Integrating Human and Computer Intelligence

Roy D. Pea

This chapter discusses some of the philosophical and empirical implications for developmental psychology of the prospect of human-computer intelligent systems, which can work together to solve problems, learn, and develop.

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The thesis to be explored in this chapter is that advances in compute applications and artificial intelligence have important implications fo the study of development and learning in psychology. I begin b reviewing current approaches to the use of computers as devices fo solving problems, reasoning, and thinking. I then raise questions con cerning the integration of computer-based intelligence with humar intelligence to serve human development and the processes of education

Expert Systems and Intelligent Tutoring Systems

Until recently, written texts have been the principal means fo storing the knowledge needed to solve complex problems. Computer have provided a radically new medium for storing and making use o expert knowledge. Expert systems are programs that embody th knowledge of experts in making judgments in a field. Such system emulate the reasoning and problem-solving abilities of human experts and they are widely used as advisory aids in human decision making They vary greatly in their representations of knowledge, its accessibil ity, its ease of modification, and in the degree to which it attempts t

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teach its user. Today, dozens of such systems serve as powerful conceptual tools for the extension and redefinition of human intellectual efforts in science, medicine, industry, programming, and education. Excellent accounts of existing expert systems and their growing importance are provided in Feigenbaum and McCorduck (1983). Prominent examples include MYCIN (Shortliffe, 1976), a medical expert system; MOLGEN (Friedland, 1979), an expert system used to design experiments in molecular genetics; and DENDRAL (Lindsay and others, 1980), an expert chemistry system used in determining the molecular structure of unknown organic compounds. Expert systems are also used as aids in ill-defined creative tasks, such as the design of integrated circuits (Stefik and de Kleer, 1983).

The heart of the process of transferring expertise to the machine lies in reducing experts' know-how to chunks of knowledge specified, for example, in terms of productions of if-then rules; that is, if specific conditions are present in a situation, then a certain action is taken (Davis and Lenat, 1981; Hayes-Roth and others, 1984). Methods for mining experts' knowledge are related to both the clinical interviewing techniques familiar to developmentalists and the think-aloud protocol methods common to cognitive psychology. The aim is to work with the experts to help them articulate what they know. Then, the domain-specific facts, algorithms, heuristics, general problem-solving strategies, and systematic understanding of a domain (for example, causal laws, probabilities) that the experts have available can be codified in computer programs that mimic the solution of novel real-world problems at an expert level of performance. The system comes to emulate human expertise through recursive iterations that eliminate the differences between experts' judgments and those of the expert system.

The problem of transfer of expertise (Barr and others, 1979) raises a host of developmental concerns: "For an expert system to be truly useful, it should be able to learn what human experts know, so that it can perform as well as they do, understand the points of departure among the views of human experts who disagree, keep its knowledge up to date as human experts do (by reading, asking questions, and learning from experience), and present its reasoning to its human users in much the way that human experts would (justifying, clarifying, explaining, and even tutoring)" (Barr and Feigenbaum, 1982, p. 80). This passage implies that system users and knowledge sources (the "experts") are in relevant respects homogeneous in knowledge. However, the knowledge in an expert system and its power are not immediately accessible to a novice, much less to a child. Most expert systems act as advisers for consultation on specific problems. They can rarely solve problems autonomously. Thus, many techniques need to be learned in order to make effective use of expert systems.

Creating systems that children can use constitutes an important problem for education and developmental psychology. The developmentalist asks the reverse of the knowledge engineer's question: How can the expertise transferred from human adults to computers be transferred back by computer to the child? The adult version (how can novices effectively use and understand the problem-solving activities of an expert system?) is now being addressed in the design of intelligent expert systems. Intelligent expert systems give correct answers or useful advice in problem situations. They also use concepts and reasoning processes that resemble those that the system user might employ. A major problem in engineering such systems has been in creating facilities that can give an explanatory account, in terms that one expects from a human, of the reasoning that underlies the advice offered.

What is the potential for expert systems for human learning and development? Can expert systems eventually offer students better access to knowledge and opportunities for development than either most teachers or spontaneous experience alone can provide? We come closer to answering these questions by considering intelligent tutoring systems—systems that go beyond possessing expert knowledge and attempt to model the student's knowledge and the learning process for acquiring expertise. These intelligent tutoring systems are designed to support students in gaining access to the expert system. For example, SOPHIE (Brown and others, 1982) functions both as an expert system and as a teaching system in prompting the student to form and test hypotheses about an electronic power supply circuit. SOPHIE has two different modes: One poses troubleshooting problems for a single person; the other simulates a gaming situation in which one team sets a fault for another team to diagnose. In the solo mode, the system sets a fault for the student to diagnose in a power supply circuit. The student can measure voltages and currents in different parts of the circuit by asking questions of the system; the aim is to figure out which component is faulty. The system evaluates the student's hypotheses about the fault by analyzing what it has told the student up to that point about the values in different components of the system and by comparing these values with the values that would obtain under the student's hypotheses. This kind of comparison involves very sophisticated circuit simulation and fault propagation techniques. The same capabilities are used to tutor students in the team gaming option. Other systems that attempt to understand the user are DEBUGGY (Burton, 1982) and ACM (Langley and others, 1984), which diagnose students' procedural errors in base-ten subtraction; the WHY system (Stevens and others, 1979), which teaches the geographical aspects of rainfall distribution by initiating a Socratic dialogue; and Boyle and Anderson's (1984) system for teaching proof procedures in high school geometry, which explicitly tutors problem-solving strategies for the construction of geometric proofs. These systems vary in the degree to which their cognitive diagnostics are theoretically and empirically substantiated.

From a developmental perspective, the educational use of expert systems must be concerned with how the novice can be supported in learning from and making use of this form of knowledge storage. Certain types of expert systems have exciting educational potential. The design of such systems must be guided by the need to address students' lack of knowledge about either the expert domain or the methods for operating the systems that use such information storage. An important task remains in creating systems capable of providing interactive environments that succeed in integrating students' intuitive theories of domain knowledge constructed through everyday experience, such as in physics (diSessa, 1983), with formal domain knowledge. Research is needed on how children's use of such systems affects the relation between cognitive development and learning. For example, how does the child novice differ from the adult novice for particular content domains, such as geometry? In the context of this question, such computer-based systems appear to have theoretical import for developmental psychology, in ways now to be addressed.

Changes in Views on Cognitive Development

After describing some characterizations of cognitive development as the construction of an invariantly ordered sequence of universal stages, I will review some recent challenges to these universal descriptions. These considerations will lead to an examination of potential uses of computer expert systems and intelligent tutoring systems for the reconceptualizing of cognitive development and to more drastic reformulations of the agenda for developmental studies.

Constructivism and Stages in Developmental Psychology. In recent decades, developmental psychologists have been preoccupied with the ongoing debate concerning research into stages of cognitive development. Driven by the seminal studies of Piaget (1983), developmental psychologists throughout the world have sought to substantiate and finely delineate the broad universal stages of cognitive development that Piaget proposed.

Piaget defined four broad stages of intellectual or cognitive development: the sensorimotor, the preoperational, the concrete operational, and the formal operational. Although recent formulations (Case, 1985; Fischer, 1980) differ in emphasis, they maintain a roughly comparable picture. Stages are major qualitative breaks in cognitive functioning that, according to Piaget (1973) have four characteristics: First, they are ordered in sequence. Second, they are integrative, in that earlier stages are an integral part of later stages. Third, they are characterized by a "whole structure," which in the case of intelligence means by an underlying system of logical operations. Fourth, in any series of stages, there is a distinction between the process of formation and the final forms of equilibrium; that is, they are progressively constructed without total preformation.

In describing the formation of the stages, Piaget placed central emphasis on constructivism, the perspective that emphasizes the interaction of the endogenous character of the organism and environment in the organism's construction of progressively more advanced stages of knowledge. Piaget (1973, pp. 2–3) emphatically contrasted the "spontaneous" or subject-initiated discovery, learning, and inventing that contribute to the construction of these broad systems of operations with "other" learning, such as the learning that occurs in schools. "I have in mind only the *truly* psychological development of the child as opposed to his school development or to his family development; that is, I will above all stress the spontaneous aspect of this development, though I will limit myself to the purely intellectual and cognitive development. Actually we can distinguish two aspects in the child's intellectual development. On the one hand, we have what may be called the psychosocial aspect, that is, everything the child receives from without and learns in general by family, school, educative transmission. On the other there is the development which can be called spontaneous. For the sake of abbreviation I will call it psychological, the development of the intelligence itself—what the child learns by himself, what none can teach him and he must discover alone; and it is essentially this development which takes time. . . it is precisely this spontaneous development which forms the obvious and necessary condition for the school development." As I will later suggest, symbolic activities with the computer may necessitate a reformulation of the concept of spontaneous learning, since the world of physical objects for child play and action is remarkably expandable through programmable symbols.

Challenges to the Piagetian Enterprise. There have been several areas of research that converge as problematic for Piaget's conceptions of development. I will review three fundamental areas: findings on the role of sociocultural factors in learning and development, on giftedness and prodigies, and on the role of knowledge in computer expert systems.

Piaget has been extensively criticized for underplaying the contribution of sociocultural factors to development (Rogoff and Lave, 1984). Contemporary work has been influenced by the theories of the Soviet psychologist L. S. Vygotsky (Rogoff and Wertsch, 1984; Laboratory of Comparative Human Cognition, 1983), who saw sociocultural factors as having important consequences on higher-level cognitive development. Formal operations are nonuniversal, particularly in cultures without schooling, a finding that was troubling even for Piaget (1972). What Piaget described as spontaneous learning is apparently insufficient to enable humans to think in terms of operations on operations, the definition of formal thought. Educational processes of sociocultural transmission, especially those involving abstract symbolic systems, such as logic, mathematics, and written language, play an essential role in the formation of such thought patterns (Laboratory of Comparative Human Cognition, 1983; Olson and Bruner, 1974).

Research inspired by Vygotsky has great significance for computer-based extensions and redefinitions of human intelligence. Vygotsky's (1978) dynamic conception of the "zone of proximal development" concerns phases in ontogenesis in which a child has partly mastered a skill but can act more effectively with the assistance of a more skilled peer or adult. The zone of proximal development is the region of skill effectiveness that lies between the child's independent functioning and the child's functioning with social support. Intelligence is viewed as a collective activity jointly accomplished between child and more able others before the child can function intelligently on his or her own. In contrast to Piaget, Vygotsky (quoted by Rogoff and Wertsch, 1984, p. 3), argued that "instruction is only good when it proceeds ahead of development. It then awakens and rouses to life those functions which are in a stage of maturing, which lie in the zone of proximal development. It is in this way that instruction plays an extremely important role in development." The central implication is that the problem-solving system formed by child and more competent others—broadened here to include computer systems—is an especially appropriate unit of analysis for studies of the development of problem-solving skills.

Findings on Giftedness and Prodigies. Further evidence against the universalist architecture of Piagetian theory is found in cognitive studies with children identified as gifted or as prodigious in their performances in such domains as mathematics, music, chess, or composition. Research on giftedness and prodigy performances among children (Feldman, 1980; 1982; Gardner, 1983) demonstrates that such individuals are not in an advanced Piagetian stage of development across tasks but that they perform on Piaget-based measures much like their same-age cohorts, even as they outperform most adults in their forte. Prior attainment of the general logical structures defining the Piagetian formal operational period is not, as these exceptional individuals illustrate, necessary for high-level domain-specific intellectual performances.

According to Gardner (1983, p. 27), a pluralistic approach to cognition, which focuses on the domain specificity of intellectual performances rather than on transdomain universal stages, posits that, "irrespective of domains, there should (in proper Piagetian fashion) be a stagelike sequence through which any individual must pass. However, individuals differ greatly from one another in the speed with which they pass through these domains; and, contra Piaget, success at negotiating one domain entails no necessary correlation with speed or success in negotiating other domains. . . . Moreover, progress in a domain does not depend entirely on the solitary individual's actions within his world. Rather, much of the information about the domain is better thought of as contained within the culture itself, for it is the culture that defines the stages and fixes the limits of individual achievement. One must conceive of the individual *and* his culture as embodying a certain stage sequence, with much of the information essential for development inhering in the culture itself rather than simply inside the individual's skull." This perspective on the development of intelligence has provocative implications for marrying the problem-solving capabilities of child and computer. Since there are distinct developmental trajectories for different content domains, rather than a general logical engine on which the development of cognitive skills in specific domains depends, then integrations are in principle possible between childhood thinking and expert or intelligent tutoring computer systems that provide developmental technologies. These integrations would serve as mental catalysts for engineering the development of high-level cognitive skills. The child would not need to await the development of general logical structures in order to become a powerful thinker.

The Role of Knowledge in Expert Systems. Similar arguments are provided by research on artificial intelligence (AI) systems. Cognitive scientists have found that extensive knowledge is necessary for expert-level performance in solving problems in every content area studied. Waldrop (1984, p. 1279) reached the conclusion that "the essence of intelligence seems to be less a matter of reasoning ability than of knowing a lot about the world." This presents a clear problem for the Piagetian approach, in which the underlying logical schemes involved in the reasoning behind a task are considered to be the core of intellectual functioning. The principal mechanisms distinguishing what Piaget described as the stages of intelligence are, for example, defined in terms of the logical operations of reasoning characteristic of that stage. What is the role for knowledge? Here Piaget introduced the convenient abstraction of *decalage* in order to deal with the theoretically inconvenient differences in the average age at which, for example, the concept of conservation is acquired for the different materials of weight, volume, and number (different content domains). The role of specific knowledge is accorded a minor role.

What are we to do, then, with knowledge in an age in which intelligent behavior is being modeled by computers and in which reasoning mechanisms, although necessary, are far less important than the web of propositions and rules that define knowledge and cognitive skill? If the weak end of the machinery of cognitive development lies in building up the appropriately organized store of knowledge structures (Carey, 1984), how then can knowledge be better acquired? How can computers as intelligent tutoring systems and learning machines in their own right help the student to develop such knowledge?

Although in broad outline the interactionist perspective that Piaget offers may be correct, the three groups of studies just reviewed imply a different vision of what constitutes the interaction environment basic to learning and development and of what experiences warrant the description of spontaneous learning through solitary discovery. The culture, as expressed through more knowledgeable others, provides apprenticeship models for the development of cognitive skills and offers advice and hints to help structure the child's discovery space as he or she proceeds through the zones of proximal development. Left to her or his own spontaneous discoveries, the child as intuitive scientist arrives too often at theories of how the physical or mathematical world works that are at odds with appropriate formal theories (A. L. Brown, 1984; Gentner and Stevens, 1983). We find eroding the artificial distinction between what one discovers alone (what Piaget chauvinistically describes as true development) and what one discovers with the aid of others, however indirect that aid may be. Children need not—indeed, in most instances, they will not—reinvent through spontaneous discovery the conceptually adequate theories about the world that science has taken centuries to identify and formulate.

Developmental Theory and Human-Computer Systems

In this section, I will consider some major questions that the possibility of human-computer intelligent systems raises for developmental theory and some of the rich prospects they offer for psychological research and for the promotion of education and development.

Two possibly but not necessarily interconnected roles for the creation of such systems may be distinguished. The first is as research tool for developmental and cognitive psychology; the second is as educational tool. In terms of the first role, by configuring the system in different ways, different explanatory models of learning and development can directly be tested. These models might be concerned with one or another of several issues: assessing whether systems that give the student prompts to promote self-questioning, planning, and monitoring lead to more effective metacognition and learning to learn (J. S. Brown, 1984; Palinscar and Brown, 1984); ascertaining the kinds of prodevelopmental roles of conflict or of confrontation of "bugs" in student understanding in developmental reorganizations of knowledge systems (Siegler, 1983); testing our understanding of the heuristics that expert teachers use to model a student's understanding and providing new learning experiences and environments at the appropriate level (Collins and Stevens, 1982; Sleeman and Brown, 1982); and providing testing grounds for knowledge assessment and cognitive diagnostics and explicit tests of intervention hypotheses in training studies (Boyle and Anderson, 1984). In terms of the second role, for educational purposes, systems can be constructed to be used autonomously by students as tools for learning new fields of knowledge and for acquiring problem-solving and problem-defining skills for specific domains.

In the paragraphs that follow, major challenges to developmental psychology posed by the coupling of human and computer intelligence are roughly ordered from the conservative to the radical in their implications. At the conservative end, they merely carry forward modifications to the Piagetian enterprise; at the radical extreme, they portend the coevolution of human and computer intelligence.

Computers and the Zone of Proximal Development. It is possible that future versions of AI systems could serve as tools for helping children move through the zones of proximal development by extending the "social" environment for cognitive growth by interactively providing hints and support in problem-solving tasks like the ones adults provide. Computers playing this role will be the information age sequel to concepts of a zone of proximal development (ZPD), in which the adult human plays the tutorial role of coconstructing with the child his or her latent developmental capabilities. In this case, the zone of proximal development is traversed with the complementary capabilities of the human-computer system. However, unlike those who have conducted most ZPD studies, I do not assume that self-sufficiency is the telos of such learning activities. Many forms of cognitive activity may require the continuing intervention of an intelligent computer system, for effectiveness or because of their complexity. Similarly, not all cognitive tasks for which ZPDs can be arranged should be ones that the child is expected to internalize for subsequent solo performances. Solo performances are not realistic in terms of the ways in which intelligent activities are organized and accomplished in the real world. They are often collaborative, depend on resources beyond an individual's long-term memory, and require the use of information-handling tools. If we took away from practicing thinkers and practitioners what we take away from children to assess their cognitive functioning, scientists could not do science, mathematicians could not do math, historians could not do history, and policy makers could not make policy. The level of task understanding necessary for the child alone is an empirical question that remains to be answered, domain by domain. For example, in arithmetical understanding, educators now emphasize estimation skills over calculation skills as the use of calculators has become widespread.

In terms of computer-based ZPD tools, there are two major ways of transforming the zone of learning environments in which interactions toward development emerge. First, microworlds, which are fairly conservative in their implications, can be created for the promotion of domain expertise; second, there are cognitive trace systems, which are more radical in their potential powers.

Microworld Pedagogic Systems. Pedagogic systems focus on cognitive self-sufficiency, much like existing educational programs, in contrast to pragmatic systems, which allow for precocious intellectual performances of which the child may be incapable without the system's support. We thus need to distinguish between systems in which the child uses tools provided by the computer system to solve problems that he or she cannot solve alone and systems in which the system establishes that the child understands the problem-solving processes thereby achieved. We can call the first kind of system pragmatic and the second pedagogic. Pragmatic systems may have the peripheral consequence of pedagogical effects, that is, they may contribute to understanding but not necessarily. The aim of pedagogic systems is to facilitate, through interaction, the development of the human intelligent system. While there is a grey area in between, and some systems may serve both functions, clear cases of each can be defined.

Pedagogic systems that use microworld provide rich opportunities for development and learning. A microworld is a structured environment that allows the learner to explore and manipulate a rule-governed universe, subject to specific assumptions and constraints, that serves as an analogical representation of some aspects of the natural world. Microworlds have other properties that cannot be described here (Papert, 1980). Pedagogic systems can use microworlds to further redefine the objects of the spontaneous learning that Piaget considered integral to development when he argued that each time one prematurely teaches a child something he could have discovered for himself, the child is kept from inventing it and consequently understanding it completely (Piaget, 1983). But, discovery by oneself is not well defined, and interactive software can further blur the distinction. Computer objects could be programmed so that the child would be subtly guided to discover them. They could provide discovery situations that conflict with the inferred worldview of the child because they are "smart" with knowledge of the flawed theories that children construct en route to expertise. For such pedagogic systems to work in promoting learning and development, we need research on the prodevelopmental roles of conflict or disequilibrium and a theory of how and when hints toward discovery are successful (Sleeman and Brown, 1982).

Microworld pedagogic systems could provide environments enabling students to learn skills and knowledge in specific domains by observing modeling of the process of solving example problems, by doing, by discovery, and by instruction. An aim can be to replicate the coincidences (Feldman, 1980, 1982) of factors that appear to lead to prodigious cognitive performances. This involves providing suitable models, a learning environment with cognitively appropriate help facilities that embody cultural knowledge and that is sufficiently engaging to command the child's intensive efforts.

Pedagogic Cognitive Trace Systems. Pedagogic systems could also be created that transform what will happen in the learning environment in ways that cannot be anticipated without building prototypes and doing observations. Cognitive trace systems can provide a major lever for cognitive development by providing tools for reflection. The fundamental idea of a cognitive trace system is that the intermediate products of mind are externalized through the process of interacting with knowledge-based computer systems. These traces expand the cognitive workspace to include a trail, as it were, of where one has been in an episode of problem solving. Thus, remembering where one has been does not interfere with ongoing processes of creation or problem solving. Such traces would provide richer sources for assessing the student's knowledge than any teacher only observing student behaviors without the system could ever process and use for effective instruction.

Cognitive trace systems may have dramatic consequences for how human beings develop cognitive skills. These systems are instances of the thinking tools provided by other symbolic media—writing, mathematics, logic, and programming—that render human thought processes external for inspection, analysis, and reflection and that have forever transformed our world of thought and action (Ong, 1982).

Three major functions can be imagined for such traces. First, for the child, an examination of these cognitive traces, possibly prompted by the computer at appropriate junctures of thought, could lead to an emergent awareness of errors in understanding. In some cases, this could also lead to an understanding of errors of execution, which misdirect the search for solution. Second, for the psychologist or teacher, such traces could be used to diagnose a child's understandings and potentially bug-ridden ideas of the domain under study and to identify the learning experiences that are necessary for instructional remediation. Third, for the computer, such traces could be used to build a model of the child's understanding and then provide next-step responsive environments.

A prototype of such a cognitive trace system has been built by John Seeley Brown and colleagues at the Xerox Palo Alto Research Center (J. S. Brown, 1984). In this system, called AlgebraLand, the computer carries out low-level procedures for transforming equations while students focus on their strategies for choosing the procedures that the computer will perform on equations. The cognitive trace function is expressed in an updated topological graph of the student's problem-solving steps. With this trace path, the student can "read" the alternative solution paths that she or he tried in order to learn from experience why some were successful and others less so.

As Boden (1979) notes in discussing Piaget's work on the development of purposive self-knowledge, children can or try to do many tasks without knowing how they do so, often without being able to correct their failures. She discusses Piaget's (1976, p. 340) account of how consciousness moves from periphery to center, since deliberate action first involves awareness only of the goal and of whether success or failure occurs, "while the fact that the scheme that assigns a goal to the action immediately triggers off the means of affecting it may remain unconscious." Later, largely because of the child's search for the reasons underlying his or her errors, consciousness "moves in the direction of the central regions of the action in order to reach its internal mechanism: recognition of the means employed, reasons for their selection or their modification en route, and the like." Cognitive trace systems could act as prime movers toward the child's grasp of consciousness in different domains by contributing to the development of this metacognitive knowledge, so important for expertise (Brown and others, 1983). But, we first will need research to determine whether such cognitive trace facilities do indeed make developmental contributions.

Integrating Child and Computer Information-Processing Systems. It is now commonplace to note limitations in human symbol manipulation abilities. As Siegler (1983, p. 129–130) observes, many "processing limitations can prevent people from attaining their goals: limitations on the number of symbols that they can manipulate simultaneously, on the speed with which they can manipulate symbols, on the depth to which they can search memory, and on their resistance to interference, to name but four." It has become a central goal of cognitive and developmental psychology in recent years to document how we utilize strategies to overcome these processing limitations of short-term memory (through such mnemonic strategies as rehearsal, elaboration, and organization) and long-term memory (through books and other materials).

Integrating the powerful information-processing systems of the computer and the frail information-processing system of the human mind may be possible. If such integration is successful, it may have great consequence for cognitive development. Empirical studies during the past decade have extensively demonstrated young children's preconcious understanding of such complex concepts as causality, number, conservation, proportions, and logical deduction in simplified task environments that avoid taxing the limits of their information-processing systems (for reviews, see Carey, 1984; Case, 1984; Donaldson, 1978). Yet it is still conventional wisdom that student access to many disciplines, such as statistics, must await a certain age. In principle, we may be able to close much of the gap between the information-processing capabilities of child and adult and ultimately of humans and computers by integrating our information-processing systems.

One central hope is that such integrated systems may provide a path out of the breakdowns of rational thinking that have been extensively catalogued recently and that appear to result in large part from the bottlenecks of human information processing. The work of Kahnemann and others (1982) on judgment under uncertainty, of Wason and Johnson-Laird (1972) on the attentional bias to positive evidence in deductive reasoning, of Luria (1976) and of Scribner (1977) on the empirical bias in logical reasoning, of Shweder (1980) and others on statistical thinking, and of Nisbett and Ross (1980) on errors in social judgment has revealed the widespread use of heuristics for thinking that leads to erroneous conclusions. We have already noted the non-universality of formal operational thinking, particularly in cultures without schooling. There should be more effective ways for people to develop these problem-solving powers. Too many people have trouble learning the formal rule- and model-oriented disciplines that pervade the modern information age—ranging from physics and mathematics to the genetic code in biology and computer programming—and the kind of problem-solving skills required for job and life successes. We are also so prone to errors of judgment, errors of reasoning, and lack of monitoring and evaluation in our decision making that most of us most of the time could usefully be propped up and reminded to become more effective.

Could AI systems be used to buttress these well-known human frailities? Could they serve educational processes of cultural transmission and redefinition in a computer age? With the integration of human and computer intelligent systems, we may be able to attenuate human processing limitations. One possible way of dealing with the problem posed by the cognitive interface between software and the child's mind is to work at providing the set of computational tools necessary so that intermediary cognitive work, which usually goes on in the child's mind and strains age-related memory and processing limitations, can become virtually perceptual work, unrestricted by such limits. The store and processes of the mind needed for problem solving can be those of the child-computer system rather than of the child only. The cognitive workspace could be expanded to include the computer screen and other computational devices.

With such systems, we may thus extend the forms of thought made possible by the symbols that Vygotsky (1978) describes as "external memory aids" to the mind—mathematics, written language, logic, and programming languages. For any content domain, from Siegler's (1983) balance beams to correlations, we should be able to build devices that enable children to circumvent the processing limitations that hamper their ability to engage in higher forms of reasoning and thinking, such as concrete and formal operational thinking. The principal caveat is that we have to show how such adjuncts to processing capacity can be designed and developed for specific knowledge domains. Only then will we find the practical obstacles to their effective use in childhood education.

Pragmatic Cognitive Tools for Higher-Level Achievements. To go further, one can imagine the invention of powerful cognitive tools that would support problem solving in domains previously considered to be difficult or even impossible for young children. In other words, programs could be devised that would serve as "cognitive props" for complex problem solving. For example, by using these programs children who were not formal operational thinkers would solve abstract problems that require formal operations.

Dennett (1978) argues that when a system, such as a software system, gets sufficiently complicated, we change the focus of descriptions from physical to intentional properties. As observers, we adopt the intentional stance and describe the system as thinking, believing, and with other intentional terms. The same is true when we discuss human-computer systems. We adopt the expert stance by attributing to such systems expertise and intelligence that we normally reserve for the human adult. We say that the system is formal operational, or clever, or very good at solving algebra problems rather than focus on the individual as the unit of developmental analysis. In fact, we can extend the well-known Turing test, a thought experiment proposed by Alan Turing (1950), to the idea of human-computer intelligent systems. In this test, a blind evaluation question-and-answer format is used to determine whether an object possesses thought. However, the Turing test is nondevelopmental; that is, it does not distinguish qualitatively different levels of intelligence. Given a developmental revision, such a test might be used to evaluate behaviors of an integrated human-computer intelligence system. Consider a child who approaches a formal operational task. The child alone may not be formal operational in his or her thinking. However, working with the computer system, the child may indeed be able to successfully solve formal operational cognitive tasks (such as control of variables or proportional reasoning). The integrated child-computer system is evaluated by the Turing test as formal operational.

This argument rests on the genetic epistemology of symbol systems. What are the implications of a tool of human intelligence for cultural development? Just as other symbol systems, such as mathematics, logic, and written language, have transformed our intellectual powers, so in principle can intelligent computer systems transform them. The concept of intelligent human-computer systems is simply an extension of this generally recognized developmental empowering by symbol systems. What makes the computer unique is its potential for modeling human intelligence. As thinking tools, computers have considerably greater potential than tools of the past, because effective use of such intellectual tools as mathematics and written language is constrained by our limited memory and information-processing abilities

(Minsky, 1983; Simon, 1977). We now have extensive gaps between competence and performance in cognitive functioning, but these gaps may narrow when human and computer intelligence are married.

This argument contrasts with Piaget's contention that better teaching and earlier experiences of the right kind cannot lead to precocious intellectual performances. He responds to the so-called American question (of accelerated instruction) by criticizing Bruner's (1960) claim that any idea, problem, or body of knowledge can be presented in a form simple enough that any particular learner can understand it. Piaget (1971, p. 21) argues that "intellectual growth contains its own rhythm. Speeding up cannot be indefinitely continued." Piaget's argument is essentially that education can at best accelerate stage development within certain limits. Successive reorganizations of knowledge exemplified by the stages are time-consuming and take much experience.

But we may resurrect these questions, since the potential of AI systems may change the terms of the acceleration debate. One may agree with Piaget's notions about the structural limitations to educational acceleration. However, Piaget's reservations were based on the performances of a solitary child. Yet children's problem-solving skills may be stretched beyond their potential when they receive aid from others, such as peers and adults. Performance in what Vygotsky called the zone of proximal development has important implications for intelligent tutoring systems that can in principle be extended to human-computer intelligent systems. It has even more radical implications for Piaget's objections to the American question.

The radical implications center on the capabilities of young children when supported by intelligent computer systems. Some developmentalists have been dissatisfied with the ZPD studies because they also view the solitary performance of the child as the fundamental unit for developmental analysis (seeing additional aids, coaching, and prompting by an adult as "cheating" in this respect), yet the issue becomes more controversial when the child is part of a human-computer intelligent system. Imagine a typical nine-year-old working with an expert system to solve formal operational problems on correlations that involve multiple variables. The child-computer system solves the problem through the integration of the computer and the child's currently functioning solitary intelligence. As already noted, the system would be considered formal operational by the criteria of the Turing test. What does this mean in terms of the child's intelligence?

At first, one is inclined to say that children are only as intelligent as they are capable of demonstrating alone, without the technological aid supplied by the computer. But this will not do. The reason is that this technological aid is similar to other aids that we readily allow and would never rip away from the child in our crudest assessments of a child's solo intelligence: such symbol systems as written language and mathematics. These systems are truly technologies, as are the symbolic artifacts of computer programs. If the child can use the computer symbol system as an aid in solving complex problems, it should be just as admissible as the thinking tools provided by written language (for example, by note taking during arithmetic calculations, or by list making in a formal operational experiment). Like mathematical and language notation, the symbolic notations used in the computational environment provide a powerful means for the child's thinking.

The consequences of these integrations are profound for developmentalists (including Piaget) bound to the assessment of intelligence in solitary settings. We should consider what these new possibilities say about stage conceptions of human intellectual development. What types of problems will emerge in the student modelling necessary for integrating computer and human intelligence, and for developing usable programs from the child's perspective? As intelligent systems become widely available, what are the implications for the emergence of highly creative mental acts in the arts and sciences throughout society? What complex ethical problems will be raised by such fusions?

Systems for the Coevolution of Human-Computer Intelligence. Tikhomirov (1981) has asked the profound question of how the mediation of mental processes by computer differs from mediation by signs. For example, does the computer introduce qualitatively different changes into the structure of intellectual processes? And how can a new stage be distinguished in the development of human mental processes?

The most speculative but also the most spectacular possibility is that human and computer intelligence will coevolve. Perhaps only by joining the strengths of human intelligence with the strengths of the computer can the potential of either be realized. It will soon be necessary for any theory of learning and development to explain not only human or computer learning (Michalski and others, 1983) and development but also their symbiotic union. This speculative discussion casts aside reservations about the need for human self-sufficiency in intellectual functioning, because integration between human and computer intelligence will be the norm in future decades. Just as the human body is no longer the major tool for physical labor, and just as a carpenter need not use only hand tools, so will mental functioning no longer be the sole province of the human mind.

To carry this speculation further, we can submit that computers will not always be so obviously external to humans in their functioning as mental tools as they now are. They may ultimately be use-transparent and serve as literal organs of intelligence, even to the extent of being integrated with the physical confines of the body, if we so desire. Hardware differences between the machinery of the mind and of the computer will be glossed over, and integration on the physical level will characterize human-computer intelligent systems. The insight comes from cognitive science: Intelligence does not need human hardware (the nervous system) to run; it is independent of hardware. The consequence is that an intelligence system (that is, a system that has the programs needed for achieving intelligent performances) need not be based in the nervous system. Until recently, we have conceived of human intelligence (realized through the nervous system) and artificial intelligence (realized through microcircuitry) as distinct. But, these two intelligences can in principle be integrated, since the hardware differences need not serve as a barrier for a new hybrid intelligence. Already, microprocessors have been integrated with artificial limbs to provide a form of internal integration of human-computer systems. Of course, there are caveats: Complex ethical issues of personal identity, rights, and dominion will emerge. But, we cannot begin such discourse without charting the possibilities.

It is important to observe that computers, as components of such systems, can serve to bootstrap human intellectual development under human control and choice. Just as adults have been able to solve complex problems with computers that they were unable to before, so children should be able to go beyond their current developmental capabilities with computer assistance. Human-computer intelligence systems will serve to extend and ultimately to reorganize what we think of as human imagination, intelligence, problem-solving skills, and memory.

Conclusions

As Tikhomirov (1981) reminds us, the computer only creates possibilities for human development, to be realized when certain technical, psychological, and social conditions are met. While I have argued that we have the technical capabilities needed for integrating human and computer intelligence, there are few exemplars to demonstrate that the psychological conditions of effective integration have been met. And, social conditions have not been adequately considered. What are the goals for computer use in our society?

One consequence of the information age is that what children will need to know to learn and develop will be drastically different from what our educational system now provides. Today, we spend decades learning the three Rs and memorizing facts that are often already outdated. A culture pervaded by AI-based developmental tools for all the basics, and also thinking tools in creative processes (such as design and invention) will lead to new definitions of intelligence. These definitions may highlight the skills that have long been the aim of a liberal arts education. Cognitive skills of information management; strategies for problem solving that cut across domains of knowledge; such metacognitive skills as planning, monitoring, and learning how to learn; and communication and critical inquiry skills will come to be valued more highly. Teaching the basic facts of the disciplines will not only not provide for an educated citizenry that can use the thinking tools of this age, but it will not even be feasible because of the information explosion.

In this chapter, there has been little opportunity to address the tough research questions that must be raised if we are to achieve success in the various levels of integration of human and computer intelligence. Developmental research is needed to elaborate the theory of cognitive tasks, the theory of stages of competence by domain, and the theory of interventions and stage transitions (Resnick, 1984) integral to the creation of computer-based developmental tools. Too little is known about how stages of knowledge are transcended to become new and more adequate constructs. Also, we know little about the expert teaching that we hope such systems would model, although substantial progress has been made in unpacking procedures of inquiry teaching or Socratic dialogue (Collins and Stevens, 1982; Arons, 1984).

This enterprise will depend on interdisciplinary collaborative work among the computer and cognitive scientists who build AI systems and the developmental psychologists, content area specialists, and educators who know so much about how the work and play of learning and development take place. Such groups can together study learning and developmental processes while simultaneously providing tools to transform the very activities of learning and development. There are no precedents. The printing press had profound cognitive and social consequences, especially in education (Eisenstein, 1979), but its effect will not compare with the consequences of interactive information tools that function with the basic currency of human thought processes, the symbol.

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