CERI

CENTRE FOR EDUCATIONAL RESEARCH AND INNOVATION

INFORMATION TECHNOLOGIES AND BASIC LEARNING

International Conference
of National Representatives and Experts
Paris, 13th-15th October 1986

GENERAL REPORT

OCDE
OECD

ORGANISATION FOR ECONOMIC
CO-OPERATION AND DEVELOPMENT

Centre for Educational Research
and Innovation

CERI/NT/86.05

RESTRICTED

Paris, drafted: 4th August 1986

dist: 8th August 1986

Or. Eng.

INFORMATION TECHNOLOGIES AND BASIC LEARNING

GENERAL REPORT

(Note by the Secretariat)

1. The attached document has been prepared by Professor Alan Lesgold, Associate Director, Learning Research and Development Center, University of Pittsburgh, United States, in his capacity as consultant to the Secretariat and General Rapporteur of the four working groups set up on Reading, Writing, Sciences and Mathematics in October and November 1985 .

2. The views expressed are those of the author and do not commit either the Organisation or the national authorities concerned.

38.019

INFORMATION TECHNOLOGIES AND BASIC LEARNING

TABLE OF CONTENTS

INFORMATION TECHNOLOGIES AND BASIC LEARNING

INTRODUCTION

1 We live in an age of rapidly changing technology. New tools to enable productive labor appear each day. Each tool affords new ways for people to perform services that others will value and pay for, while it simultaneously replaces a previously valued human skill. Combined with the increased lifespan in OECD countries, the pattern of continual technological change forces most workers to acquire new skilled job roles in the midst of their productive lives rather than only at the beginning. In addition, the demands of participatory democracy are beginning to impose a similar need for continual learning. Citizens in OECD countries regularly face decisions of historically unprecedented complexity. In court procedures requiring juries, such as the IBM antitrust case that spent so many years in U. S. courts, the ability of average citizens to understand issues of technological and intellectual property has been challenged, a challenge that goes to the core of constitutional democratic government.

2 Modern economic and political demands require a basic education of higher quality. While many of our grandparents acquired a lifetime's occupational skills in a single apprenticeship of three to fourteen years and relied on education only to prepare them for participation in democratic government, on-the-job apprenticeship, and transactions in a simple marketplace, our children will need to be more continually educable. Because the unskilled productive roles in our society are first to be replaced by machines and because a spirit of egalitarianism requires more universal education, we now, for the first time, ask our schools to teach all of the children. Thus, we need a higher quality of basic schooling, and we need to provide it much more universally than we ever have before.

3 Faced by these needs, there has been a partly positive and partly negative pressure on governments to provide better basic skills education in the school systems. Not understanding that everyone needs these skills, not just those whom schools easily teach, and not understanding that a higher level of basic skills is needed than ever before, the public has demanded a "return" to basic skills education as the focus of the educational system. More likely, there was no period of ideal, universal basic skills education, so the "return" must be a step forward. Nonetheless, we must now provide a high quality education to all children in those basic skills that can support continual learning and relearning, training and retraining, throughout citizens' lives.

4 The basic skills needed appear much the same as before. Our children must learn to acquire information, to communicate, to reason qualitatively and quantitatively, and to solve everyday problems. They especially need the

self-aware skills that will permit them to continue learning on their own. Traditionally, and today, these skills can be summarized with the terms reading, writing, mathematics, and science. However, it is important to note that those traditional subjects can also be taught in ways that defeat the goal of building reasoning, problem solving, learning, and communicating skill. Memorizing a definition does not teach one to use the methods of science to solve problems. Memorizing a number fact does not lead ipso facto to improved quantitative skill or understanding. Transforming sentences from one tense to another does not teach one to communicate. Each of these acts might enable additional learning but is not itself sufficient.

5 Going beyond the rote and the trivial is labor-intensive. Students' essays need to be critiqued; their mathematical problem-solving skills need to be analyzed and sometimes remediated; the information they gain from reading a text needs to be challenged and evaluated. All of this requires teacher time and skill. However, our school systems are under great economic pressure and have been for a long time. This is the dilemma. Providing high quality basic skills education sufficient to meet the needs of a long life in a rapidly changing world is expensive and may require skills that are not always present in those willing to be teachers.

6 Two forces have appeared that might enable us to solve this dilemma: inexpensive information processing power and a blossoming cognitive science that can rigorously study, understand, and improve the educational process. The ever-increasing availability of cheap computational power makes it possible to imagine computers being used to supplement the limited supply of human teachers. However, as in every area of computer usage, educational computer applications cannot be developed without an understanding of what it is we want the computer to do. Computers have been employed most rapidly in areas where there is clear understanding and widespread agreement on what information processing activities are desired, e.g., accounting, routine assembly-line operations, and the performance of mathematical computations.

7 Until recently, there has not been much potential for clear theory and practical technology in education. Thus, it is no accident that computers have been used to mimic a variety of teaching practices, some good and some bad. Further, since the most valuable teaching practices — encouraging, coaching, explaining, criticizing — are the hardest to describe with precision, they have been least likely to appear in educational computing products. While a number of products that are quite simple have been designed by excellent teachers, they often depend upon having an excellent teacher at hand when they are used and are thus of more limited value.

8 Fortunately, great progress has been made in understanding the processes of learning and thinking. Psychologists, computer scientists, linguists, and philosophers have contributed to a cognitive science that is beginning to have sufficient power to drive the development of intelligent computer systems that can engage in rich interactions with a student and promote learning. Similarly, techniques are being developed that afford a better opportunity to understand how such artifacts as educational computers are received in real classroom settings and what effects they really have. Together, the tools of cognitive science and

rigorous methods from anthropology and psychology offer the possibility that computer systems can be vested with sufficient intelligence to function as major teaching tools, supplementing and enhancing a teacher corps whose numbers are insufficient and whose members vary in capability. Indeed, if the best teachers' methods can be understood and reproduced (even partially) by computers, then those computers can not only teach but also serve as examples of effective teaching from which other teachers can learn.

9 Sensing that all of this promising scenario exists in prototype fragments but that most current computer usage in schools is still primitive and of uncertain value, the OECD Secretariat worked with Member countries to create four working groups to examine the state of educational uses of new information technologies in the basic skills areas of reading, writing, mathematics, and science. The members of these groups are listed in Appendix A to this report. Each group met at OECD in Paris in October or November, 1985. Thereafter, group members interacted with the group chairs by electronic mail and the post, and the group chairs developed reports of conclusions the groups had reached.[1]

10 The groups agreed that there is great potential for uses of new information technologies in education. They further agreed that education stands at a crossroads. The reification of ineffective teaching practices into computer artifacts will not improve education, nor will handing potentially useful information tools to teachers who have not been trained to use them. While the computer revolution and the emergence of cognitive science offer the hope of improving the effectiveness and productivity of education, a major effort is needed to refine and demonstrate new educational science and technology and to train teachers to use the new tools. Without such an effort, the computer will simply be one more potential tool that is ignored or misused by our schools.

11 The Working Groups' conclusions are summarized in the final section of this report, and the specific details of those conclusions are most important in assuring that effort focused on educational technology is not wasted. A brief summary of the issues and concerns common to the four groups must include the following:

- The new information technologies afford the opportunity for new classroom teaching methods. They also change the relative value of various skills in the labor market. Both of these changes require a careful examination of current curriculum content and instructional methodology for all grades and forms of schooling.

- While much of the software currently available to schools is not adequate, each group was able to identify a number of items which had demonstrable positive effects in the classroom.

- As noted above, the cognitive instructional sciences and technologies offer great potential for improving the productivity and effectiveness of education, but only if high quality research, development, dissemination, training, and evaluation efforts are made.

• Because computers are specialized to cheaply execute routine algorithmic performances, higher-order thinking skills become more important in assuring that our children can be productively employed. Because human activities, when aided by technologies, become more complex, these same skills are needed by all who wish to participate fully in democratic government. Fortunately, it appears that the very same technologies that make analytic skills more important also can be used to help teach those skills.

CONTEXTS FOR PLANNING AND DECISIONS

12 Overall, the conclusions of the Working Groups must be viewed from the perspectives of several contexts. First, there is the policy context. Decision makers in national governments and local schools have problems they must address, and the conclusions in this report are relevant to those problems. Second, there is the pedagogical context: what must be taught and how shall we teach it? Finally, there is the technological context, in which new things continually become possible and in which some exciting possibilities become affordable. Each of those three contexts is addressed below.

THE POLICY CONTEXT[2]

13 The policy context within which uses of technology for education must be considered is complex and includes forces which compete with each other and with efforts to achieve long-term improvements in education. There are a variety of economic and commercial considerations that must be taken into account, and there are also a variety of social and political concerns. The fundamental social contracts on which our society and its political systems are based have been placed in jeopardy by the recent and continuing explosion of technology, and this has produced many strains.

Economic and Commercial Considerations

14 Economic forces work on many timescales, from generations to years to hours. Our social structure is based upon expectations for lifetimes and even for multiple generations. If I work hard, then I can earn enough money to live in a place with good schools and good teachers, and I can send my child to a university. If I am less wealthy or more idealistic, I can support a government that will select my child for elite education that opens the doors to a more pleasant life. However, these cause-effect relations take place over years, even decades. Rapid technological change helps to produce an economy that optimizes with respect to periods of three months to one year, since no one can predict what will happen ten years from now.

15 Thus, we see industry demanding particular training for our children. Of greatest interest to a business is that the children graduating from school soon should have the skills needed to fill jobs that exist today without requiring expensive on-the-job training. Education that can support continual learning as jobs change in character is a longer-term proposition. Further, if many businesses are now using specific pieces of software or specific computers, there will be a pressure to

use these in schools, so that new workers come already familiar with the equipment of the job.

16 A second economic pressure comes from the computer industry. Every computer company hopes that schools will buy its products, both for the direct sales this will generate and because those who use a particular computer in school may be more inclined to buy one later on for their business. All computer businesses within a country can agree that only computers made in that country should be used in its schools. Further, there is great pressure on schools to buy computers in quantity, since the education market is, because of the number of schools and students, attractively large. Small countries are impressed with the prospects of such industries as educational software, because of the minimal investment needed to begin such businesses. Another, more subtle, pressure favors simplistic software, since the costs of training teachers to use the software, consulting on how to use it, and even maintaining staff to determine the validity of warranty complaints (e.g., did the computer fail because it was defective or because the teacher used it inappropriately) are all very high.

17 Prices change very rapidly in the personal computer market, but the mechanisms for making purchase decisions are often slow and cumbersome in schools. As a result, schools often have underpowered and nonstandard computers that happened to be the cheapest available the day information was gathered and that may not run any of the most useful software. Low budgets and the inability to purchase opportunistically and quickly have tended to force standardization of computer hardware for education that is not otherwise prominent in the business world. As a result, many routine (but educationally useful) tools of the commercial sector are not available to schools.

18 Only a clear sense of what possibilities can be realized, and when, and at what cost, can drive the strategic planning needed to overcome the economic forces that tend to force low-efficiency computer uses onto schools.

Social and Political Considerations

19 In many countries, parents and young people are pressuring schools to buy computers. Parent associations sometimes buy the first computers for a school and thus help shape the choice of hardware for the future. School leaders are under pressures of varying types in matters of educational technology. Parents believe that familiarity with the specific computers of today will make their children more employable tomorrow. They see advanced uses of computers in mass media fiction and ambellished documentary presentations and want their children to be part of a world of tomorrow that is only partly real. Since most people have difficulty understanding how much of a computer application comes from the operator and how much from the computer or whether the application can generalize beyond the specific demonstration situation, they associate more power with small personal computers than is actually present.

20 Misunderstanding about computers is widespread and easily manipulated. A few years ago, a minority group in an American city opposed use of computers in schools because they suspected that schools in their area would lose their teachers and be taught only by machines. Some administrators oppose all computer usage

in schools because the particular hardware and software they experienced was worthless. Others are driven by experiences in fantasy environments, such as the Disney Epcot Center.

21 What is needed to improve on this situation, in which self-perpetuating poorly-informed decisions dominate? The recommendations we have made go beyond the usual calls for research, better planning, and the abandonment of self-interest by the powerful forces within our society, though aspects of each of these idealistic requirements are identified as critical. We also call for a strategy of prototype development, demonstration, and evaluation. The first substantial uses of the information technologies for education will be expensive, but a sense of what is possible must be developed before cost is optimized. Few parents, businessmen, politicians, or teachers have seen schools in which the computer is as pervasive as the textbook. Only by seeing demonstrations of what is possible can they begin to develop a critical understanding of what is desirable.

22 As noted in a later section of this report, the computer is also ideally suited for testing educational ideas, since it can keep detailed records of what actually happened in an educational interaction with a student. More generally, evaluation is critical to the future of computers in education. The bulk of the educational software currently available is clearly of minimal use, and some is probably detrimental. The good products must be identified, and the characteristics of good products must be documented. This process must be intensive, since superficial standards are worse than none at all.

23 Finally, demonstration and evaluation must take place in real school settings, since it is characteristic that most innovations work when tested in ideal settings and fail when placed unsupported in impoverished school sites. There are two sides to this. First, the purpose of demonstration must be to determine what is practical, so one outcome should be a clear understanding of what level of teacher training and institutional support is needed for a system to be effective. Second, initial demonstrations may need to be supplemented with resources schools do not generally have; we do not want to rule out an approach as useless in principle if it merely needs tuning to make it practical.

I THE PEDAGOGICAL CONTEXT

24 In approaching the task of describing the potential of new information technologies for education, it is important to take sophisticated account of the specific needs and economic limitations of each OECD country's education system. Further, it is important to attend to recent results in cognitive science that help clarify the appropriate uses for new information technologies. To date, the reaction of the less wealthy countries has been to favor the more mundane uses of computers that can work on very minimal hardware, on the argument that (a) improvements in education are needed immediately, and (b) bigger computers are expensive. However, bigger computers keep getting cheaper, and the real benefits of the new technologies lie not in what is already possible but rather in what is just starting to be possible. This is because the less wealthy countries are least able to provide an adequate cadre of master human teachers and least able to afford the inefficient current forms of education, in which many students fail to achieve more than the temporary ability to pass school tests.

25 In recent years, much has been learned about expertise in many different areas, and one way to view education is as the conveying of expertise to children. We continue to expect our children to be facile at the basic skills of reading, writing, and arithmetic computation, but increasingly, we also expect them to respond flexibly, which is a sign of expertise, to continuing technological change. This is in striking contrast to earlier views of basic skills, which treated them as routines to be automated. It still seems appropriate to think of *facility* as a core requirement for basic skill, but it no longer is appropriate to think of these skills as being completely routine. Rather, facility seems to involve not only minimal load on conscious thinking capacity but also knowledge of how to apply routines adaptively to a wide range of situations. That is, we want our children to be experts in applying the thinking and communicating skills that our increasingly technological world requires.

26

- We expect children to be able to use their arithmetic skills in everyday life, not just to be able to solve numerical problems their teachers set for them.
- We expect children to understand what they read and relate it to what they already know, not simply to store a copy of a symbol stream in their heads.
- We expect children to learn to communicate effectively in writing, not just to transform the ideas of others into sequences of grammatical sentences.
- We expect that the science training our children receive will prepare them to understand the complex decisions about new technologies that citizens must make in the future, not just to be able to carry out routines that are already automated and done by robots in our factories.

With these goals in mind, a few comments on the recent course of basic skills education and of instructional science seem in order.

GOALS AND PROBLEMS OF EDUCATION IN BASIC SKILLS SUBJECTS

27 While the basic skills are highly regarded throughout the OECD countries, there are widespread difficulties that seem to affect basic skills education in multiple OECD countries.[3] Not every country has every problem, or notices it, but each is sufficiently widespread to be worthy of mention.

Student problems

28 a. Time exerts great pressures on education. There is a rush to cover course material, and the slower student often falls progressively behind. In cumulative subjects like mathematics, the eventual result is that students end their mathematics learning altogether. Paradoxically, a number of studies suggest that only minutes of each school day are spent in learning inducing activities, that much time is lost to classroom management activity and to the inability of the teacher to deal directly with every student at the same time. As new subjects accumulate faster than old topics are deleted from the curriculum, this problem increases.

b. The pressures produced by the time problem just mentioned, combined with other weaknesses of education systems, have led to a widespread belief that educational standards have been lowered. In response to this, a variety of achievement monitoring programs have begun in various school systems. One effect of these programs is to focus student and teacher attention on aspects of subject matter performance that are perhaps too shallow to sustain later learning. For example, it is easier to focus on memorizing number facts than to try to understand the underlying relations that generate those facts.

c. There are sex differences in learning. Girls initially do better at learning to read, and boys tend to prevail in the later years of math and science.

d. The rapid pace of our society, and particularly the media, reinforce the belief of many children that skills can be acquired very quickly, when the results of recent psychological investigations suggests that thousands of hours of practice underlie any form of expertise.

e. A variety of forces and beliefs result in too much stratification between the pursuit of advanced levels of basic skills vs. technical training. As a result, the more able students leave school with no exposure to technical skills or practical technology and those following vocational tracks leave with inadequate basic skills and an impaired ability to learn on their own or to be trained for different jobs. Again, there are sex differences, with bright girls being particularly deprived of practical technology experience.

Teacher Problems

29 a. Teachers do not receive adequate training once they are on the job. As a result, they are often trying to teach what they were taught rather than potentially more generative basic skills.

b. As discussed above, a variety of examinations shape the goals teachers have. In addition to direct monitoring of student achievement, the entrance and placement examinations of universities also shape teachers' goals more than do in-service workshops, teacher journals, and other information sources.

c. Teachers with long histories of service may not have received adequate training in dealing with the wide range of ability levels now represented in our classrooms.

d. Many teachers of mathematics and science have not received adequate post-secondary training in those subjects. Thus, they are unnecessarily narrow in the content and teaching strategies they can employ and have an incomplete sense of the goals of basic education in those fields.

e. Areas of sparse population cannot attract or support the most skilled teachers, especially in science and mathematics.

Curriculum Problems

30 a. The basic skills areas are dynamic, shaped by progress in science, mathematics, and the humanities. However, the curriculum is seldom changed in these subjects, so children receive an education couched in terms of ideas that are sometimes foreign and sometimes obsolete. Superficial reactions to the call for a "return" to basics have increased this problem, in some cases.

b. The updating needed represents knowledge that is also missing in the adult population, so there is need for refresher courses in basic skills for adults. Also, of course, there is need to carry the new goal of universal basic skills education back to the generations yet alive for which that goal was not existent or not achieved.

c. All of the basic skills involve both procedural and factual knowledge. Factual knowledge, acquired through memorization, is only a fragment of the total competence needed, yet school are generally organized to best teach that fragment.

d. The lack of adequate emphasis on the procedures of math, science, writing, and reading is made worse by a lack of adequate resources and classroom structures for providing individual attention to each student, even though detailed critical feedback seems to be essential to the learning of these skills. Increases in class size, combined with increases in the diversity of aptitudes in a class, further compound this problem.

e. There are a number of demonstrations, especially in mathematics and science, that key concepts are not acquired by most students, even though they pass tests involving those concepts. The knowledge apparently does not generalize beyond the world of textbook examples.

f. Especially in science, the amount of important knowledge continues to grow. It is always easier to add to the curriculum than to redesign it, and thus we see a continuing pattern of teaching less about more. Combined with the enduring bias toward memorizing of facts, this trend insures a continual force toward superficiality of learning.

Facilities Issues

31 a. Schools have inadequate laboratories, often consisting mostly of outmoded equipment. Funds are usually not available for laboratory refurbishment, which is expensive.

b. Even when equipment is appropriate, it is often poorly maintained. In many cases, no one in a school knows how to maintain the equipment or even how to arrange for it to be maintained.

WHAT DOES COGNITIVE SCIENCE HAVE TO OFFER?

32 Against this long list of educational problems, there are, as noted above, two new forces to be employed: (1) the ability of the computer to cheaply and speedily replicate information processing of great complexity and (2) a new science of

thinking and learning, cognitive science. In this next section, we briefly discuss the contribution that cognitive science can play. In particular, we address recent research done on the nature of human expertise and on how an expert's knowledge can be taught to a novice. This work is of relevance, since it is quite reasonable to think of the basic skills as a set of expertises that we expect all our children to acquire. Indeed, perhaps this viewpoint is part of the antidote to the excessive focus on memorization of facts that has been mentioned above.

Goals of Education: The Psychology of Expertise

33 Considerable work has been done comparing experts with people of lesser skill in a variety of domains. While this approach has a smaller literature in the school subject matters, there are several findings that recur in all the domains of skill thus far investigated. These findings seem appropriate sources of suggestions for concerns that likely carry over into school subject skills as well.

34 *Understanding vs. executing procedures.* A repeated finding is that compared to novices, experts spend more of their time understanding a problem situation and less of their time actually carrying out the solution process. For example, given a textbook problem, physics experts work at understanding it and then use that understanding to suggest a solution. Novices, including students who have taken a physics course, immediately try to fit an equation to what is given, without first understanding the problem. Many school subject textbooks and teachers tend to reinforce students' procedural approach. Math textbooks almost always cluster problems of a given type into one place. Thus, students may learn very superficially to apply one algorithm to those problems without ever learning when that algorithm is appropriate. Put another way, we often teach the THEN side of IF-THEN rules without spending enough time on the IF side. When teachers offer rules of thumb that are themselves superficial, this makes things worse.[4] We should ask whether the approaches currently being used will move students toward expertise or merely reinforce superficial and generally useless knowledge.

35 *The threefold way.* Another emerging principle is that expert performance can come from multiple sources. Specifically, expert performance comes from a mixture of three capabilities: efficient but flexible basic routines, substantial general knowledge in the relevant domain, and powerful strategic skills that enable one to reason beyond one's current knowledge. To some considerable extent, these three sources of successful performance are interchangeable. That is, if a person is short of one of the three, this can be made up by greater strength in the other two. For example, very bright students can often solve geometry problems, especially multiple choice test items, without ever having studied geometry, using just their everyday knowledge of vocabulary and of lines and shapes combined with powerful reasoning strategies. At the other extreme, a student might do well on a test item dealing with "analytic" aptitudes if he knew specific routines for dealing with the type of problem posed, even if his general analytic capabilities were limited.

36 In evaluating new technologies, it is important to consider whether the devices and programs we examine aim at what is most important to teach. Some software teaches algorithms without ever expanding higher-order thinking skills, thus overlapping rather than improving upon existing educational practice. Other programs may allow the clever student to succeed too often on generalized or "weak" methods,[5] never seriously engaging the specific domain the program purports to address. Much research remains to be done on this problem,

particularly on the relationship between understanding and performance. However, the concerns expressed above are already worth addressing.

Learning

37 The strongest contribution of the cognitive sciences to education is to provide a clear understanding of the active nature of thinking and learning. In contrast to earlier views of learning, which characterized the process as one in which responses were tied reflexively to categories of stimulation or symbols were passively accepted and stored, an emerging view is that knowledge is constructed. This viewpoint is not novel. Philosophers, and psychologists like the early Gestalt psychologists and such contemporaries as Hochberg, have long held this position. What is more recent is the emergence of sufficient methodology, in the form of formal theorizing approaches and methods for verifying formally stated theory, to allow serious testing and elaboration of *how* knowledge is constructed.

38 Much of current education, and especially of educational technology, aims either at drill or at the storage of knowledge in students' heads, rather than at what knowledge students might construct in response to interactions with a computer system. If we really believe that students learn by constructing their own knowledge, then the specific words we spray on them in lectures or show them on book pages have only a temporary importance. They are, in Robert Glaser's terms, *pedagogical* knowledge, temporary knowledge important only as a means to induce the desired learning in the student.

39 The implication of this is that technological artifacts for the classroom must be examined in sufficient depth to determine what *learning activities* they induce, not what words they display. From a more conservative point of view, it will also be critical to determine empirically that their *potential* for learning activity is actually realized. For example, discovery environments, such as the *Logo*, offer the potential for considerable learning but no specific guidance to the student or the teacher. In contrast, the approach taken with *Logo* by Howe in Edinburgh attempts to assure realization of that potential by providing rather specific directions concerning the activities which might lead to important learning.

40 The specific question raised by this difference is the extent to which empirical evidence favors one approach over the other. The more general issue is the relationship between technological artifacts and the specific teacher expertise that may be required to use those artifacts to advantage. Using computer tools to make up for a lack of trained teachers requires understanding which of those tools can stand alone and which depend upon skilled teaching by a person.

41 As is described in the section below on The New Technological Context, a technology sufficient to be useful does exist, though it needs refinement. Computer tools can now be used to create simulated laboratories in which students can be guided through the discovery of basic scientific principles, practice the higher order skills of problem solving and critical evaluation, and learn how to learn. The didactic classroom, in which knowledge must be communicated verbally and abstractly, can be supplemented by laboratories that are abstractions, in the sense that they exist only on computer screens, but concrete, in the sense that they faithfully emulate real phenomena and are manipulable by the student. The practice opportunities offered by written assignments and worksheets can be supplemented by practice with immediate feedback and coaching from an intelligent computer tutor. However, the

availability of these potentially useful artifacts is not enough. There must be a sound pedagogical plan for using them.

MOTIVATION

42 Motivation continues to be a fundamental problem in schools, and there has not been as much progress in understanding it as there has been in understanding learning and thinking. However, consideration of the use of new information technologies would be incomplete without consideration of student motivation. Common sense, and the existing body of empirical research, suggest that students, like other people, invest part of their time in efforts to deal with new situations. When these efforts are highly successful, they are no longer necessary and are abandoned. When they are largely unsuccessful, they are also abandoned as fruitless. What appears to be needed is enough success to convince the student that progress is being made and enough challenge to convince him/her that more work is needed and will be worthwhile. It is possible that the level of challenge must be set differently for different students, too. None of this is very controversial, but it already suggests three principles that should govern the design and evaluation of educational practices, including computer software for education.

a. The context in which new skills are taught and practiced should match the student's worldview sufficiently to seem highly relevant but should contain sufficient novelty to present a challenge (i.e., to suggest that the new material is needed by the student).

b. The student must be able to recognize success and progress. If necessary, the teacher or instructional computer program must help the student to identify individual successes and to recognize progress. For example, a student may not easily recognize that a revised essay is better than an earlier version or that he is faster or more accurate in solving certain mathematics problems than he was a few days ago.

c. It may be necessary to vary the size of challenges posed to different students, since part of any student's experience is a sense of general likelihood of success or failure. Research by Carol Dweck suggests that some students may need to have their understanding of how successes occur challenged, since they attribute too much to luck and too little to effort.

TEACHER TRAINING

43 The issue of necessary teacher competence is important. We should consider whether new in-service training will be required before the emerging computer tools can be used by current teachers. More broadly, we might ask whether some of the tools now appearing can educate the teacher as much as the student. Again, the principle that learning represents the construction of knowledge must be kept in mind. The question to ask is whether the immediately apparent activities for the teacher in using a new information tool will induce the learning of new techniques for using that tool and perhaps even extend the teacher's knowledge of the domain being addressed. For example, one can develop tools for teachers that allow them to design specific problems to be solved by the students. The vocabulary that is used and the choices teachers must make in specifying problems might well teach them something about the problem solving portion of the mathematics curriculum. Thus, if a teacher must make choices that relate to core curricular concepts in order to generate worksheets for students or

homework assignments, he will develop a clearer sense of the content he is teaching. We note that existing materials are often organized by superficial terms, e.g., one-digit vs. two-digit problems rather than according to the specific strategies they teach or the specific principles they demonstrate.

II THE TECHNOLOGICAL CONTEXT

EXISTING INFORMATION TOOLS FOR STUDENTS

44 The bulk of this section addresses the prospects for systems that would actively teach students or provide them with a new and special kind of practice environment. However, there are many conventional tools developed for broader use that can also be used to advantage by students. These possibilities are listed in the individual reports, but a few possibilities are also summarized here.

Word Processing

45 The most immediately useful tool for students is in fact also the most immediately useful in office environments, the word processor. In real work, we invest the right amount of labor in each communications task. If standard verbiage will do, we copy it from a computer file into a letter, for example. On the other hand, when new ideas must be communicated, we may revise our text dozens of times. In school situations, this does not happen. Because of the high cost of reading texts and of recopying and revising them in a paper and pencil world, there has been a continual decrease in the amount of writing students do and the amount on which teachers give them feedback, expecially in non-writing subjects. The word processor can return to writing the role of shaping and refining ideas.

Idea Organizers and Hypertext Systems

46 Programs are beginning to appear that go beyond text processing to allow people to structure ideas that they are developing. Some tools are very simple, mere outline development aids. However, some allow text to be viewed from many different levels of detail, and a few go beyond text to handle graphs, drawings, and charts as well. The discussion below of *Notecards* gives a sense of the leading edge of this technology, but less complex tools are already appearing for some common microcomputers. It is likely that school children could use such tools to help develop, organize, and express their ideas in written form.

Databases

47 Rather than simply give students books of predigested facts to memorize, it would be nice to teach them how to retrieve and critically understand databases of texts, numbers, and other information structures. As databases begin to be distributable on compact disks and powerful computer systems for retrieving and manipulating data structures become available, students can be given practice in skills of evaluating, understanding, and using information that will remain useful over a lifetime, rather than memorizing facts with relatively short shelf lives.

Spreadsheets

48 Finally, we note that the spreadsheet tools that are now widely prevalent have great potential for student use. Specific possibilities are addressed in the report

of the Mathematics Working Group, but these tools will also be useful in science classes, too. As integrated spreadsheet and filing programs become more common, these too can be brought to the classroom with good effect.

49 In summary, the marketplace is doing a good job of selecting out information processing applications that are truly helpful in communicating and solving problems. Surely basic education, which has problem solving and communications skill as its primary goal, must interact with these developments by providing students with chances to develop their skills while using the tools that adults use. Because the tools were initially developed for people with little or no computer experience, they (at least the better ones) may readily adapt to classroom use, too.

NEW HARDWARE POSSIBILITIES

50 Two primary new hardware technologies are emerging which provide the potential vehicles by which new forms of education might be delivered. First, there are powerful personal workstations which have the speed needed to run large artificial intelligence programs, the graphic capabilities to permit detailed visual displays (both text and pictures), and the temporary (memory chips) and permanent (magnetic disk) memory to support large-scale educational systems. Samples of the screen displays for such systems and descriptions of some of the instructional systems are presented later in this proposal.

51 A second type of instructional delivery vehicle is the intelligent compact disk player. While the larger videodisk has not been very successful in the market, the smaller compact disk has become very popular as a means of conveying high quality audio recordings and also as a means of distributing massive amounts of data and computer programs. A single compact disk can hold over 500 million characters of information, enough for any of the following: (a) 100 intelligent instructional programs; (b) 7000 pictures; (c) 90 minutes of symphony-quality music; or (d) 20 hours of telephone-quality voice. Mixtures of all of these on one disk are quite possible.

52 As experience is gained in developing educational software, it is becoming clear that much more versatility and computational power is needed for the development effort than for the delivery system on which the final product will be used. Further, once the strategy of developing on a powerful computer for delivery on a simpler one is adopted, it is possible to precompile images and decision tables in many cases, further decreasing the requirements for a delivery machine. One sensible approach might be to use some of the less expensive professional workstations, to develop educational software and then to deliver it on a CD-ROM player designed for the consumer market. This approach is addressed below. It is important to note that even the cheap delivery systems described will be many times more powerful than the computers being used in most schools today. Because of the high cost of software development talent and its scarcity, it will not be possible to support substantial development of more advanced educational products for school machines with much less than 500,000 characters of memory and a processor of the power of the 68000 chip family.

Advanced Personal Computers for Software Development

53 Most of the tools needed for advanced educational software development can be found in the powerful artificial intelligence workstations now selling for $20,000 to $100,000 each. These machines are not that much more powerful than some of the personal computers now being sold. Indeed, it is already possible to pay a second company to convert a Macintosh Plus into a machine that is virtually identical, in terms of basic capability (four megabites and a 68020 processor), to the AI workstations. However, the software tools for educational product development are only beginning to appear. Nonetheless, it seems feasible to think of software development taking place on any of a number of products that will sell next year for about $3,000 to $5,000. To these products must be added an ability to store and retrieve video displays — at least static video. This also will be possible, it appears, as write-once video disks appear.

54 What is missing from this scenario is the appropriate software. Some of what is needed is being developed by consortia of universities who have as their goal the design of a cheap workstation for use in college classes. However, it will probably be necessary for national governments to fund the development of tools that are adapted especially to basic skills education. Nonetheless, this is at least feasible. Such systems will need to permit full exploitation of the computer-generated graphics, video, and audio possibilities that can be delivered with the type of system described below. Further, because of the complexity of display possibilities and the likely changes over the next decade, the development systems should support the use of object-based languages that permit appropriate decoupling of the specifics of displays from their content.

The Compact Disk Player and its Evolution

55 For instructional delivery, the compact disk player seems the most sensible possibility. Driven by the audio recording market, compact disk players are becoming ever more sophisticated and powerful. Companies are beginning to think of new consumer products that would interact with the user and that would have the ability to deliver not only audio, but also computer line graphics, video images, and high-quality text displays. The user would interact via a pointing device, such as a mouse, or, if necessary, via a keyboard. Within a few years, if adequately driven by the consumer market, such systems might cost less than $1,000 each. As can be seen from Appendix B, which describes the basic capability likely to exist in such a system, it would be much more than most school computers have today, even if considered just as a computer (e.g., it will have most of the capabilities of a 512K Macintosh).

56 Because of the market success of the compact disk player, such a product will appear by next year. It will be affordable and will have most of the capabilities of the artificial intelligence workstation. Appropriate media standards are now under development. These machines, designed for the entertainment market, will nevertheless have substantial temporary memory, high-quality video and audio, and a high-speed processor. Because they are aimed at the entertainment market and a large sales volume, they will be priced initially at barely over $1,000 (not including monitor) and will probably drop to $500 by 1990 or before.

57 This market fact means that even less-wealthy OECD countries can count on using the new technology. The time for serious cognitive research and development is at hand. Today's prototypes will be deliverable as affordable products for the education world faster than we can design and build them.

The Economics of Educational Product Development

58 It is easy, and currently commonplace, for school officials to react to the most recent and advanced educational systems as impossibly expensive. The hardware possibilities just discussed will not solve the problem of software production costs, which will remain very high for good products. Nonetheless, such systems seem to have great potential for improving education where teacher quality is low or education costs unbearably high (e.g., at least for science and math education). We should fully examining the implications of the most advanced possibilities. But, we should also give some consideration to the evolution paths whereby such technology might reach school children.

59 The rapporteur has spent some time in rather heated arguments with a U. S. Air Force economist over this matter and has discussed it at some length with a colleague, Walter Schneider. It appears that few if any organizations (even large governments) will be able to routinely commission the development of the richest intelligent instructional systems now possible for whole curricula. This means that some amount of at least implicit cooperation will be required among organizations before systems of the complexity of *Notecards*,[6] *AlgebraLand*,[7] and even the Anderson geometry tutor[8] can be developed and implemented in schools. However, if even a few such programs are widely publicized, we can expect to see numerous efforts to build most of their capability into smaller systems.[9] Every OECD country should at least be in this wave of followers and should be closely watching and talking to the leaders.

60 One example of the diffusion of ideas developed on powerful artificial intelligence machines involves *Notecards*. *Notecards* was first developed on a Xerox 1109 artificial intelligence workstation. Since then, many of its ideas have been moved to systems designed at Carnegie-Mellon University for the IBM PC RT and to software designed at the University of Michigan for the Macintosh. As a result, within a year, some students will be using these tools on personal computers to help organize and understand the contents of college texts and lectures.

61 While many routes exist whereby sound educational ideas can, once demonstrated in prototype form, be brought to the mass market, the original large-scale ventures will require funding by national or international institutions. One must remember that each of these systems rests upon a substantial body of deep cognitive theorizing and task analysis. The exemplary systems just mentioned are really prototypes used to clarify researchers' broad theoretical efforts. Others that could be mentioned test current theory through the design of systems for industrial training.[10] Further, these exemplary systems represent the quantum jump needed to move practice away from traditional formats for human-machine interaction and to develop control structures for instructional systems.

62 What is most likely to be successful is a sort of dialectic, in which these extremely expensive prototype efforts from wealthy countries are confronted by the smaller and cheaper products of private enterprise and less-wealthy countries. Perhaps aspects of the space programs of some western countries have similar properties when they lead to "spin-off" products that are then brought to the consumer by private entrepreneurial efforts in other countries. Given such a scenario, the potential of new cognitive science and technology can be synthesized with a concern for cost control. We should give attention to the costs issue and to developing more ideas on how new potential can be successfully and economically used.

EDUCATIONAL METHODS USING THE NEW TECHNOLOGY: EXAMPLES AND EVALUATION

63 Intelligent computer-based instructional systems, which are made possible by continuing advances in cognitive science, have two major values. As a tool for education, they permit forms of learning that are not readily enabled by conventional means. As laboratories for rigorous ecologically valid research on learning, they are a means of testing and expanding sound cognitive theory that is relevant to education.

64 For education, intelligent computer instructional systems afford the opportunity for an enriched extension of laboratory instruction, both in the sciences and in other subjects for which laboratories are not currently available. A second use is to provide practice in carrying out complex mental procedures, often with intelligence coaching or feedback about performance that is immediate and pertinent. Laboratory and practice experiences, as well as other forms of learning, can form the basis for educational conversations, providing a concreteness that assures that the student accurately understands what the computer qua teacher is saying and that he/she has appropriate referents for initiating his own queries and responding to those of the machine. Finally, new approaches to the description of causal relations allow the use of computer simulations that are overtly explained in ways that can be understood and that can lead to conceptual learning.

65 In addition to their uses in improving education directly, intelligent instructional systems also are important tools for research. First, they permit more detailed data to be gathered and more complex treatments to be applied, making them well-suited to the testing of cognitive theories, which are often complex. Second, they offer hope of a more rigorous experimental educational psychology, since it is easier to have replicable treatments if they are administered by a machine than if they result from verbal instructions given to teachers.

66 These two roles for the computer, as a medium for education and as a medium for research, have a deeper interconnection. The computer affords new approaches to education and to the performance of cognitive skills that are so substantial as to require a fundamental redesign of both the content of courses and the principles of learning whereby content gives rise to curriculum. The next few sections develop, explain, and provide examples of the points made above.

Exploratory Environments (Laboratories)

67 Increasingly, recent cognitive psychology has supported the view that learning is a constructive process, that the learner constructs new knowledge in response to experience. Some experiences occur in the world of objects, some in the world of talk (didactic instruction), and some in the world of reading. In every case, though, it appears that learners use their prior subject-matter knowledge and certain more general skills of learning to make sense out of their experience, to decide what changes in their knowledge it suggests. Thus, what is remembered from a text is a function of the prior knowledge the reader brings to it, and what is remembered from a laboratory experiment depends on what the learner knew to look for.

68 What this means is that effective learning involves taking a position on instructive experiences, deciding that they merit certain changes in what one knows or what one is prepared to do. The position taken by an effective learner should be one that is consistent with the current situation he faces, his goals, and his prior knowledge. Perhaps an appropriate position will leap out at the learner immediately, but perhaps it will not. Our own everyday experiences suggest that there might be value in taking a tentative position and then testing it. This suggests that learning will be most efficient when such testing can be done easily and accurately.

69 When an instructor speaks to a class, testing of knowledge constructed from his utterances is difficult. Generally, the need for a test arises in the midst of processing the instructor's speech, making any "thought experiments" difficult and potentially interfering with initial processing of subsequent utterances. Questions can be asked of the instructor, but with a large class, allowing all such questions would use up too much of the lecture period. Class discussions allow the development and testing to be a group experience but still involve "thought experiments." When learning is from a book, "thought experiments" are also possible, but when learning from a school laboratory experiment, the concrete artifacts of the experiment may be more memorable, allowing more complete learning.

70 Of course, it is possible to create laboratory environments that permit concrete experiments rather than "thought experiments." That is, the learner reasons to himself

> If I do X to Object Y, then the knowledge I have constructed leads me to expect that Z will occur.

and he is able to test his reasoning. The ability to concretely test hypotheses provides a means for accurately constructing knowledge without having to mentally simulate exactly the material one doesn't yet understand. Presumably this is one source of the utility of laboratory experiences for learning.

71 There is, of course, no guarantee that students placed in a laboratory will automatically take advantage of its efficiency as a learning environment. They may need to be taught skills for learning, and they may need coaching or guidance as they attempt to use the laboratory. Because of bad controls and inadequate

conceptualization of experimental questions, not all of the experimental literature on the utility of laboratory experiences is easily evaluated. There have been a number of experiments on the utility of "discovery learning," but these have tended to be horse races in which the contending approaches were not adequately specified. There are a few results suggesting that "guided learning" is better than either didactic instruction or discovery learning, where "guided learning" seems to be more or less the same thing as coached work in a laboratory environment.

72 Empirical support notwithstanding, the above-stated rationale suggests that laboratory experiences may be critical to education in situations when there is high probability that the student cannot construct knowledge reliably without testing it against reality (actually, against accurate representations of the scientist's reality, the theory). Traditionally, science courses have included laboratories for more or less this reason.[11] It is an unfortunate reality that laboratory instruction is becoming less available to students even as we become more able to understand why it is important.

73 There are many reasons for the decline in laboratory instruction. First, it is expensive: it requires sometimes-delicate and costly equipment, while textbooks are cheap and more or less indestructible.[12] Having a lab for a course requires both money and the procedures for replacing and maintaining equipment on short notice, neither of which schools tend to have. Second, laboratories require better teachers, since a wider range of on-line handling of student inquiries is necessary, as are certain physical and cognitive skills — for doing demonstrations. Third, they are potentially dangerous in some cases. Demonstrations involving slightly radioactive compounds, bullets, and other attention-eliciting props were common in my education but probably would not be acceptable in the current age of litigation.

Laboratories Are Not Just for Science Courses

74 Fortunately, the computer can provide a variety of laboratory environments, at least in simulation form. The "what if" questions that students need to ask in order to test the knowledge they are constructing can be asked via simulation without danger. Further, the experiments a student performs in a simulation environment are repeatable without the cost of new chemicals or the replacement of broken or melted glass. Indeed, experimentation as part of learning is no longer even restricted to the sciences. For example, tools exist for experimenting with different text structures and argument forms and with the implications of different economic principles. Here are a few examples.

75 John Seely Brown, Frank Halasz, Tom Moran and others at Xerox Palo Alto Research Center are experimenting with a system called *Notecards*[13] which allows students to assemble notes into both graphic and textual representations of the arguments they wish to make. The simplest representation *Notecards* permits is that of note cards spread about the screen as they might otherwise be spread on a desk. Even for this mundane use, the system offers certain advantages, such as the availability of word processing tools for making notes, the ability to make

notes of different size, and (via scrolling) the ability to put more on a note card than can be visible at one time.

76 However, *Notecards* goes further, providing new tools for organizing one's ideas (and even the process of having ideas). For example, each note card can contain pointers to other note cards that contain elaborations, substantiations, rebuttals, and other kinds of related information. With these links between notes established, the system can even assemble one's notes into a first draft which can then be edited by the student. One can also develop an outline as a graph structure. *Notecards* will build such a structure from a set of note cards that contains linking information, and it will also create the textual note cards corresponding to any nodes that are added to such a graph. The graph becomes an experimentally manipulable object.

Conceptual Reification of Process

77 The capabilities of *Notecards* help to illustrate a basic capability that is built into the best computer tools for exploratory learning. This is the support for reification by the student of the processes in which he has been engaged. The idea is that components of the act of writing can be actively labeled and manipulated. It is not just that students who want to lay out their texts as a graph are provided tools for doing so. Rather, the process of editing as manipulating the relationship between complex networks of ideas and linear, running text is made more explicit, understandable, and manipulable itself as an object of thought.

78 The features that characterize *Notecards* as a potentially useful laboratory environment can also be seen in other environments, including some based in very simple computers. For example, Brown, Burton, and other colleagues at Xerox have also developed a prototype mathematics environment called *AlgebraLand*. This environment provides tools for simplifying equations and for understanding the process of simplification. Simplifying equations is a difficult task for many high school students. One reason for this is that their arithmetic and algebraic skills are not very strong or very practiced and they also do not understand quite what the process of simplification is all about.

79 *AlgebraLand* supports their efforts to practice simplification by giving them a menu of operations that can be performed on equations (e.g., "divide both sides by ....," "add ... to both sides," etc.). It also draws a diagram illustrating the steps the student already has taken. The menu helps remind the student what operators he has available for the problem he faces, and the diagram helps him realize what procedure he is carrying out and provides a basis for thinking about possible strategies. It also permits mental replays of recent actions, allowing the student to reflect consciously on which of his plans have worked so far.

80 Such displays may be a less labor-intensive way of accomplishing part of the same plans that are followed in the reciprocal teaching strategies that have been studied in recent years (e.g., Palinscar & Brown, 1984). These teaching or tutoring strategies are designed to help the student focus directly on understanding what he is noticing in a learning situation and on consciously

constructing knowledge. Presumably, displays that make concrete a record of what the student has been doing can be helpful in this process. What still needs to be provided is feedback on the student's constructed knowledge. To some extent, that may be inferrable by the computer from the structure of the display, just as we ask the student to make such inferences.

81 For example, a student, after looking at several of his recent efforts to simplify algebraic equations, may induce that certain strategies are especially effective. As that student does additional exercises, the computer can determine whether his performance patterns match heuristics that are goals for the instruction. If not, it can call the student's attention to particular "instant replay" diagrams that show the utility of such a strategy or even work a few problems for the student and compare its path in such a display to the student's path. Later, in can behave less optimally and ask the student to make comparisons, so that the student gets practice in evaluating his processing activities.

Practice Environments (Simulators)

82 A related, but not identical, use of computers in education is as a practice environment. For certain purposes, notably pilot training, extremely sophisticated simulators have been available for a number of years. Due to the tremendous savings in fuel costs, aircraft, and human life, these trainers became feasible very early in the computer era. They are expensive and large (many occupy whole buildings). More recently, development of practice environments that can run on personal computers and relatively inexpensive artificial intelligence workstations has become possible, making the use of the computer to support practice more feasible for less critical areas of training and education.

83 The initial effect of the cognitive shift in psychological theory was to emphasize understanding over skill. Thus, it represented a move away from an instructional theory built around practice to one built around initial learning. John Anderson's evolving theory of acquisition (1976, 1983) has now returned practice to the foreground, since it contains both initial learning mechanisms and other mechanisms which are driven by practice. Specifically, initial learning is seen as involving the particularization of general procedural knowledge, the acquisition of verbal (declarative) knowledge, and the use of existing declarative knowledge by relatively general procedures. Practice, in turn, builds and strengthens more specific procedures and makes them more flexible.

84 The critical issue in practice is assuring that the procedure that is practiced is the correct one. For example, one reason homework is not always effective as a practice mechanism is that there is no guidance or feedback from the teacher at the time that the student is actively thinking about the problem. Initial attempts to use the computer to provide practice opportunities involved providing right-versus-wrong feedback to students after they attempted each problem in a set of exercises, along with some summarizing data that sometimes permitted off-line evaluation of the student's current level. However, such feedback did not tell the student what was wrong with the incorrect performance.

85 The simplistic level of feedback provided by a generation of "electronic page turner" programs derived from two sources. First, there was the behavioral view

that learning consisted in waiting for the student to make the correct response (or at least a response that is closer to being correct than past efforts) and then reinforcing that correct responding. Indeed, in cases such as simple arithmetic, where a student can often figure out why his answer is incorrect, such an approach might be sensible. However, when more complex conceptual learning, or even complex performances, are the target of education, the kind of feedback needed is more complex.

86 Suppose that you were practicing tennis serves. Relative to simply waiting for good form and then rewarding it, a decent coach might make some suggestions that might help you discover how to serve with good form. Indeed, if a coach simply said "wrong!" every time you served incorrectly, you would probably not recommend him/her to your friends. We recognize that in sports, practice without good coaching is not necessarily very productive.[14] We need to have a skilled teacher look at our performance and suggest small, manageable changes that will bring us closer to optimal performance.

87 In order for a computer to provide such coaching, it needs to know what to say in response to performances that are at varying points along the learning curve. Put another way, intelligent coaching programs need to be able to look at student performance and evaluate it with respect to expert performance, deciding what the student can already do and what could lead the student a bit closer to expert performance. This requires three kinds of knowledge: knowledge of expert capability, knowledge of how to recognize the specific capabilities of a student, and knowledge of the course and mechanisms of learning.

88 When we speak of an intelligent tutoring system, then, we mean one which has these three types of knowledge. A number of practice environments have been built in prototype form, and a few have either become commercial products or have influenced commercial ventures.

89 Some domains, such as computer programming, for example, contain knowledge which is acquired primarily through practice. The critical content of a computer programming course is not the small number of language conventions but rather the ability to write programs, a skill which comes through practice. More generally, intelligent instructional systems are compatible with a trend within cognitive psychology to see relatively complex procedural skills more as skills and less as bundles of declarative wisdom. This tendency has certainly been increased by the presence of two kinds of learning theories in the broad cognitive psychology world.

90 Anderson's theory (1976, 1983) explicitly calls for much learning to take place through practice. It is via practice that very general heuristics gain the specificity and domain-specific tailoring they need to be powerful. More generally, it is through practice that conscious, temporary-memory-limited procedures are "compiled" into efficient, relatively-automatic form. The other main contender for a theory of learning, the family of massively parallel network theories, also is practice-driven. Only through practice can the specific path weightings that are distributed throughout a parallel network be properly set.

91 Overall, then, we see that the trend toward viewing practice as a key cognitive learning activity is supported and manifested in the computer tools for cognitive practice that are beginning to appear.

Increasingly Complex Microworlds

92 A particularly powerful approach to the design of practice environments was introduced almost a decade ago by Fischer, Brown, & Burton (1978). This is the concept of increasingly complex microworlds. The basic idea is that from the outset, an entire skill is practiced, but in increasingly complex environments. The specific analogy offered by Fischer and his colleagues was that of skiing. Prior to the invention of the short ski, training in skiing consisted of a long period of exercises that were done without skis. this is because skiing was dangerous, and considerable muscle control and mental preparation were required before it could be done safely. Many potential skiers gave up before they ever got to the slopes. Others tried using skis before reaching the high levels of strength and preparation that were required, and ended up with broken legs.

93 With the invention of the short ski and the safety binding, the whole situation changed. People were almost immediately on the slopes, using progressively longer skis and attacking progressively more complex slopes as they became more competent. Overall, more people learned to ski than before, and more attained true expertise. Training time to reach a given level of skill was cut dramatically. The wholistic approach, combined with carefully selected increasingly more complex practice situations, was a great success.

94 However, it did become necessary for skiing instruction to be designed more carefully, and more preparation was required before instruction could be offered. A more specific curriculum needed to be developed, and appropriate slopes had to be selected that embodied just the right challenges and prevented the need for skills not yet acquired. For example, initial runs needed to be made on a slope that ended in an uphill segment, because initially students did not know how to stop themselves.

95 It is now regularly asserted that perhaps cognitive skills might be taught by providing practice in progressively more complex simulated environments, presented on a computer. For example, students could, from the outset, be doing science rather than memorizing its outcomes. Initially, they might be given a lot of tools that summarize data and help them keep track of their hypotheses and hypothesis-testing strategies. Later, some of these "crutches" could be removed, just as training wheels are removed from a child's bicycle. Fischer has written of the need for "cognitive oscilloscopes" to help students see the structure of complex data they may encounter in such environments (Boecker, Fischer, & Nieper, 1985). There is great promise in this concept of increasingly complex microworlds, and it is already being used in a number of laboratories to produce technical training systems (e.g., at Bolt Beranek and Newman in Cambridge, MA, and in the Learning Research and Development Center in Pittsburgh). The experience so far is that the approach is very powerful but that the "crutches" must be carefully tailored to the environment. As a cartoonist recently noted, training wheels work better on bicycles than when learning to ride an elephant!

Bases for Educational Conversations

96 In some respects, practice and exploration are not very different. Consider, for example, medical practice. Deciding what is wrong with a patient is the major activity of medical practice. Accordingly, one would assume that practice environments for learning medicine would involve practice in making such diagnoses. On the other hand, a medical case (and the knowledge to which the case relates) is, in a very real sense, an exploratory environment. The student must try to account for all of the symptoms with a concise explanation derived from models of disease and of organic function. More generally, any problem solving task can be couched within an exploratory environment, where the problem space and available problem-solving operators are made explicit, to be manipulated explicitly by the student.

97 This being the case, a critical part of the process of designing an intelligent practice environment for an intellectual activity as complex as medical diagnosis is to determine the core activity around which instruction should center. For medicine, this is the model of the specific patient (Clancey, 1986). All activity focuses on understanding the patient, given his symptoms. Another critical part of the design task is to understand the fundamental conversation forms that are part of the core activity. In the case of medicine, the fundamental conversational form is probably the consultation, in which one physician discusses a case with another, seeking and offering advice. Indeed, important current research focuses on understanding the speech acts that occur when one or both parties to a consultation are trying not only to advise, but to teach (cf. Evans & Gadd, 1986).

Symbiosis of Cognitive Research and Instructional Design

98 In summary, the design of intelligent practice environments involves considerable cognitive psychology. The nature of instructive conversations, their speech acts and the educational strategies they can employ, must be understood. The domain of expertise itself must be understood. Especially important, the fundamental cognitive activity of the domain must be identified, and theories of domain content and its acquisition must be developed, before intelligent guidance of the cognitive practice can be offered.

99 The primary costs and the fundamental activities in building intelligent computer-based instructional systems involve developing specific understanding of the subject matter to be taught and formally representing that understanding in the computer software.

Causal, Functional Explanations

100 In spite of the position taken above, not all of learning is practice of procedures. Part of education is to impart understanding. In this area, as well, there have been important advances. A driving force in this area has been the analysis of expertise (Chi, Glaser, & Rees, 1982). An important characteristic of expert performance in solving problems is that experts invest substantial proportions of their total effort in representing or modeling the problem they face. From such a

representation, they then proceed toward a solution. Less-expert problem solution is, instead, characterized by reliance on superficial cues.

101 Work on the nature of the mental models has focused on several issues, including the nature of the models (e.g., Gentner & Stevens, 1983), how they are used in cognitive activity, and how they might be conveyed (e.g., de Kleer & Brown, 1984). The issue of what it takes to understand and explain the functioning of devices is an important general issue for artificial intelligence research that goes beyond concern about instructional systems. Any expert system with a critical task will have to be able to explain its decisions and performance to humans who use it, or it won't be trusted. Further, certain tasks machines may perform, such as diagnosing failures in complex equipment, will require some amount of reasoning from basic understanding about equipment function.

102 When designing the knowledge that constitutes understanding of a device, there are two important levels of that knowledge, the behavioral level and the functional level (cf. de Kleer & Brown, 1984). Behavioral descriptions tend to describe individual device components. For components such as those in electronic systems, the behavioral description is an account of the input/output relations for the device. For example, the description of a resistor is given by Kirchoff's and Ohm's Laws. It is useful for such descriptions to be organized as qualitative constraints, e.g., If the voltage across a resistor increases, the current will also increase.

103 A description of the behavior of each device, while often all that students are taught, does not constitute an adequate description of how the total system encompassing those devices works. For example, knowing how transistors, resistors, capacitors, diodes, and chokes work does not tell one how a radio works. The knowledge of how a system composed of various devices works is called functional knowledge. A primary part of functional knowledge is an understanding of how changes in one part of a system affect other parts.

104 Powerful computer tools can be developed for teaching functional knowledge. Such tools represent a major new force in science and technology education (and perhaps other areas as well). This is partly because they can provide a more faithful view of overall system function than can be provided by direct experience. Consider the task of explaining what is happening when a digitally tuned radio is tuned to a particular station. In experiencing the tuning process, the effects of pressing the tuning button are instantaneous. In reality, though, a complex cluster of changes propagate through the system. A computer simulation can unfold those changes in "mythical time," showing each successive qualitative change in a device of the system (de Kleer & Brown, 1984). The changes can be examined at various levels of grain, from individual transistor logic to large functional units. System relationships that are not viewable in the real world can still be enacted on the screen.

105 The verbal description of system function is not adequate for conveying this sort of knowledge, since expertise includes not only the ability to describe standard intrasystem relationships but also the ability to predict the effects of various inputs to the system, a procedural skill likely to require practice. What the

computer can do is to provide a good arena for that practice, the world of mythical, but functionally accurate, time.

106 Psychological research, even in its most basic flavor, is heavily influenced by applications possibilities and requirements. Because we can now teach functional understanding better, we have more incentive, and can give higher priority, to studying what functional understanding is and how it is acquired. It is likely that work in this area will be substantial in the near future. Further, the ability to present causal information in tractable form will raise a new set of frontier questions about how else we can understand function. In subatomic physics, the simple causal account just given is not appropriate to describing certain systematic relationships. By being able to more easily teach some knowledge that was formerly hard to teach, we also set the stage for dealing with the next problem on the list, explaining fundamentally stochastic systems.[15]

The Computer as Research Assistant

107 In addition to being an important new teaching force, the computer is an important new research instrument for educational psychology. In the past, experiments could either be done at a very microscopic level in the laboratory or at a very diffuse and general level in the classroom. Because artificial intelligence methods allow us to specify processes in terms of the underlying principles that describe or generate them, the treatments in computer-based educational experiments can be both more complex and better controlled. Because all of the transactions, the learning conversations, are machine mediated, a complete record of the subject's behavior is also being recorded, in machine-readable form. The result is that there is potential for a much more rigorous and much more detailed empirical psychology of education to match the more elaborate theoretical work now being done. Without this new empirical power, it is unclear that the theoretical work will progress toward clear applicability.

PROMISING AREAS OF RESEARCH AND PROTOTYPE DEVELOPMENT

108 As a means of summarizing some of the material above from a different perspective, a few candidate topics for increased research and prototype development support are briefly discussed below. These are a well-chosen sample, but still only a sample, of the issues and concerns raised by the Working Groups.

a. Intelligent tutoring systems are starting to be developed and tested. The skills needed to do this development are not yet readily taught, except through apprenticeship. There is need for support of projects with specific mandates to (i) develop generally usable software architectures, curriculum development procedures, and programming tools for intelligent tutor development; (ii) evaluate the effectiveness of specific intelligent tutoring methods, since the approach, taken as a whole, is too diffuse to evaluate; and (iii) study the effects of intelligent tutor availability on the organization and function of classrooms and schools.

b. In order to provide appropriate advice to a student, a human teacher intelligent tutor must have some representation of a student's current capabilities. Such a representation can be very diffuse and general (e.g., the student is on Chapter 5 of the text and is generally a slow student), or it can be very specific (e.g., the student understands how to subtract in a single column but does not understand how to regroup over a zero, so he fails to do problems such as *402 - 219* correctly). Many students seem to pass through the same basic learning states in the same order, but at different paces, so the general student modeling approach may be sufficient for some purposes. On the other hand, some students develop incomplete or incorrect mental procedures which teachers cannot easily detect. Perhaps the only way to remediate them is via very detailed diagnosis followed by highly tailored advice. While these general truisms are apparent, there is not a well-principled means for deciding how deep a student diagnosis capability must be for a particular application. Since such diagnosis is computationally expensive and difficult to design in the first place, it would be good to have some rules of thumb for when to do it.

c. Clearly, we would like our children to have very general skills, so they can attack any situation they encounter. However, there is considerable evidence that competence in any domain requires considerable domain-specific knowledge. Research is needed to clarify the methods for teaching domain-specific knowledge. Specifically, we need to know how to promote the abstraction of more general, transferable skills from specific learning, how to tailor instruction to the level of learning skills the student already has, and how to enhance those learning skills.

d. The final topic in this sample of R&D funding suggestions is quite different, but equally important. This is the use of the most powerful educational applications of the new information technologies to teach teachers. Every major worker in the field of educational technology gives lip service to the need for teacher training, yet not enough occurs. If the information tools we have discussed are so valuable to students, then surely it should be possible to build some that are tailored for in-service education of teachers. We envision a school in which the teacher wants to use the computer for learning whenever the students are not using it. Such an environment is possible, but initial prototype and demonstration efforts must be created and funded. Organizationally, this has been difficult because funding for educational computing is aimed at students, while teacher retraining is handled by separate administration in most countries.

Fostering Cooperation between Researchers in Different Countries

109 One means for both spreading information about uses of information technologies in education and increasing the rate at which research and development occurs in this area is to improve communications possibilities for researchers in different countries. EARN and BITNET offer important advances in this area, and it is critical that the researchers who drive technology development, curriculum development, and teacher training in each OECD country have access to these networks and maintain contacts with appropriate laboratories in other countries.

III IMPLICATIONS FOR EDUCATIONAL PRACTICE AND CONTENT

A FORCE FOR CHANGING CONTENT, CURRICULUM, AND PRINCIPLES OF LEARNING

110 In recent work my associates and I have conducted for the Air Force, we looked at the training and the on-the-job skills of Airmen who repair navigation instruments on planes. We found that those Airmen who were doing best on the job had a clearer and more elaborated sense of how aircraft systems operate and of how faults in system components can be detected. That is, they had better procedures which they also better understood. This requirement of skill plus understanding is common in many knowledge domains that are taught via formal schooling, and it is often not attained. Children often do not understand the meaning of arithmetic operations they perform, the rationale for writing an outline before writing a research paper, the reason for performing a chemistry lab procedure in a certain way. Auto mechanics sometimes do not understand the reasons for manufacturers' instructions on the repair of new technology, such as fuel injection systems.

111 Because we feel that skill without understanding is insufficient, and it usually is, courses and training programs tend to include both a conceptual component and a procedural component. Regrettably, these are usually treated as two entirely separate activities. The student gets some crude set theory and he also learns arithmetic, but the two are not connected. The technician is taught basic electrical concepts as well as procedural algorithms but does not understand how the two relate. One important promise of computer-based exploratory systems is that procedures can be represented and labeled in various ways, allowing them to become objects of the conceptual world as well as things to do.

IMPLICATIONS FOR INSTRUCTIONAL PRACTICE

112 As one reads the reports of various commissions and task forces on education in the western countries, a common theme emerges, the need for better development of problem solving and other higher-order thinking skills in our children. Rapid social and technological change implies a continuing need for flexibility and for skills of efficient learning. That which is routine, for which we can easily teach children algorithms, is a sensible target for automation. What is left for human work roles are positions requiring judgement, flexibility, and the shaping of existing procedures to novel situations. Those who hold jobs which appear to be rather routine in their requirements will find continuing need to be retrained to use new equipment or fill different roles. It is likely that the pattern will continue of exporting high technology jobs to less-developed countries as we come to understand how to organize "cognitive assembly lines."

113 This suggests that new curriculum must emerge that extends subject matters to emphasize the solving of everyday as well as technical problems, something schools have never done universally well. Those who develop the new materials and approaches may want to consider specifically how information processing tools can be useful adjuncts for teachers as they pursue this new curriculum item.

114 We offer one example of the way in which computer tools can dramatically change the content of a course. Many students take computer programming courses as part of the basic skills curriculum. Just as language arts courses have often succumbed to the overuse of syntax exercises instead of emphasizing writing and revising of essays and other genre, so computer programming courses tend to emphasize syntax over the design of algorithms, especially when taught in elementary or high schools. This is because the computer will reject any program that is syntactically ill formed. Efforts to help students deal with the syntax barrier to computer science sometimes compound the problem. For example, one well-meaning college taught BASIC for the first six weeks, because it has an easy syntax, and then switched to PASCAL, which is easier to use in demonstrating the structure of algorithms. Of course, the students complained because they now had to master two syntaxes.

115 In recent years, researchers have started to develop structured editors that permit students to write down programs without even knowing the syntax. In essence, the student specifies a plan structure for his program and then fills in details. The editor will not let him make a mistake and provides advice that is in terms of the algorithm being coded, not punctuation. One such editor, called GNOME, was developed at Carnegie-Mellon University. A similar approach has been used by Jeffrey Bonar and Eliott Soloway to build an entirely new curriculum, and Bonar has built a tutor to be used as a problem solving environment within that curriculum. Students begin by specifying, in everyday terms, using a menu, a plan for solving the problem. "Gworky, The Friendly Troll" appears on the screen as necessary to provide advice. Then they translate the plan into a formal representation of an algorithm. Finally, they use a structured editor, which eliminates the need to worry about superficial aspects of program punctuation, to write a program that carries out the algorithm. Throughout, the tutor offers coaching, eliminates the distractions of programming details that are superficial but potentially overwhelming, and proceeds by starting from the student's understanding and working toward the target knowledge.

Recurrent Themes during the Working Group Meetings

116 A number of themes recurred in the various working groups, even though each addressed a different subject matter. A brief summary of themes relevant to educational practice and content cannot do justice to the many good ideas expressed, but perhaps the list which follows will prompt the reader to examine the four individual working group reports.

a. *Adapting to a world full of information tools.* Our children will have cheap tools for doing many things that people once did for high wages. These tools make possible new thinking performances that are not currently part of our curricula. We need to consider whether to teach more about how to compile larger documents now that word processing tools make this easier. Perhaps we should focus more on scientific reasoning processes, since some of the knowledge we have today will be obsolete quite soon. Perhaps even more attention to critical evaluation of arguments is needed in the era of media politics, saturation advertising, and massive contasts in standards and styles of living among peoples that watch each other on television. Perhaps we need to rethink the role of arithmetic drill in the mathematics curriculum in the age of the cheap calculator.

b. *Concreteness of instruction.* Lectures are inherently abstract, but learning thrives on concreteness. Perhaps the new tools for reifying mathematical, rhetorical, and scientific processes of understanding, inference, and evaluation can permit a much more concrete set of instructional methods while simultaneously providing a chance for more children to make important abstractions. The use of tutored or coached learning environments can also help to clarify understanding and to promote analytic thinking.

c. *Technical aids.* Calculators, word processors, and other tools should not be kept out of the classroom just because curricula have yet to take account of their existence. While there may be good reasons for students to learn to do things that information tools can do for them, they should also be learning to use those tools routinely.

d. *Blending of disciplines.* All of the working groups debated whether there should be more unification of the curriculum. The new information tools straddle the boundaries between reading, writing, science and mathematics, and it would be tragic if they were sequestered into one domain or another simply to avoid the need to consider whether reading and writing, for example, might not be better taught partly in the context of science. Most of the new information tools will be useful in most or all of the four subject areas.

e. *More research and analysis for curriculum development.* We can no longer assume that it is obvious to all of us what should be taught as part of the basic skills. While our intuitions are valuable in avoiding faddish oscillation in curricular goals, deep thinking and research is needed to clarify the specific thinking processes that are particularly hard for students to master. The curriculum should be designed to assure that learning of those critical skills is facilitated.

f. *Teacher retraining.* New insights into what to teach and how best to teach it will not improve education unless teachers currently in the field acquire facility in using this new knowledge. This facility will include skills, which require coached practice, and will be grounded in curricular specifics. They cannot be taught in a lecture of a few hours.

g. *Social effects of new information technologies.* With the new tools of thinking and practice in using them, the rich child with certain home computers will have a strong advantage over the poor child whose parents cannot afford and do not themselves experience computer tools. Failure to act strongly to modify the curriculum and children's classroom experiences to take account of the new information technologies has the effect of multiplying the multigeneration influences of individual wealth and parental social status.

h. *Individualization.* By providing productivity-enhancing information tools, we can allow teachers to more readily teach all of the children in their classes. Currently, some children may be a few years behind their classmates in reading and math skills while others may be years ahead. Without individualized instruction, the slow child is frustrated and the gifted child trained to be mentally lazy. With a sufficient array of instructional tools, students who are moving at a different pace can get at least some of their instruction at an appropriate level, even if there are many childen in each class.

RECOMMENDATIONS

117 The Working Groups made a number of recommendations which are summarized in this last section. Some of these recommendations represent advice to all levels of government and society, while others are specifically proposed to OECD countries for national actions or to the OECD Secretariat for specific actions in its 1987 programme of work. The general character of these recommendations is consistent with a pattern that decision makers have seen for a number of years. Each time new resources become available for education, some good occurs, but many actions are taken without clear enough understanding and consequently with minimal positive impact. The availability of the new information technologies, powerful as they are, has led to the same pattern. Computers do not teach, they do not manufacture knowledge, they do not explain, they do not (in any enduring way) motivate. They are simply an artifact that humans can use to achieve a variety of effects great and small, positive and negative. As tools, they are potentially able to multiply human capability as dramatically as the book, the steam engine, the television, and electrical generator — for good or evil. School leaders throughout the OECD countries manifest disappointment over the minimal extent of the good that has thus far been achieved. However, we feel that the computer will be a powerful, positive force in education. Exciting outcomes are discussed in the Working Group reports. The recommendations below build upon these initial successes. We also note that the computer makes such radical changes in our society that unusual strategies must be employed to optimize its contribution. Ordinarily, marginal investments in education lead to marginal improvements. In using computers, marginal investment often leads to frustration and rejection. Planning, purpose, targeted research, and significant teacher training will be needed to realize the information technologies' full potential.

118 The specific character of these recommendations is important, for they specify research and implementation actions that we believe are needed in order for the potential of the new information technologies to be realized for education. Particular problems in economically and efficiently using the technologies, in training teachers to take advantage of them, in shaping curriculum to take advantage of them, in developing and delivering tools based on them economically have been addressed, and those problems have driven the efforts of the working groups. Action on these recommendations is a critical step in using the only opportunity on the horizon for multiplying the productivity of our educational system to achieve the goal of basic education for all citizens that is adequate to prepare them for life and work in an economic world in which the rapid changes in productive technology that we can expect will require continual learning and relearning, training and retraining.

EFFECTIVE EDUCATIONAL SOFTWARE

119 Because of a shortage of well-trained teachers, which is greatest in mathematics and science education, effort should be invested in systems that can supplement the limited supply of teachers. Research and development is needed to bring about the tools that instructional designers can use to create effective educational software. Currently, too much specialized computer-related skill is required, displacing attention from the content and quality of the curriculum. In

addition, efforts should be made to involve teachers and students in curriculum design and to produce tools that teachers can adapt to their needs, not rigid systems that coerce students and teachers into unfamiliar modes of classroom activity. Work is needed particularly on the following:

a. Tools for building intelligent tutoring systems and coached exploratory environments.

b. Utilities to facilitate coding, modification, and translation (to different computer languages and for use in different human language communities).

c. Data banks of misconception specifications, diagnostic tests, video images, and student information resources.

d. Tools for building graphics and student-computer interfaces, tasks that consume much of the development time for computer-based instruction and on which much of its success or failure depends.

e. Tools for rapidly encoding enough information about the structure and content of electronic text databases so that students' informational retrieval tools can readily use them.

f. Methods for evaluating computer-presented lessons.

120 Exemplary prototypes for which annotated source programs and well-crafted design notes are in the public domain are needed to facilitate training of instructional designers. Among the prototypes that would be of great value are:

a. Intelligent tutoring systems.

b. Programs especially sensitive to differences in cognitive capabilities, i.e., examples of software which tailors instruction to individual students' capabilities.

c. Guided exploratory environments.

d. Tools for written composition, editing, and revision.

e. Instructional systems that exemplify contributions of cognitive science.

f. Advanced applications that can be delivered on common microcomputers (such as those with MS-DOS, Unix, or Macintosh Plus operating systems).

121 Demonstration and evaluation centers are needed in each OECD country (smaller countries might share development and use of such centers, of course) at which the following activities can occur:

a. The approaches in different countries and different cultural groupings can be compared.

b. Prototype information products for education can be compared and evaluated.

c. Long-term software and instructional development efforts can take place (the field suffers from too much fragmentation and insufficient follow-up of preliminary demonstrations).

122 Demonstration and courseware development projects with the following characteristics are needed in each OECD country:

a. Close interaction among related efforts in different countries.

b. Involvement of entire schools rather than isolated classrooms.

c. A commitment of teachers in the demonstration projects to adapt their teaching and their use of new information technologies to better prepare students for living in the information age.

d. Ready access for all students to computers and software during regular school classes, study hours, and after school.

e. Close collaboration among students, teachers, teacher educators, software developers, and researchers.

f. Opportunity for teachers and students to work out their own ways of teaching and learning with the new information technology without having to make regimented use of methods and curriculum imposed from outside.

g. Thorough documentation and dissemination of results and evaluation data.

123 Real schools are not as ideal as the protected environments of demonstration projects. Sometimes, teachers are reassigned at the last moment to teach subjects they know little about. Sometimes, no one has the authority to call someone to fix a classroom computer when it breaks, or even to buy more paper for the printer. Sometimes, the students who need the most help are removed from class for remedial work and thus miss the lessons on how to use the computer or have insufficient time to finish significant computer-based work. A recurring complaint is that software is poorly documented. These recurrent problems, found in classrooms throughout the world, highlight the need for educational, organizational, social, and economic research and policy analysis on how technology can become incorporated effectively into real classrooms. Appropriate topics for such research include:

a. Use of new information technologies by students in economically disadvantaged areas (with attendant potential problems of poor equipment, little parental support, negative attitudes on the part of teachers and/or administrators, etc.).

b. Use of new information technologies by non-native speakers, and the common special problem of multilingual classroom populations.

c. Teacher training in new technology-using instructional methods and new curriculum content.

d. Computer tools are not always used as expected, nor do they always achieve the goals their makers set for them. Sometimes, positive changes occur that were unanticipated (e.g., a teacher who told one working group member that the main thing her students had learned from using a certain software package was not how to write better, but how to work together). Sometimes, apparently powerful tools are ineffective, and we need to study how the potential of new information technologies is blunted when new computer tools are adapted to conform with prior classroom norms and values instead of being used to facilitate new learning.

124 ***Recommendation 1:*** *Each OECD country needs a national center where educational software prototypes can be developed, pilot-tested, evaluated, and demonstrated. Many problems need to be solved before such tools can be used effectively outside such centers. Consequently, an important part of demonstration efforts must be the development and testing of teacher training and a clarification of the institutional and classroom contexts in which potentially valuable products can work effectively. An important additional outcome of demonstration efforts can be a set of tools for more efficient educational software development, but this will not happen unless it is specifically mandated and supported. At the international level, it would be useful to monitor such demonstration efforts and disseminate information about them to member countries. Further, Member countries may need assistance in establishing such demonstration centers, perhaps from visiting teams during the planning phase. Providing these international survey and assistance functions would be a very worthwhile task for OECD to undertake.*

CURRICULUM AND CLASSROOM PRACTICE

125 The existence of new information technologies calls into question the content of the basic curriculum. More important, technology affords an opportunity and a challenge — a reconceptualization of learning and an integration of subject matters is made more feasible (and more necessary) by information processing tools. Students can use graphing tools to analyze data, word processors to facilitate science report writing, intelligent tutoring systems to help them learn to read more effectively, text and graphic databases to gather data for social studies projects, etc.

126 Whether radical or incremental curriculum changes occur, teachers need to be trained in the content and rationale of technology-sensitive curricula and in the technology-enhanced means for teaching these curricula. Development of such new curriculum should be done by teams that include teachers, subject matter specialists, cognitive instructional specialists, and technology experts, and the programs developed must provide for the training of teachers in the new content and new knowledge delivery modes. Particular attention should be given to helping teachers understand their own partly-pre-information-age world views, conceptual frameworks, and thinking strategies and how these differ from those of their students, who have been raised in a technology-rich world.

127 ***Recommendation 2:*** *In each member country, there should be a re-examination of the curriculum for basic skills education in light of the changes wrought by the new information technologies. Particular attention should be given to the knowledge that children raised in a technological world bring with them to the classroom and to whether the separation of curricula for the different basic skills is still productive. These efforts will proceed more efficiently if there are ongoing international surveys and analyses of basic skills curriculum projects in Member countries and a means for facilitating cooperation and information sharing among these projects. Here again, OECD could make an important contribution.*

MATTERS OF INTERNATIONAL COMMERCE IN TECHNOLOGY

Which Informational Technologies Can Educational Systems Afford?

128 As each new level of computer tool has appeared, new educational possibilities have become evident. Researchers have wanted to develop prototype instructional systems that exploit the new power. As the information and computation revolution matures, it is becoming necessary to supplement analyses of what is possible with forecasting of what will be affordable. To the extent that instructional development focuses on equipment that will become inexpensive, it will have far greater impact. Today, certain capability that has not yet entered the classroom can safely be predicted to become as cheap as the cheapest microcomputers now in use. Other equipment, solely because of marketing technicalities, will reach a floor price that is still beyond the means of the average classroom. OECD countries are urged to be sensitive to the need for the industrial marketing expertise that can assist in determining how close to applicability various research and development projects really are.

Issues for International Cooperation

129 The economic questions posed above can also be addressed from the viewpoint of national policies for development and intellectual property protection of information products. Before the full educational potential of information products can be achieved, certain issues must be addressed by the international community. These include the setting of standards for educational software, the facilitation of easy exchange of software concepts and development techniques, and the development of means for promoting the storage of information in forms that permit it to be used for educational purposes.

130 *Software quality.* Thousands of educational software programs exist, and they have improved steadily over the years. But quality is still a problem. For instance, in the United States less than 30 percent of commercial educational software meets minimal standards of technological acceptability; many that do may fail to be pedagogically acceptable. Hence, educational software must be selected cautiously. Although significant advances in industry have occurred in the development of software tools and methods, the fruits of these development tools have yet to be felt in the educational marketplace. Still, new technology for quality software development can be used to educational advantage. More resources should be devoted to producing high-quality transportable software and developing shared methods of software testing and evaluation.

131 *Hardware and software exchange.* Technology is unevenly developed throughout the world. One cannot help notice the insularity of nations developing new technologies. While many new software techniques have great commercial value and cannot be distributed freely, the market for educational software needs to be stimulated by demonstrations of what is possible. Technologically advanced countries should establish economically feasible methods of sharing effective educational software concepts with other countries, through demonstrations, international interest groups, and joint ventures that transfer technology to other

cultures. Exemplary hardware and software should be adapted for international use.

132 *Hardware and software standards.* Regulation and coordination of new technologies are major international concerns. Internationalization of an operating system, for instance, demands that it be adapted to differences in local customs (dates, abbreviations, decimal delimiters, numerical codes for alphabetic characters and diacritical marks, etc.). In addition, student-computer interfaces must display text and allow responses in the user's own language. Finally, software documentation must be translated. Because of these problems, international standards are necessary. Without standardization, gains by one educational group are unavailable to others. Support should be given to open system architectures, in which information can flow, without hardware or software incompatibilities, across different computer systems. With such sharing, educational advances in one part of the globe can be transmitted instantaneously around the world. Most important, for the future of international hardware and software, is the creation of products with modular components that can be easily changed to adapt to the character representations and languages of different countries. International groups can work together to build such architectures.

133 ***Recommendation 3:*** *It is critical that the potential of the new information technologies for education not be thwarted by accidents of the marketplace. Achieving affordable and effective basic skills education is a matter of the highest importance to each member country. Member countries, in developing standards for hardware and software and in making policy for protection of intellectual property rights, should give special attention to the impact of such policies on education. Further, they should, in planning future technology uses, attend both to what is possible with various technologies and also to which technologies will, because of forces outside the education sector, be particularly affordable or particularly expensive. The OECD Secretariat can play a useful role in collecting and disseminating such information.*

COGNITIVE AND INSTRUCTIONAL SCIENCES

134 Research in the cognitive and instructional sciences, especially research using formal and computational techniques from artificial intelligence, is essential if the full potential of new information technologies for education is to be realized. Current applications efforts represent but the beginnings of what can be achieved if we better understand human thinking skills and their acquisition. A number of research areas of especial importance are identified in the Working Group reports and the above summary. These include:

a. Improved principles and methods for analyzing and describing the student's current competence, for diagnosing student knowledge, for analyzing student errors in cognitive performances, and for mapping performance onto the student model.

b. Environmental, instructional, and personal psychological influences on acquisition of concepts and procedures.

c. Methods for stimulating the learning of concepts and mental procedures.

d. Nonverbal mental models and their acquisition.

e. Metacognitive skills (skills for learning, self-management, and attacking problems that go beyond the textbook).

f. How the social organization of the classroom environment affects each of the above.

135 ***Recommendation 4:*** *The OECD Member countries should give high priority to the cognitive and instructional sciences in setting national priorities for educational research. OECD itself might play a useful role by surveying and reporting the activities of Member countries in carrying out the needed research (e.g., level of expenditure, graduate student support, number of active investigators, topics of projects, etc.) and by facilitating international cooperation in these efforts. Electronic communications networks for this purpose have become available, and an electronically accessible directory of researchers involved in this area would be very helpful in stimulating a higher level of international cooperation in adapting education to the new technologies.*

REFERENCES

Anderson, J. R. (1976). *Language, memory, and thought.* Hillsdale, NJ: Erlbaum.

Anderson, J. R. (1983). *The architecture of cognition.* Cambridge, MA: Harvard University Press.

Boecker, H.-D., Fischer, G., & Nieper, H. (1985). *The enhancement of understanding through visual representations.* Unpublished manuscript. Boulder, CO: University of Colorado, Institute of Cognitive Science.

Chi, M.T.H., Glaser, R., and Rees, E. (1982). Expertise in problem solving. In R. Sternberg (Ed.), *Advances in the psychology of human intelligence* (Vol. 1). Hillsdale, N. J.: Lawrence Erlbaum Associates.

Clancey, W. J. (1986, February). *Qualitative student models.* Working Paper No. KSL-86-15. Stanford, CA: Stanford University, Knowledge Systems Laboratory.

Evans, D. A., & Gadd, C. S. (1986, March). *Models for automated medical consultation.* Unpublished manuscript. Pittsburgh, PA: University of Pittsburgh, Decision Systems Laboratory.

Fischer, G., Brown, J. S., & Burton, R. (1978). *Aspects of a theory of simplification, debugging, and coaching.* Proceedings of the Second National Conference of the Canadian Society for Computational Studies of Intelligence, Toronto.

Gentner, D., & Stevens, A. L. (Eds.). (1983). *Mental models.* Hillsdale, NJ: Erlbaum.

de Kleer, J., & Brown, J. S. (1984). A qualitative physics based on confluences. *Artificial Intelligence, 24,* 7-83.

Palinscar, A. S., & Brown, A. L. (1984). Reciprocal teaching of comprehension-fostering and comprehension-monitoring activities. *Cognition and Instruction, 1*(2), 117-175.

NOTES

[1] I am very grateful for the cooperation of the four Working Group Chairmen, Professor Gilbert de Landesheere of Belgium, Dr. Bertram Bruce of the United States, Professor Yves Le Corre of France, and Professor Jim Howe of the United Kingdom. Without their major efforts in distilling the comments of their colleagues, there would have been no conclusions for me to introduce and summarize. It has been an honor to work with them. Further, I know that they would join me in pointing out that a number of individual Working Group members provided substantial amounts of assistance, writing portions of the reports, surveying educational computing uses in the various countries, etc. Their efforts exemplify the selfless spirit on which international cooperation depends.

[2] This section borrows from a presentation by Pierre Duguet, Principal Administrator, OECD Paris. I thank him for making a copy of that presentation available to me. I have modified his ideas and added to them. Thus, he should not be blamed for assertions with which the reader may disagree.

[3] These problems are directly raised in Prof. Le Corre's report of the Science Working Group, but they seem to be general to other basic skills areas and to be implicit in the other reports.

[4] For example, teachers may tell students that whenever a problem contains the word *altogether*, they should add the numbers stated in the problem to reach a solution.

[5] Newell and Simon called methods that did not use domain-specific knowledge "weak" methods.

[6] *Notecards* is a trademarked product of Xerox Special Information Systems that was developed at Xerox Palo Alto Research Center. It allows complex arguments to be assembled into a database. Relations between assertions of an argument structure of the sort used by Toulmin (and earlier Aristotle) can be indicated explicitly between pieces of text, graphics, and other information sources. When used as a writing and thinking tool, data can be added anywhere in the relational structure, and the system can later be asked to assemble the structure into a linearized text. When used to analyze the validity of arguments, it permits gaps in the supporting structure for the argument to be noticed more easily.

[7] *AlgebraLand* is a research prototype under development at Xerox Palo Alto Research Center. It allows students to see the structure of their problem solution paths as they try to simplify algebraic expressions. Thus, it helps students overcome the usual gap between processes and understanding in mathematics learning.

[8] A program developed by John R. Anderson at Carnegie-Mellon University in Pittsburgh. It shows students their evolving proofs as graphs, in which proof lines are nodes and their antecedents are links. Thus, proof is shown metaphorically as finding a path between the premises and the conclusion. Students are coached and help is available as they proceed to do their proofs. Further, the screen display is organized to minimize the temporary memory load the student faces in doing a proof.

[9]which, given the improvements in hardware costs over the several years such efforts will take, may not be much smaller

[10]Each of the U. S. Armed Services has several such demonstration projects underway at present.

[11]There was also the desire to teach "laboratory skills," the skills of using laboratories to test communal constructions of knowledge, or scientific theories.

[12]U. S. textbook investment per child per course per year is perhaps $5 to $7, and the amount spent on computers in the past few years equals the total textbook investment since the founding of the United States in 1776.

[13]*Notecards* is the Trademark for a product of Xerox Special Information Systems.

[14]Indeed, Gagné (Personal communication, April, 1986) tells of relating unsuccessful practice results to Harry Harlow, who thereupon posed Harlow's Practice Law: "Practice may not always improve performance, but it does always take time."

[15]This may include not only subatomic physics but also certain social phenomena. For example, how does one explain how the actions of a few terrorists totally alter the tourism economics of a large part of Europe and Asia? New explanatory methods are being designed and are becoming teachable. This, in turn, poses important challenges to cognitive instructional psychology.

APPENDIX A: PROPERTIES ENVISIONED FOR A CONSUMER-MARKET, INTERACTIVE COMPACT DISK PLAYER

Audio: Plays Compact Disk stereo, but can also provide one, two or three sound channels at once. Can provide lower qualities of sound, too, allowing more storage in each disk. Sound tracks selectable and changeable during play.

Video: Provides TV quality static pictures (256 colors) with the possibility for computer-generated graphics animated on top of video stills. Changes video images as fast as 1/second, with cuts and dissolves via two frame buffers.

Interaction: Has a single universal control system that can output either NTSC or PAL video from the same disk. As easy to use as a phonograph. Is not sold as a computer, so is not as terrifying to the average user. Standardized character and keyboard coding to permit easy use in any country. Possibly compatible with large-format video disk systems.

Marketing: Is priced to sell as a premium-quality audio compact disk player, perhaps at about $1,000 including mouse and keyboard. Is sold as an appliance, not as a computer.

Computer power: We estimate that the power of a relatively fast 32 bit processor and about 500,000 characters of storage would be needed to achieve these publicly announced capabilities. Within a year or two, such capability will be within price range.

APPENDIX B: WORKING GROUP MEMBERS AND CHAIRMEN

READING

Chairman: Gilbert de Landsheere, Belgium

Michael Canale, Canada

Jean Foucambert, France

?r A.J. Aarnoutse, Netherlands

Martin J.C. Mommers, Netherlands

Ingvar Lundberg, Sweden

Robert W. Lawler, United States

Alan C. Purves, United States

Andee Rubin, United States

WRITING

Chairman: Bertram Bruce, United States

Claire Woods, Australia

Ann Cameron, Canada

Anneli Vähäpassi, Finland

Gunther Eigler, Germany

Naomi Miyake, Japan

Kees de Glopper, Netherlands

Hildo Wesdorp, Netherlands

Mike Sharples, United Kingdom

Lawrence Frase, United States

SCIENTIFIC AND TECHNOLOGICAL CONCEPTS

Chairman: Yves Le Corre, France

Steve Murray, Australia

Peter Tillett, Australia

William J. Egnatoff, Canada

Jean François Le Ny, France

Hermann Härtel, Germany

Heinz Mandl, Germany

Hans Spada, Germany

John O'Brien, Ireland

Hidetsugu Horiguchi, Japan

Bob Wielinga, Netherlands

Bernard Levrat, Switzerland

Margaret Cox, United Kingdom

Alfred Bork, United States

Observer: Gérard Weidenfeld, France

ARITHMETIC AND MATHEMATICAL CONCEPTS

Chairman: Jim Howe, United Kingdom

Steve Murray, Australia

Peter Tillett, Australia

Alain Taurisson, Canada

Maryse Quéré, France

John Kelly, Ireland

Maria Teresa Molfino, Italy

Hidetsugu Horiguchi, Japan

Heleen B. Verhage, Netherlands

Tim O'Shea, United Kingdom

Judah Schwartz, United States