsky (e.g, 1962, 1978) and Luria (1976, 1979) generalized the historical materialism that Marx and Engels developed for physical instruments and applied it to a historical analysis of symbolic tools such as written language that serve as instruments for redefining culture and human nature. What Vygotsky (1978) recognized was that "the sign acts as an instrument of psychological activity in a manner analogous to the role of a tool in labor" (p. 52). A similar instrumental and dialectical perspective is reflected by recent studies of the "child as a cultural invention" (Kessel & Siegel, 1983; Kessen, 1979; White, 1983). Take for instance, Wartofsky's (1983) statement of the shift in perspective:

> Children are, or become, what they are taken to be by others, and what they come to take themselves to be, in the course of their social communication and interactions with others. In this sense, I take "child" to be a social and historical kind, rather than a natural kind, and therefore also a constructed kind rather than one given, so to speak, by nature in some fixed or essential form. (p. 190)

Using a Vygotskian perspective, which stresses the functional reorganization of cognition with the use of symbolic technologies, Cole and Griffin (1980) argued that the amplifier metaphor has important shortcomings. (Later, I further illustrate such shortcomings, as revealed by uses of computers as electronic spreadsheets and problem-solving aids in mathematics.) Specifically, they discussed how symbolic technologies qualitatively change the structure of the functional system for such mental activities as problem solving or memory. These fundamental changes are likely to go unnoticed if one thinks only with the amplifier metaphor. Cole and Griffin highlighted, in particular, how Luria enriched the term "function" for psychology. We are often inclined to assume one-to-one correspondences between functions and structures (e.g., planning is the function of the frontal cortex). In contrast, Luria speaks of the function of respiration, not as the function of particular tissue, but as an entire functional system consisting of many components, such as the motor, sensory, and autonomic nervous systems. Cole and Griffin (1980) noted that for Luria, "functional systems are distinguished not only by the complexity of their structure, but also by the flexibility of the roles played by constituents" (pp. 347–348).

Cole and Griffin illustrated how Vygotsky, in similar fashion, saw shifts in functional systems for thinking as the sine qua non of developmental change:

> I have attempted to demonstrate that the course of child development is characterized by a radical alteration in the very structure of behavior; at each new stage the child changes not only her response but carries out the response in new ways, drawing on new instruments of behavior and replacing one psychological function by another. (Vygotsky, 1978, pp. 72–73)

By contrast, Cole and Griffin (1980) note how use of the term "amplify" means to make more powerful, and to amplify in the scientific sense "refers rather specifically to the intensification of a signal (acoustic, electronic), *which does not undergo change in its basic structure*" (p. 349). As such, "amplify" leads one to unidimensional, quantitative theorizing about the effects of cognitive technologies. As evidence of such tendencies, Cole and Griffin discuss how a pencil can be thought of as amplifying the power of a sixth grader's memory for a long list of words when only the outcome of the list length is considered. But it would be distortive, they suggest, to go on to say that the mental process of remembering that led to the outcome was amplified by the pencil because "remembering" in the two cases refers to two qualitatively different activities. The pencil did not amplify a fixed mental capacity called memory; it restructured the functional system for remembering, and thereby led to a more powerful outcome (at least for the purpose of remembering more items).

Olson (1976) makes similar arguments, following Ong (1971) and Havelock (1973, 1978), about restructurings of thinking processes created through written language. For example, logical analysis of arguments for consistency/contradiction becomes possible because memory limitations for oral language are mitigated, and print (rather than oral narrative) provides a means to store and communicate cultural knowledge. It is important to note that the specific restructurings of cognitive technologies are rarely predictable; they have emergent properties that come to be discovered only through their use. In this sense, as Dilthey (1976) urged, human history, like evolution (Gould, 1980a), is a postdictive discipline rather than a predictive discipline.

Software as Cognitive Technology and the Reorganization Metaphor

Let us now turn to the advent of programmable electronic symbolic technologies and see whether the concerns about the amplification metaphor raised by a cultural-historical perspective have heuristic value for our present purposes. Does the reorganization metaphor serve well in its place? Specifically, how might computer-based cognitive technologies such as software fundamentally restructure the functional system for thinking?

A cultural-historical analysis of computer software qua thinking tool is illuminating. I discuss three cases in detail and mention several others in which software has qualitatively changed both the content and flow of the cognitive processes engaged in human problem solving. In particular, the what and the when of the constituent mental operations that a person contributes to the computer-aided problem-solving efforts have undergone substantial change.

Example 1: Electronic Spreadsheets

An illustration of computer technologies that can reorganize, and not merely amplify, mental functioning is the electronic spreadsheet, such as *Visicalc* and *Lotus 1-2-3* (e.g., Levy, 1984). Several million copies have been sold since they appeared in late 1979. Electronic spreadsheets are software programs for microcomputers. The screen images physically resemble paper ledger sheets, with cells organized in rows and columns. But the resemblances end there. In an electronic spreadsheet, one can place a number, a calculation, or a formula in the formula area of any spreadsheet cell, which can subsequently be edited, copied, or moved. The results of calculations in the formula area appear as the content of the cell. The most dramatic difference from static paper spreadsheets is that one can change cell entries and see the repercussions of that change recalculated immediately throughout the spreadsheet. Many lines of thought can be simultaneously activated in the form of dynamic "living" plans, and their outcomes compared in terms of crucial variables. This what-if property has dramatic consequences for the cognitive activity of budgeting (and financial modeling), in ways to be described.

Before 1979, ledger sheets representing financial quantities, formulas relating these quantities, and their change over time were either recalculated by hand after every change or modeled with main-frame programs under the control of data-processing departments. Executives doing the financial planning were not involved in these operations. Microcomputer budgeting has become a highly creative means for generating and testing various scenarios in complex financial situations for what could be, given different hypothetical assumptions. The effort required to formulate such scenarios in the past and to update them regularly made such exploration unfeasible, except (in limited fashion) by main frames under control of data-processing departments, not the executive.

In terms of the reorganization metaphor, the tool has restructured the mental work of budgeting. The what has changed: The predominant constituent mental operations for the financial planner are now planning and hypothesis testing by means of interactive development and testing of different models for budgets. The when, or the temporal sequencing, of mental operations in the functional system for budgetary thinking has also changed: Now the planner can opportunistically and flexibly test hypotheses in the model virtually wherever and whenever he or she wants. For example, any hypothesis on relationships between cells can be tested by modifying formulas and observing the recalculated results.

Beyond the quantitative amplification of efficiency—some estimate time-saving ratios of 80:1—business planners now run vast numbers of complex experiments in this cognitive playground for playing hypothesis-comparison games, including many more variables than before. They also have a better understanding of the interdependencies of their component operations than before this tool was available.

This tool has also qualitatively changed the organization of budgetary justification and argumentation. Electronic spreadsheets are now commonly used, unlike anything before, to quantitatively justify business decisions in group discussions by on-line comparisons with alternatives, and the dynamic what-if capacities of such systems make it possible to display immediately the consequences of different approaches to a problem that may be suggested during the meeting.

Finally, at the company level, the microcomputer electronic spreadsheet has decentralized financial planning. Everyone is doing it. The number of mediating links between planning and testing financial models has been reduced rather than increased by the computer technology, and executives report feeling more in control of their futures.

Example 2: Software for Problem Solving in Mathematics

Similarly, mathematics educators have begun to argue that the use of symbolic manipulation programs such as muMath, MacSyma, and TK!Solver for doing algebra leads to a profound shift in the functions and structure of mathematical thinking from mechanical operations to problem-solving operations (Conference Board of the Mathematical Sciences, 1983; Fey, 1984; Maurer, 1984a, 1984b; National Science Board, 1983). For example, the microcomputer program muMath can easily do complex equation solving, including solution of numerical and literal equations, factoring of polynomial expressions, evaluation of definite and indefinite integrals, differentiation of elementary functions, solution of equation systems, and simplification of equations, even those with radicals (Kunkle & Burch, 1984; Wilf, 1982). What implications does "the disk with a college education" have for how students think mathematically?

To take one example, a student using muMath spends time primarily in algorithm design and search (solution-path-finding) of appropriate operators rather than acting as a mechanic for calculating numerical expressions. The central role of search in using computer-based mathematics problem-solving software may become clearer in *AlgebraLand*.

Consider linear equation solving. Search is not a central concept in algebra instruction today, but a central insight of cognitive science is that learning problem-solving skills in math fundamentally involves search, that is, knowledge about when to select what subgoals, in what sequence. In most classroom instruction in algebra equation solving, the teacher selects the operator to be applied to an equation (e.g., add to both sides), and the student carries out the arithmetic. The pedagogical flaw in this method is that students do not know when to select the various subgoals (Simon, 1980) when solving equations alone, even if they know how to execute subgoals (e.g., to do the arithmetic once the divide operation has been selected).

Originally created several years ago at Xerox PARC by J. S. Brown, K. Roach, and K. VanLehn, and currently being revised by C. Foss for work with middle-school students, *AlgebraLand* is an experimental system for helping students learn algebra from doing problems (J. S. Brown, 1984b). A picture illustrating some of the features of the system to be discussed is displayed in Figure 1.

The task for the student in this figure is to solve the equation for N (shown in the Solve for N window on the figure's right side). Algebraic operators listed in the Basic Operations window on the bottom right side (e.g., Combine-Terms, Add to Both Sides, Distribute) can be selected to apply to the whole equation or to one of its subexpressions. After selecting the operation and where to apply it, the student can execute it. This creates a second algebra expression.

The Record Window (upper right) shows the steps taken to a solution. Its left column lists all the intermediate expressions; its right column shows each operation used to transform an expression. The Search Space Window records all the solution steps the student explored. This space is represented graphically as a search tree that displays solution paths with all the backtracking points and problem-solving moves made while trying to solve the equation. In this case, the student took three different approaches to solving this equation, reflected in the three branches from the original equation. Each intermediate expression that resulted from applying the Do Arithmetic operator appears in boldface for perceptual clarity. *AlgebraLand* performs all the tactical, algebraic operations and arithmetic calculations. Students only select the operator and its scope of application, effectively eliminating errors in arithmetic or application of operators, and leaving them free for the real mental work of search and operator evaluation.

Operators are also provided for exploring solution paths. There is an UNDO operator that returns the equation to its immediately preceding state and a GOTO operator (not on the menu) that returns to any previous state. Stu-

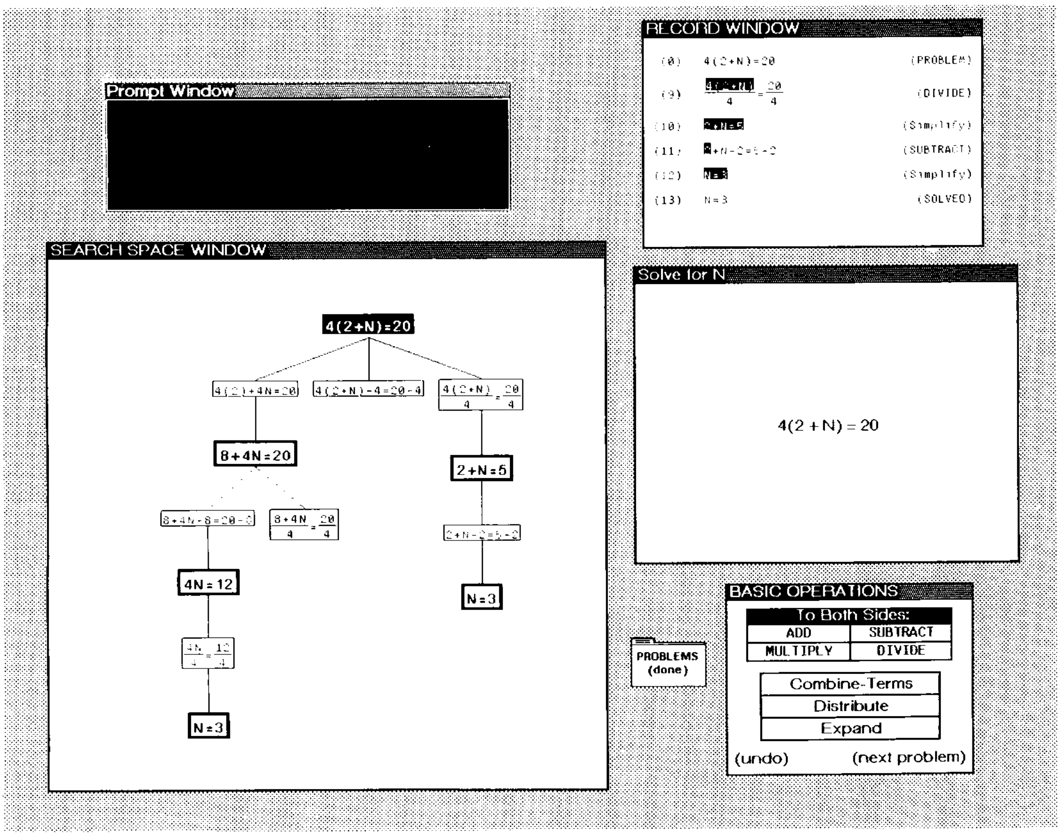

Figure 1. The AlgebraLand screen.

dents can also back up a solution path by applying the inverse of a forward operator (e.g., selecting Divide after they have just applied Multiply).

Because the windows show every operator used and every state the equation was transformed into, students have valuable opportunities to learn from specific tracks of their problem solving, and they play with possibilities. They can explore the search paths of their solution space, examine branch points on one stem where an operation was used that led down an unsuccessful path, and on another stem, try an operation started down a path toward solution. Then they can study features of the equation at the branch point which may have originally recommended the optimal operation to be used. Guided by this hypothesis for what worked, they can test it out in future equation solving. These learning activities are not possible with traditional methods for learning to solve equations. The cognitive technology offered by *AlgebraLand* affords new opportunities for different forms and types of learning through problem solving that were not available in static, noncomputer-based symbolic technologies for solving equations.

In summary, the computer environment *AlgebraLand* emphasizes a procedure diametrically opposed to the traditional instructional method described. With *AlgebraLand*, the student chooses when to apply operators, and the computer carries out the mechanical procedures to transform the equation. Students are thus challenged by the problem of search for and discovery of a path of operations that will lead from the problem state to the goal of solving for the unknown. Note how without the graphic availability of the search map, the problem-solving process would be ephemeral, especially when a student's cognitive processes are regularly diverted to applications to operators.

Learning effective search skills in algebra equation solving is not a trivial task. The cognitive technology of *AlgebraLand* reorganizes the learning in a way that appears to highlight more fundamental skills to be learned—the functional system of mathematical thinking for the equation-solving task. Similar reorientations are evident in recent artificial intelligence tutors in the programming language LISP (Anderson & Reiser, 1985) and geometry proofs (Boyle & Anderson, 1984). The required constituent operations are redirected. Calculation of arithmetical operations is eliminated, but students can now analyze and learn from an explicit written history of their problem-solving moves in searching for the path of operators. *AlgebraLand*, with its focus on problem-solving strategies as the crucial human component to equation solving, thus provides students with the opportunity to become familiar with the idea of search, to understand the importance of search in a specific case, and to learn how to improve their search. In systems such as these, the tracks of the process of education can be highlighted and learned from in a dynamic, interactive way never possible through more static instructional media (Bruner, 1960). And with the rich derivational base of possible operations and paths of search, new frontiers of play emerge, which could be supported by gaming options.[1]

The consequences for math education and for what mathematical thought requires that result from these new cognitive technologies are remarkable: Students can and need to learn, among other problem-solving skills, how to search effectively. And although estimation skills are still central, error-free computation of sequences of operations on numbers and formulas is no longer as important a mental activity in mathematical problem solving.

Example 3: Writing With Outliners and Idea Organizers

Two dramatically different kinds of computer-based writing technologies have appeared recently, each designed to better serve the exteriorization and revision of thinking processes that written language allows (cf. Pea & Kurland, in press).

The first type of writing tool is the outlining program, and it provides a rich technology for interactively creating and revising a structured, top-down plan of a written document. Several commercially available examples for microcomputers are *ThinkTank* (Living Videotext) and *Framework* (Ashton-Tate). Their essential property is the capacity they afford the writer of portraying an outline at different levels of detail without revising its contents. With this facility, one can quickly flip (usually in a keystroke or two) between different perspectives on the document, analyze its part-whole relationships,

[1]I am grateful to Jerome Bruner for directing my attention to the new playgrounds of mind we are finding and exploring through the ludic possibilities of interactive media.

and make and test revisions for their goodness of fit accordingly. Users report greater experimentation with alternate organizational schemes and vastly more attention during cycles of revisions to how the details of their text contribute to the purpose of the whole.

Notecards (J. S. Brown, 1984a) is a minicomputer tool created at Xerox PARC with a different orientation: It encourages bottom-up discovery and definition of relationships among ideas that the writer may initially have in mind only haphazardly or which do not yield easily to top-down structuring early in the writing process. Through cycles of shuffling and filing of notecards according to categories one can define, one can progressively discover idea structures during writing, which are based on ideas collected from texts, and their annotation and linking by various relations (e.g., the rhetorical relations of evidence, comment, argument), which can then be reorganized into a map around which text can be generated. VanLehn (1985) has described in vivid detail his experiences with the powers of *Notecards* as a tool or reorganizing the process of rhetorical analysis of a complex text. He describes how, by explicitly tagging the nature of relationships between arguments and evidence with *Notecards*, he found loopholes in the intricacies of his own competitive argumentation for specific assumptions in his highly complex artificial intelligence model of learning to subtract (VanLehn, 1983).

In both cases, structurally distinctive features of the writing technologies provided the possibilities for reorganizing one's writing processes and for trying out different activities during writing. The closing of the temporal gaps between thought and action, between hypothesis and experiment, that these technologies enable and the rapid cycles of propose-test-revise that they thereby allow (much like the bases of spreadsheets and mathematics software) appear to have deep qualitative effects on how problem solving occurs, which are not anticipated or captured by the amplifier metaphor.

Other Examples

Beyond the salient cases I have described, in which human problem-solving activities are reorganized and not just amplified by computer-based cognitive technologies, other noteworthy examples that would admit complementary analysis include: (a) complex planning aided by project management software and "cognitive workbench" planning programs; (b) interactive computer programming, particularly in exploratory programming environments such as InterLisp-D (Sheil & Masinter, 1983); (c) using computer data-bases (including icon-based graphic data-base systems, e.g., Filevision for the Apple Macintosh) and graphing software as tools for exploratory data analysis, for organizing data, and for framing and testing conjectures of patterns among variables in the data (Conference Board of the Mathematical Sciences, 1983; Steen & Albers, 1981; Tufte, 1983; White, 1981); and (d) using simulated *microworlds* to explore principles of Newtonian mechanics (diSessa, 1983) and systems of mathematics (Abelson & diSessa, 1981) in intuitive rather than formal terms.

Further examples, less accessible today to schools because they tend to run on supermicros or minicomputers, but equally dramatic in their cognitive implications for reorganizing mental processes, are: (a) powerful simulation programs, often incorporating highly realistic graphics, for exploring the workings of complex systems, such as electrical systems (SOPHIE; J. S. Brown, Burton, & deKleer, 1982) or physical plants (STEAMER; Hollan, Hutchins, & Weitzman, 1984); and (b) artificial intelligence programs such as expert systems and knowledge-based intelligent tutors. Expert systems (Davis & Lenat, 1981; Feigenbaum & McCorduck, 1983; Hayes-Roth, Waterman, & Lenat, 1984) are programs that emulate reasoning processes of experts in a field, which are today used primarily by adults to support and guide complex problem solving. For example, they dovetail with the decision-making processes of humans in medical diagnosis (Shortliffe, 1976), design of new chemicals, computer-assisted design and manufacturing (e.g., Stefik & deKleer, 1983), industrial scheduling, and automated factories (Mason, Brady, Hollerbach, & Lozano-Perez, 1983). Knowledge-based intelligent tutors (Sleeman & Brown, 1982) build detailed models of student understanding and embody in their interactions a theory of tutoring. Available examples support learning in geometry (Boyle & Anderson, 1984), programming (Anderson & Reiser, 1985), arithmetic (Burton & Brown, 1979), geography (Carbonell, 1970), medical diagnosis (Clancy, 1983), electronic troubleshooting (Brown et al., 1982), and other technical fields, and the field of machine learning now addresses fundamental issues that dovetail the concerns of developmental and instructional psychology (e.g., Mitchell, Utgoff, & Banerji, 1983; VanLehn, 1983). Issues concerning the broader relevance of these types of cognitive technologies for the future of human learning and development are discussed in Pea (1985).

Summary

In all of the cases described, computer technology has come to provide cognitive power tools that improve the process of bringing thought into communicable expressions in such significant ways that, once the tool is understood and used regularly, the user feels wanting if it is not available because it has opened up new possibilities of thought and action without which one comes to feel at a disadvantage. It becomes an indispensable instrument of mentality, and not merely a tool (Minsky, 1983; Simon, 1977). The cognitive power of a technology is defined relative to a user's perspective: What is a power tool today may be mundane tomorrow. It is therefore far more than an enhancement in efficiency of mental operations or an increase in problem-solving skills that software may offer. The quantifiable products of problem solving have indeed been enhanced, as the amplification metaphor would lead us to observe, but the software has also restructured the thinking activities involved in such a major way that computer users come to discover new methods of thinking about their mental tasks and unanticipated ways of using the technologies. Thus, there are emergent properties of computer-aided thought that are unrecognized when one subscribes solely to the amplifier metaphor.

It is also noteworthy that, almost without exception, the paradigm cases of cognitive technologies are ones designed for and used by adults, who we typically suppose to have developed the skills that become reorganized with the tool's support. But what of the children for whom this assumption is not valid? This issue is addressed shortly.

Implications of the Reorganization Metaphor for Cognitive Technologies in Education

How is education responding to these developments? Are its methods and aims keeping pace with these transformations of the students' world? Education has not, by and large, accommodated to these latest cognitive technologies. Instead, it has assimilated the computer to its earlier fact-oriented agenda. For the most part, computers are not being used to extend and redefine the powers of the child's intellect and expressive powers. The prevalence of fact-oriented computer-assisted instruction in schools today is well documented. A major reason for this may be a commitment to the amplifier metaphor. With efficiency and speed in achieving already-defined (and easily measurable) educational objectives as the goal, drill and practice software offering more exercises in less time is a logical choice. Although many educators have begun working to remediate this situation (e.g., Shavelson et al., 1984; Sheingold, Martin, & Endreweit, in press) less effort has been devoted to thinking about the ways in which computers can help serve as cognitive technologies to reorganize both the individual mental life of students (and teachers) and the broader context of the educational environment.

Many schools now offer or have mandated courses in computer literacy—often courses about computers rather than courses about using computers—and in 1984 over a million precollege students in the United States took computer programming, learning primarily the syntax and semantics of a specific programming language. More rarely did they learn the problem-solving and thinking skills that can be exemplified through the symbolic medium of programming (Pea & Kurland, 1984).

What are some alternatives? Before embarking into this question, the terrain on which we travel must be noted. The reorganization perspective, unlike the amplifier perspective, is noncommital with respect to whether the consequences of the reorganization of mental activities are positive or negative, developmental or regressive. Here, as in the study of "child development," as Kaplan (1983) indicates, developmental progress is not to be conflated with the march of history; "development" is a value concept, not a descriptive one. In contrast, the amplifier metaphor seems to carry with it the idea that faster and more efficient is better—the cognitive technology offering a means more adequate to the task at hand. But this begs the question that the reorganization perspective makes problematic: What shape do we want the effects of computers in education to take? For example, television has opened up new global channels of visual communication and tremendous educational potentials; at the same time, some believe that this medium has hampered written language literacy because so much of the children's time is spent listening and watching rather than engaging in literacy activities. And Plato's familiar critique of written language in the *Phaedrus* as a technology that will weaken our memories makes clear the dark side even of writing as a technology. We are always in a situation in which we must consider the positive and negative outcomes of a new technology.

Thus, we must go beyond the recognition that cognitive technologies can reorganize mental functioning to arguments for the specific ways in which they should do so, arguments that are theoretically and empirically grounded in our best guesses and our best psychological analyses about what people will need to know during their lifetimes.

Education, whether formally or informally acquired, is by its very nature a moral activity, in which choices are made to direct the paths of learning to socially valued goals. What should be the aims of learning and development, and how can education support these processes? Which of our current learning objectives—many of them historical remnants of curricula defined in the 19th century—are no longer valuable and which new ones are? There are some aspects of our students' world that demand our attention, and that appear to warrant a novel approach to these issues.

Looking to the Information Society

What we have arrived at is the question of what education is going to be in this information age. Our children now live in an information society increasingly dependent on computer-stored information and knowledge, and on the use of computer tools for transactions with that information to try to understand and manage its complexities. A defining feature of this new society has been the information explosion: Over 500 different computer databases are available, and 3 million new reports are published each year (Kerr, Braithwaite, Metropolis, & Sharp, 1984). Knowledge obsolescence is a central problem in most fields, and America's corporations spent 60 billion dollars last year reeducating their employees. Indeed, the Nobel laureate Herbert Simon has pressed the point that in this information age "knowing" has become redefined as a verb of access rather than possession. To know is no longer to have knowledge in one's own memory, but to be able to effectively search for, find, and use the information one needs for particular purposes.

There are profound consequences of this paradigm shift for what we do in education and for thinking about appropriate roles for computer-based cognitive technologies. Although the current uses of computers in education are leading to documentable reorganizations of mental activities and of the contexts of learning, they are often unproductive ones when measured against the purposes of helping students acquire transferable knowledge that will be useful over the long term. That is why we need an explicit layer of value analysis—which educational goals are most central, with respect to what purposes—to inform the choice and design of cognitive technologies for education.

With our predominantly fact-oriented curricula, we are hardly preparing our children for the lifelong learning the information age requires. Regardless of our media, our aim should no longer be the hopeless task of pouring an ocean of facts through a straw into the child's memory in hopes of the well-bucket coming up full when it is needed. Instead, we can work to help children learn for themselves how to seek out, organize, and use information for different purposes. From this orientation, education is envisioned as a process of enabling independent, critical, and unique thinkers to take initiatives individually and collaboratively to pose and solve problems, and to apply and develop their learning and thinking skills while accomplishing these tasks. This will require assembling a new vision for education in an age of technology that recognizes the causal powers of the individual (Harre, 1984; Harre & Madden, 1975). It appears that knowledge of facts will still be useful, but as usable materials for thinking about events and problems and to help guide actions, not as ends in themselves nor as inert memory entries to be accessed at the time of assessment and then forgotten.

An Explicit Cognitive Skills Emphasis Is Central

For the reasons described, it seems that a productive approach for cognitive technologies in education will begin to: (a) define the cognitive skills children will require to be in control of their own learning and information management and (b) design and create new technologies to help support the attainment and use of these skills. The learning of such skills would thus become an explicit rather than a tacit objective of education.

Among other aims that we see as central in the forms of information literacy called for today are:

1. A new emphasis on cognitive skills of information management (Hawkins, Mawby, & Ghitman, in press), including problem posing/question definition (S. I. Brown & Walter, 1983), flexible strategies for information retrieval, information schematization and inference, textual summarization and intertextual integration.
2. A renewed emphasis on written communication and critical inquiry skills (e.g., evaluation of sources of information and claims to knowledge).
3. Metacognitive and self-regulatory skills (A. L. Brown, 1978) such as planning ahead, comprehension monitoring (Wagoner, 1983), cognitive resource management or control (Schoenfeld, 1985b), and learning how to learn (Dansereau, 1985; Weinstein & Underwood, 1985).
4. Strategies for creative thinking and problem solving (e.g., brainstorming; problem decomposition; and proposing, testing, and debugging approaches to a problem) and systematic decision-making methods (e.g., decompositional approaches to comparing utilities of choices, e.g., cost-benefit analysis) that crosscut knowledge domains.
5. Cooperative group problem solving (Slavin et al., 1985) and negotiation skills.

Why are these types of skills important? They are important because they appear to characterize the cognitive performances of expert problem solvers in a great variety of disciplines, as the artificial intelligence literature and cognitive science studies attest (e.g., Barr & Feigenbaum, 1982; Brown, Bransford, Ferrara, & Campione, 1983; Greeno & Simon, in press) and because they are high-yield skills that promise utility throughout the life span, unlike a traditional fact-oriented curriculum (Boyer, 1983). These broad families of skills also crosscut the too often segregated domains of the traditional curriculum, and we would hope that new cognitive technologies developed to support them could be used throughout schooling.

A skills-oriented approach does not mean, however, as some recent thinking skills programs presuppose (e.g., deBono, 1985; Whimbey & Lochhead, 1980), that these skills can be effectively taught (i.e., for subsequent use) devoid of detailed emphases on domain-specific applications. Surely method without content is blind. Schoenfeld's research (1985a) on teaching and student learning of general heuristics such as "draw a diagram" for mathematics problem solving makes this point clearly: One must ask what kind of diagram. Similarly, Soloway (in press) demonstrates the centrality of domain-specific knowledge for learning general problem-solving heuristics for writing Pascal computer programs, such as "break the problem into parts" (Descartes' "divide and conquer" heuristic). He finds that without prior experience in solving problems in that domain one cannot identify the subproblems that it makes sense to break the problem up into! The application of the general heuristic needs to be guided by its prior historical applications in the specific knowledge domain under consideration.

Thus, it appears that general skills can be an instructional emphasis, but that they must be learned through content-driven examples (cf. A. L. Brown, 1985; Glaser, 1984). It seems very likely that effective computational tools can be devised for learning and practicing such skills through problem solving across different content domains.

Software Needed for Promoting Transferable Cognitive Skills

Many forward-looking educators and schools have begun to use the thinking tools used by adults to solve problems in such disciplines as business, history, math, and science—software for graphing, data-base management, word-processing, and spreadsheet software. The difficulties of integrating adult versions of these tools (designed for different users and different purposes) into the curriculum have come to be realized. Versions of these tools specifically designed for children have begun to appear, including the widely used Bank Street Writer (word-processing program; Kurland, in press) and the Quill writing system (Rubin & Bruce, in press).

For example, in school studies conducted by Char and colleagues at our center (Char, Freeman, & Hawkins, 1985; Hawkins, Char, &

Freeman, 1984), it has been found that the powerful information-handling tools provided by data-base management programs require new skills—in problem definition, planning for searches of the data-base fields, and so on—that middle school children have not yet acquired, and which even highly creative teachers who deeply value critical inquiry and information literacy are unsure how to teach. How can technologies for education serve not only as tools for thinking, but as tools for helping thinking skills develop?

There are currently no computer technologies that tutor the development of thinking and metacognitive skills important for lifelong learning and problem solving. Although curricula for the teaching of thinking and problem-solving skills, such as those of Venezuela's Project Intelligence (Herrnstein, Nickerson, de Sanchez, & Swets, 1983), which was developed with the assistance of Harvard University and Bolt, Beranek & Newman, have proliferated in the last 5 years (see reviews in Nickerson, Perkins, & Smith, 1985; Segal, Chipman, & Glaser, 1985), we find no computer-based systems for achieving these aims.

Several projects under way at Bank Street may contribute to visions of what is possible. In one, we are building and testing software tools for helping children learn to engage in critical inquiry and construct a personal perspective about various topics, particularly in science, throughout the curriculum. In a second project, we are building and testing a software environment to encourage the development and use of systematic decision-making skills, including problem definition, analysis of alternatives, evaluating attributes of alternatives, and various heuristics for comparing choices. Paramount in each case is the creation of effective and enjoyable tools for learning through doing, and student understanding of how to proceed that will transcend the specific problem domain under study. Our belief is that if we create useful tools for thinking in these ways, the new visions of education described earlier will at least be possible because they are technically feasible.

What we believe may be required are cognitive technologies for education that embody an explicit knowledge transfer architecture, that emphasizes transfer activities in their very structure. We are exploring this design approach in a current research and development project on cognitive skills. In the design of IDEA (Integrated Decision Envisioning Aid), a specific domain of decision-making—family chore planning—is used to introduce generalizable aspects of systematic decision-making skills (e.g., goal monitoring, constraint planning, defining the space of alternative choices; analysis of attributes of alternatives; plan evaluation and monitoring). Multiple examples of the application of each targeted general decision-making method are provided by the software. In this way, the learner can at any time explore or be guided to learning generally useful aspects of methods they are learning to apply in this specific case. We believe that by combining the functions of a domain-specific problem-solving tool with those of a general thinking skills coach, an effective program for learning complex thinking skills will emerge.

Toward an Activist Research Paradigm in Educational Technologies

What implications may be drawn from these considerations for how we do research in the area of educational technologies? As we consider these issues, it is worthwhile recognizing that we are not meeting an earlier problem, for it has never been possible for education to be so outdated before. We need tools to achieve new aims for information age education that are an order of magnitude more obviously effective than those we use today—the educational equivalent of the automobile, the light bulb, or the television. Each demanded revolutionary changes in existing social, cultural, and economic conditions; each led to virtually universal acceptance and to new, unimagined uses, reshaping human activities in consequence. How can we get there?

As we do our work today, the research cycle that leads from research proposal planning, writing, and funding to research activities, analyses, writeup, review, and publication is roughly 3 to 5 years. Then, of course, the pipeline model for the impact of research on education, with the assumed basic research/applied research dichotomy, includes the extra step of translating the findings of the research into educational practices, a difficult path to travel and one that often is not taken (Husen & Kogan, 1984). My conclusion is that there is not enough time and the problems are too important for us to replicate this research model in our studies of educational technologies. We bet on the irrelevance of our work if we rely on off-the-shelf software and limit ourselves to describing what happens when it is introduced to the classroom.

What more is needed? We need to design and engineer environments for the transferable learning that an information age requires. More specifically, to inform education effectively, theory and practice will need to be unified through the invention of research-informed electronic learning systems that work in educational settings. As Greeno (1985) has recently argued, "important advances in instructional technology and in basic cognitive science will occur as an integrated activity" (p. 2). Research and development activities can be united in the creation of educational software prototypes, which are designed and built by interdisciplinary teams of researchers, educators, and developers, and progressively modified in response to formative testing with students. These prototypes can provide sophisticated learning environments for students and simultaneously serve as research tools for determining how skills and knowledge develop with these new cognitive technologies. I would argue that these technologies can serve as the educational infrastructure linking psychological research to educational practice, which Champagne and Chaiklin (1985) suggest is necessary for cognitive science studies to have significant classroom applicability.

Coda

It may appear strange that I have primarily highlighted the potential positive effects of computers as reorganizers of mental functioning. but in the absence of prototypes guided by positive visions of what could be, it is unlikely that we will ever learn what our education can become. Just as the child needs tools to think with (Papert, 1980) as he or she learns to define and solve problems, so do we as we work to reshape the aims and methods of a computer-enhanced education responsive to the challenges of an information society. We need to create a plurality of concrete prototypes of electronic learning environments to work with, whose effects positive and negative, can be empirically examined, reshaped, reassessed, and debated, rather than the armchair-inspired critiques of computers in education that have tended to overemphasize the future representativeness of current software (Sloan, 1985).

Seventy years ago, John Dewey (1915) criticized an American education that had yet to adapt to the changes wrought by the Industrial Revolution: "the primary waste is [not money or things but] human life, the life of the children while they are at school, and afterward because of inadequate and perverted preparation" (p. 59). Much the same applies today as we try to reshape an education for the information age.

As in Dewey's days, we are in need of fundamental change, guided by research on student learning with emerging cognitive technologies and by communal dialogues about redefining educational aims. Everyone is a stakeholder in this reformative enterprise: Teachers, parents, researchers, industry and business, and policy makers all stand to gain or to lose. Working together to shape the technologies that will reorganize human thinking, we may be able to create a new system of education that respects the creative spirit and flexibility of the human intellect, that builds on and discovers new worlds of cognition, action, and play made possible by the remarkable symbolic powers of computers, and that yields resilient thinkers and actors, ready to meet future worlds more radically different than we can now even begin to imagine.

References

Abelson, H., & diSessa, A. A. (1981). *Turtle geometry: The computer as medium for exploring mathematics.* Cambridge, MA: MIT Press.

Anderson, J. R., & Reiser, B. (1985). The LISP tutor. *Byte, 10,* 159-175.

Barr, A., & Feigenbaum, E. A. (Eds.). (1982). *The handbook of artificial intelligence* (Vol. 2). Los Altos, CA: William Kaufmann.

Boyer, E. L. (1983). *High school: A report on secondary education in America.* New York: Harper & Row.

Boyle, C. F., & Anderson, J. R. (1984, April). *Acquisition and automated instruction of geometry proof skills.* Paper presented at the annual meeting of the American Educational Research Association, New Orleans, LA.

Brown, A. L. (1978). Knowing when, where, and how to remember: A problem of metacognition. In R. Glaser (Ed.), *Advances in instructional psychology* (Vol. 1, pp. 77-165). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Brown, A. L. (1985). Mental orthopedics, the training of cognitive skills: An interview with Alfred Binet. In S. F. Chipman, J. W. Segal, & R. Glaser (Eds.), *Thinking and learning skills: Current research and open questions* (Vol. 2, pp. 319-337). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Brown, A. L., Bransford, J. D., Ferrara, R. A., & Campione, J. C. (1983). Learning, remembering, and understanding. In J. H. Flavell & E. M. Markman (Eds.), *Cognitive development* (Vol. 3, pp. 77-166), of P. H. Mussen (Ed.), *Handbook of child psychology* (4th ed.). New York: Wiley.

Brown, J. S. (1984a). *Idea amplifiers: New kinds of electronic learning environments.* Palo Alto, CA: Xerox Palo Alto Research Center, Intelligent Systems Laboratory.

Brown, J. S. (1984b). Process versus product: A perspective on tools for communal and informal electronic learning. In S. Newman & E. Poor (Eds.), *Report from the learning lab: Education in the electronic age* (pp. 41–57). New York: Educational Broadcasting Corporation, WNET.

Brown, J. S., Burton, R., & deKleer, J. (1982). Pedagogical, natural language, and knowledge engineering techniques in SOPHIE I, II, and III. In D. Sleeman & J. S. Brown (Eds.), *Intelligent tutoring systems* (pp. 230–282). New York: Academic.

Brown, S. I., & Walter, M. I. (1983). *The art of problem posing.* Philadelphia, PA: Franklin Institute Press.

Bruner, J. S. (1960). *The process of education.* Cambridge, MA: Harvard University Press.

Bruner, J. S. (1966). On cognitive growth II. In J. S. Bruner, R. R. Olver, & P. M. Greenfield (Eds.), *Studies in cognitive growth* (pp. 30–67). New York: Wiley.

Burton, R. R., & Brown, J. S. (1979). An investigation of computer coaching for informal learning activities. *International Journal of Man-Machine Studies, 11,* 5–24.

Carbonell, J. R. (1970). AI in CAI: An artificial intelligence approach to computer-aided instruction. *IEEE Transactions on Man-Machine Systems, MMS-11*(4), 190–202.

Cassirer, E. (1910). *Substance and function and Einstein's theory of relativity.* Mineola, NY: Dover.

Cassirer, E. (1957). *The philosophy of symbolic forms. Vol. 3: the phenomenology of knowledge.* New Haven, CT: Yale University Press.

Champagne, A. B., & Chaiklin, S. (1985, April). *Interdisciplinary research in science learning: Great prospects and dim future.* Paper presented at the annual meeting of the American Educational Research Association, Chicago, IL.

Char, C., Freeman, C., & Hawkins, J. (1985, April). *Incorporating database software into the classroom context: An ethnographic study.* Paper presented at the annual meeting of the American Educational Research Association, Chicago, IL.

Char, C., Hawkins, J., Wootten, J., Sheingold, K., & Roberts, T. (1983). *"Voyage of the Mimi": Classroom case studies of software, video, and print materials.* New York: Bank Street College of Education, Center for Children and Technology.

Clancy, W. J. (1983). *GUIDON* (Tech. Rep. No. STAN-CS-83997). Stanford, CA: Stanford University, Department of Computer Science.

Clement, C. (1984, August). *Analogical reasoning and learning computer programming.* Paper presented at the Harvard University Conference on Thinking, Cambridge, MA.

Cole, M., & Griffin, P. (1980). Cultural amplifiers reconsidered. In D. R. Olson (Ed.), *The social foundations of language and thought: Essays in honor of Jerome S. Bruner* (pp. 343–364). New York: Norton.

Conference Board of the Mathematical Sciences. (1983). *The mathematical sciences curriculum K–12: What is still fundamental and what is not.* Washington, DC: Author.

Dansereau, D. F. (1985). Learning strategy research. In J. Segal, S. Chipman, & R. Glaser (Eds.), *Thinking and learning skills: Relating instruction to basic research* (Vol. 1, pp. 209–239). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Davis, R., & Lenat, D. B. (1981). *Knowledge-based systems in artificial intelligence.* New York: McGraw-Hill.

DeBono, E. (1985). The CoRT thinking program. In J. W. Segal, S. F. Chipman, & R. Glaser (Eds.), *Thinking and learning skills: Relating instruction to basic research* (Vol. 1, pp. 363–388). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Dewey, J. (1915). *The school and society* (rev. ed.). Chicago: University of Chicago Press. (Original work published 1900)

Dilthey, W. (1976). The construction of the historical world in the human studies. In H. P. Rickman (Ed. & Trans.), *W. Dilthey, Selected writings* (pp. 168–245). New York: Cambridge University Press.

diSessa, A. A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A. Stevens (Eds.), *Mental models* (pp. 15–33). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Feigenbaum, E. A., & McCorduck, P. (1983). *The fifth generation: Artificial intelligence and Japan's computer challenge to the world.* Reading, MA: Addison-Wesley.

Fey, J. T. (Ed.). (1984). *Computing and mathematics: The impact on secondary school curricula.* College Park, MD: National Council of Teachers of Mathematics.

Freeman, C., Hawkins, J., & Char, C. (1984). *Information management tools for the classroom: Exploring database management systems* (Tech. Rep. No. 28). New York: Bank Street College of Education, Center for Children and Technology.

Glaser, R. (1984). Education and thinking: The role of knowledge. *American Psychologist, 39,* 93–104.

Goody, J. (1977). *The domestication of the savage mind.* New York: Cambridge University Press.

Gould, S. J. (1980a). Senseless signs of history. In S. J. Gould, *The panda's thumb: More reflections in natural history* (pp. 27–34). New York: Norton.

Gould, S. J. (1980b). Shades of Lamarck. In S. J. Gould (Ed.), *The panda's thumb: More reflections in natural history* (pp. 76–84). New York: Norton.

Greenfield, P. (1972). Oral and written language: The consequences for cognitive development in Africa, the United States, and England. *Language and Speech, 15,* 169–178.

Greeno, J. G. (1985, April). *Advancing cognitive science through development of advanced instructional systems.* Paper presented at the annual meeting of the American Educational Research Association, Chicago, IL.

Greeno, J. G., & Simon, H. A. (in press). Problem solving and reasoning. In R. C. Atkinson, R. Herrnstein, G. Lindzey, & R. D. Luce (Eds.), *Stevens' handbook of experimental psychology* (rev. ed.). New York: Wiley.

Harre, R. (1984). *Personal being.* Cambridge, MA: Harvard University Press.

Harre, R., & Madden, E. H. (1975). *Causal powers: A theory of natural necessity.* Oxford, England: Basil Blackwell.

Havelock, E. (1973). *Prologue to Greek literacy.* Cincinnati: University of Oklahoma Press for the University of Cincinnati Press.

Havelock, E. (1978). *The Greek concept of justice.* Cambridge, MA: Harvard University Press.

Hawkins, J. (1985). *The interpretation of Logo in practice* (Tech. Rep. No. 34). New York: Bank Street College of Education, Center for Children and Technology.

Hawkins, J., Char, C., & Freeman, C. (1984). *Software tools in the classroom* (Final Report to the Carnegie Corporation).

Hawkins, J., Mawby, R., & Ghitman, M. (in press). Practices of novices and experts in critical inquiry. In R. D. Pea & K. S. Sheingold (Eds.), *Children and microcomputers: Theory, research, and development from Bank Street's Center for Children and Technology.* Norwood, NJ: Ablex.

Hawkins, J., & Sheingold, K. (in press). The beginning of a story: Computers and the organization of learning in classrooms. In J. Culbertson & L. L. Cunningham (Eds.), *Uses of microcomputers and other technology in edu-*

cation. Chicago: University of Chicago Press.

Hayes-Roth, F., Waterman, D., & Lenat, D. (Eds.). (1984). *Building expert systems.* Reading, MA: Addison-Wesley.

Herrnstein, R. J., Nickerson, R. S., de Sanchez, M., & Swets, J. A. (Eds.). (1983). *Project Intelligence: The development of procedures to enhance thinking skills.* Cambridge, MA: Bolt, Beranek & Newman, Inc.

Hollan, J. D., Hutchins, E., & Weitzman, L. (1984). STEAMER: An interactive inspectable simulation-based training system. *AI Magazine, 5,* 15–27.

Husen, T., & Kogan, M. (Eds.). (1984). *Educational resarch and policy: How do they relate?* Oxford, England: Pergamon.

Kaplan, B. (1983). Genetic dramatism. In S. Wapner & B. Kaplan (Eds.), *Toward a holistic developmental psychology* (pp. 53–74). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Kerr, D. M., Braithwaite, K., Metropolis, N., & Sharp, D. H. (Eds.). (1984). *Science, computers, and the information onslaught.* New York: Academic.

Kessel, F. S., & Siegel, A. W. (Eds.). (1983). *The child and other cultural inventions.* New York: Praeger.

Kessen, W. (1979). The American child and other cultural inventions. *American Psychologist, 34,* 815–820.

Kline, M. (1972). *Mathematical thought from ancient to modern times.* Oxford: Oxford University Press.

Kunkle, D., & Burch, C. I., Jr. (1984). Symbolic computer algebra: The classroom computer takes a quantum leap. *Mathematics Teacher, 77,* 209–214.

Kurland, D. M. (Ed.). (1984). *Symposium: Developmental studies of computer programming skills* (Tech. Rep. No. 29). New York: Bank Street College of Education, Center for Children and Technology.

Kurland, D. M. (in press). Designing a word processor for children: The Bank Street Writer. In R. D. Pea & K. S. Sheingold (Eds.), *Children and microcomputers: Theory, research, and development from Bank Street's Center for Children and Technology.* Norwood, NJ: Ablex.

Kurland, D. M., Clement, C., Mawby, R., & Pea, R. D. (in press). Mapping the cognitive demands of learning to program. In J. Bishop, J. Lochhead, & D. N. Perkins (Eds.), *Thinking.* Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Kurland, D. M., & Pea, R. D. (1985). Children's mental models of recursive Logo programs. *Journal of Educational Computing Research 1,* 235–243.

Langley, P. (1985). Learning to search: From weak methods to domain-specific heuristics. *Cognitive Science, 9,* 217–260.

Levy, S. (1984, November). A spreadsheet way of knowledge. *Harper's,* pp. 68–64.

Luria, A. R. (1976). *Cognitive development: Its cultural and social foundations.* Cambridge, MA: Harvard University Press.

Luria, A. R. (1979). *The making of mind: A personal account of Soviet psychology.* Cambridge, MA: Harvard University Press.

Mason, M. T., Brady, J. M., Hollerbach, T. J., & Lozano-Perez, T. (1983). *Robot motion: Planning and control.* Cambridge, MA: MIT Press.

Maurer, S. B. (1984a). College entrance mathematics in the year 2000. *Mathematics Teacher, 77,* 422–428.

Maurer, S. B. (1984b). The effects of a new college mathematics curriculum on high school mathematics. In A. Ralston & G. S. Young (Eds.), *The future of college mathematics* (pp. 153–175). New York: Springer-Verlag.

Mawby, R. (in press). Proficiency conditions for the development of thinking skills through programming. In J. Bishop, J. Lochhead, & D. N. Perkins (Eds.), *Thinking.* Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Minsky, M. (1983). Why people think computers can't. *Technology Review, 86,* 65–81.

Mitchell, T. M., Utgoff, P. E., & Banerji, R. (1983). Learning by experimentation: Acquiring and refining problem-solving heuristics. In R. S. Michalski, J. G. Carbonell, & T. M. Mitchell (Eds.), *Machine learning: An artificial intelligence approach* (pp. 163–189). Palo Alto, CA: Tioga Press.

National Science Board Commission on Precollege Education in Mathematics, Science, and Technology. (1983). *Educating Americans for the 21st century.* Washington, DC: National Science Foundation.

Nickerson, R. S., Perkins, D. N., & Smith, E. E. (1985). *Teaching thinking.* Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Olson, D. R. (1976). Culture, technology, and intellect. In L. B. Resnick (Ed.), *The nature of intelligence* (pp. 189–202). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Olson, D. R. (1977). From utterance to text: The bias of language in speech and writing. *Harvard Educational Review, 47,* 257–281.

Olson, D. R. (1985). Computers as tools of the intellect. *Educational Researcher, 14,* 5–8.

Olson, D. R., & Bruner, J. S. (1974). Learning through experience and learning through media. In D. R. Olson (Ed.), *Media and symbols: The forms of expression, communication, and education* (pp. 125–150). Chicago: University of Chicago Press.

Ong, W. J. (1971). *Rhetoric, romance, and technology: Studies in the interaction of expression and culture.* Ithaca, NY: Cornell University Press.

Ong, W. J. (1982). *Orality and literacy: The technologizing of the word.* New York: Methuen.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas.* New York: Basic Books.

Pea, R. D. (1985). Integrating human and computer intelligence. In E. L. Klein (Ed.), *New directions for child development. No. 8: Children and computers* (pp. 75–96). San Francisco, CA: Jossey-Bass.

Pea, R. D., & Kurland, D. M. (1984). On the cognitive effects of learning computer programming. *New Ideas in Psychology, 2,* 137–168.

Pea, R. D., & Kurland, D. M. (in press). Cognitive technologies for writing. In E. Rothkopf (Ed.), *Review of research in education* (Vol. 13). Washington, DC: American Educational Research Association.

Pea, R. D., Kurland, D. M., & Hawkins, J. (1985). Logo and the development of thinking skills. In M. Chen & W. Paisley (Eds.), *Children and microcomputers: Formative studies* (pp. 193–212). Beverly Hills, CA: Sage.

Rubin, A. D., & Bruce, B. C. (in press). QUILL: Reading and writing with a microcomputer. In B. A. Hutson (Ed.), *Advances in reading and language research.* Greenwich, CT: JAI Press.

Schoenfeld, A. (1985a). *Mathematical problem solving.* New York: Academic.

Schoenfeld, A. (1985b). Metacognitive and epistemological issues in mathematical understanding. In E. Silver (Ed.), *Teaching and learning mathematical problem solving* (pp. 361–379). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Scribner, S., & Cole, M. (1981). *The psychology of literacy.* Cambridge, MA: Harvard University Press.

Segal, J. W., Chipman, S. F., & Glaser, R. (Eds.). (1985). *Thinking and learning skills: Relating instruction to basic research* (Vol. 1). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Shavelson, R. J., Winkler, J. D., Stasz, C., Feibel, W., Robyn, A. E., & Shaha, S. (1984). *Teaching mathematics and science: Patterns of microcomputer use* (Tech. Rep. No. R-3180-NIE/RC). Santa Monica, CA: Rand Corporation.

Sheil, B. A., & Masinter, L. M. (Eds.). (1983). *Papers on Interlisp-D.* Palo Alto, CA: Xerox Palo Alto Research Center.

Sheingold, K., Hawkins, J., & Char, C. (1984). "I'm the thinkist, you're the typist": The interaction of technology and the social life of classrooms. *Journal of Social Issues, 40,* 49–61.

Sheingold, K., Martin, L. M. W., & Endreweit, M. E. (in press). Preparing urban teachers for the technological future. In R. D. Pea & K. Sheingold (Eds.), *Children and microcomputers: Theory, research, and development from Bank Street's Center for Children and Technology.* Norwood, NJ: Ablex.

Shortliffe, E. H. (1976). *Computer-based clinical therapeutics: MYCIN.* New York: American Elsevier.

Simon, H. A. (1977). What computers mean for man and society. *Science, 195,* 1186–1191.

Simon, H. A. (1980). Problem solving and education. In D. Tuma & F. Reif (Eds.), *Problem solving and education* (pp. 81-96). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Slavin, R., Sharan, S., Kagan, S. Hertz-Lazarowitz, R., Webb, C., & Schmuck, R. (1985). *Learning to cooperate, cooperating to learn.* New York: Plenum.

Sleeman, D., & Brown, J. S. (Eds.). (1982). *Intelligent tutoring systems.* New York: Academic.

Sloan, D. (Ed.). (1985). *The computer in education: A critical perspective.* New York: Teachers College Press, Columbia University.

Soloway, E. (in press). Kids should learn to program. *Harvard Educational Review.*

Steen, L. A., & Albers, D. J. (Eds.). (1981). *Teaching teachers, teaching students.* Boston: Birkhauser.

Stefik, M. J., & de Kleer, J. (1983, April 21). Prospects for expert systems in CAD. *Computer Design,* pp. 65–76.

Tufte, E. R. (1983). *The visual display of quantitative information.* Cheshire, CT: Graphics Press.

VanLehn, K. (1983). *Felicity conditions for human skill acquisition: Validating an AI-based theory* (Tech. Rep. No. CIS-21). Palo Alto, CA: Xerox PARC.

VanLehn, K. (1985). *Theory reformulation caused by an argumentation tool.* Palo Alto, CA: Xerox PARC.

Vygotsky, L. S. (1962). *Thought and language.* Cambridge, MA: MIT Press.

Vygotsky, L. S. (1978). *Mind in society: The development of the higher psychological processes.* Cambridge, MA: Harvard University Press.

Wagoner, S. (1983). Comprehension monitoring: What it is and what we know about it. *Reading Research Quarterly, 18,* 328–346.

Wartofsky, M. (1983). The child's construction of the world and the world's construction of the child: From historical epistemology to historical psychology. In F. S. Kessel & A. W. Sigel (Eds.), *The child and other cultural inventions* (pp. 188–215). New York: Praeger.

Weinstein, C. E., & Underwood, V. L. (1985). Learning strategies: The *how* of learning. In J. Segal, S. Chipman, & R. Glaser (Eds.), *Thinking and learning skills: Relating instruction to basic research* (Vol. 1, pp. 241–258). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Whimbey, A., & Lochhead, J. (1980). *Problem solving and comprehension: A short course in analytical reasoning* (2nd ed.). Philadelphia: Franklin Institute Press.

White, S. (1983). Psychology as a moral science. In F. S. Kessel & A. W. Sigel (Eds.), *The child and other cultural inventions* (pp. 1–25). New York: Praeger.

White, S. (1981). The new liberal arts. In J. D. Koerner (Ed.), *The new liberal arts* (pp. 1-12). New York: Alfred P. Sloan Foundation.

Wilf, H. S. (1982). The disk with the college education. *American Mathematical Monthly, 89,* 4–8.