The Uses of Computers in Education

The huge information-processing capacities of computers make it possible to use them to adapt mechanical teaching routines to the needs and the past performance of the individual student

by Patrick Suppes

As other articles in this issue make abundantly clear, both the processing and the uses of information are undergoing an unprecedented technological revolution. Not only are machines now able to deal with many kinds of information at high speed and in large quantities but also it is possible to manipulate these quantities of information so as to benefit from them in entirely novel ways. This is perhaps nowhere truer than in the field of education. One can predict that in a few more years millions of school children will have access to what Philip of Macedon's son Alexander enjoyed as a royal prerogative: the personal services of a tutor as well-informed and responsive as Aristotle.

The basis for this seemingly extravagant prediction is not apparent in many examinations of the computer's role in education today. In themselves, however, such examinations provide impressive evidence of the importance of computers on the educational scene. As an example, a recent report of the National Academy of Sciences states that by mid-1965 more than 800 computers were in service on the campuses of various American universities and that these institutions spent $175 million for computers that year. The report goes on to forecast that by 1968 the universities' annual budget for computer operations will reach $300 million and that their total investment in computing facilities will pass $500 million.

A similar example is represented by the fact that most colleges of engineering and even many high schools now use computers to train students in computer programming. Perhaps just as important as the imposition of formal course requirements at the college level is the increasingly widespread attitude among college students that a knowledge of computers is a "must" if their engineering or scientific training is to be up to date. Undergraduates of my generation who majored in engineering, for instance, considered a slide rule the symbol of their developing technical prowess. Today being able to program a computer in a standard language such as FORTRAN or ALGOL is much more likely to be the appropriate symbol.

At the graduate level students in the social sciences and business administration are already making use of computers in a variety of ways, ranging from the large-scale analysis of data to the simulation of an industry. The time is rapidly approaching when a high percentage of all university graduates will have had some systematic training in the use of computers; a significant percentage of them will have had quite sophisticated training. An indication of the growth of student interest in computers is the increase in student units of computer-science instruction we have had at Stanford University over the past four years. Although total enrollment at Stanford increased only slightly during that period, the number of student units rose from 2,572 in 1962-1963 to 5,642 in 1965-1966.

The fact that time-sharing programs are rapidly becoming operational in many university computation centers justifies the forecast of another increase in the impact of computers on the universities [see "Time-sharing on Computers," by R. M. Fano and J. J. Corbató, page 128]. Under time-sharing regimes a much larger number of students can be given direct "on line" experience, which in itself is psychologically attractive and, from the practical viewpoint, facilitates deeper study of the use of computers. There is still another far from trivial way in which the computer serves the interests of education: The large school system that does not depend on computers for many administrative and service functions is today the exception rather than the rule.

The truly revolutionary function of computers in education, however, lies in the novel area of computer-assisted instruction. This role of the computer is scarcely implemented as yet but, assuming the continuation of the present pace of technological development, it cannot fail to have profound effects in the near future. In this article I shall describe some experiments in computer-assisted instruction that are currently being conducted at levels ranging from the comparatively simple to the quite complex and then examine some unsuspected problems that these experiments have revealed. First, however, the reader deserves an explanation of why computer-assisted instruction is considered desirable at all.

The single most powerful argument
for computer-assisted instruction is an old one in education. It concerns the
advantages, partly demonstrated and partly conjectured, of individualized in-
struction. The concept of individualized instruction became the core of an ex-
plicit body of doctrine at the end of the 19th century, although in practice it
was known some 2,000 years earlier in ancient Greece. For many centuries the
education of the aristocracy was primarily tutorial. At the university level
individualized tutorial instruction has been one of the glories of Oxford and
Cambridge. Modern criticisms of the method are not directed at its intrinsic
merit but rather at its economic inefficiency. It is widely agreed that the more
an educational curriculum can adapt in a unique fashion to individual learners
—each of whom has his own characteristic initial ability, rate and even "style"
of learning—the better the chance is of providing the student with a successful
learning experience.

The computer makes the individualization of instruction easier because it
can be programmed to follow each student's history of learning successes and
failures and to use his past performance as a basis for selecting the new prob-
lems and new concepts to which he should be exposed next. With modern
information-storage devices it is possible to store both a large body of cur-
riculum material and the past histories of many students working in the cur-
riculum. Such storage is well within the capacity of current technology, whether
the subject is primary school mathematics, secondary school French or elemen-
tary statistics at the college level. In fact, the principal obstacles to comput-
er-assisted instruction are not technological but pedagogical: how to devise
ways of individualizing instruction and of designing a curriculum that are suited
to individuals instead of groups. Certain obvious steps that take account of differ-
ent rates of learning can be made with little difficulty; these are the main things
that have been done so far. We have still, however, cut only a narrow path
into a rich jungle of possibilities. We do not have any really clear scientific idea
of the extent to which instruction can be individualized. It will probably be some
time before a discipline of such matters begins to operate at anything like an ap-
propriately deep conceptual level.

A second important aspect of com-
puters in education is closer in charac-
ter to such familiar administrative func-
tions as routine record-keeping. Before
the advent of computers it was extreme-
dly difficult to collect systematic data on
how children succeed in the process of
learning a given subject. Evaluative
tests of achievement at the end of learn-
ing have (and will undoubtedly continue
to have) a place both in the process of
classifying students and in the process of
comparing different curriculum ap-
proaches to the same subject. Nonethe-
less, such tests remain blunt and insen-
sitive instruments, particularly with
respect to detailed problems of instruc-
tion and curriculum revision. It is not
possible on the basis of poor results in
a test of children's mastery of subtrac-
tion or of irregular verbs in French to
draw clear inferences about ways to im-
prove the curriculum. A computer, on
the other hand, can provide daily infor-
mation about how students are perfor-
ming on each part of the curriculum as it
is presented, making it possible to evalu-
ate not only individual pages but also
individual exercises. This use of com-
puters will have important consequences for
all students in the immediate future.
Even if students are not themselves
receiving computer-assisted instruction,
the results of such instruction will cer-
tainly be used to revise and improve or-
dinary texts and workbooks.

Let me now take up some of the work
in computer-assisted instruction we
have been doing at Stanford. It should
be emphasized that similar work is in
progress at other centers, including the
University of Illinois, Pennsylvania
State University, the University of
Pittsburgh, the University of Michigan,
the University of Texas, Florida State
University and the University of Cali-
ifornia at Santa Barbara, and within
such companies as the International
Business Machines Corporation, the Sys-
tems Development Corporation and
Bolt, Beranek and Newman. This list is
by no means exhaustive. The work at
these various places runs from a primary
emphasis on the development of com-
puter hardware to the construction of
short courses in subjects ranging from
physics to typing. Although all these
efforts, including ours at Stanford, are

<table>
<thead>
<tr>
<th>CORRECT</th>
<th>WRONG</th>
<th>NO ANSWER</th>
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<tr>
<td>FIRST DAY</td>
<td></td>
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<tr>
<td>SECOND DAY</td>
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IMPROVEMENT IN LEARNING is one evident result of drill and practice. The graph
summarizes the results of a six-day drill on the commutative, associative and distributive
laws of arithmetic. The computer program covered 48 concepts; each day's session pre-
sented 24 problems. Two days' drill therefore reviewed all 48 concepts, although no identi-
cal problems were presented during the six days. By the last day student responses were
more than 90 percent correct and the speed of reply was twice what it was at the start.

100 80 60 40 20 0 2 4 6 8 10 12
STUDENT RESPONSES (PERCENT) RESPONSE TIME (MINUTES)
still in the developmental stage, the instruc-
tion of large numbers of students at
computer terminals will soon (if acade-
mic and industrial soothsayers are
right) be one of the most important
fields of application for computers.

At Stanford our students are mainly
at the elementary school level; the ter-
minals they use, however, are also suit-
able for secondary school and university
students. At each terminal there is a
visual device on which the student may
view displays brought up from the com-
puter memory as part of the instruction
program. A device that is coming into
wide use for this purpose is the cathode
ray tube; messages can be generated
directly by the computer on the face of
the tube, which resembles a television
screen. Mounted with the cathode ray
tube is a typewriter keyboard the stu-
dent can use to respond to problems
shown on the screen. At some additional
cost the student can also have a light
pen that enables him to respond directly
by touching the pen to the screen in-
stead of typing on the keyboard. Such
device is particularly useful for stu-
dents in the lowest elementary grades,
although when only single-digit nu-
merical responses or single-character
alphabetical ones are required, the use
of a keyboard is quite easy even for
kindergarten children to learn.

After the display screen and the key-
board the next most important ele-
ment at a terminal is the appropriate
sound device. Presenting spoken mes-
sages to students is desirable at all edu-
cational levels, but it is particularly
needed for younger children. It would
be hard to overemphasize the impor-
tance of such spoken messages, pro-
grammed to be properly sensitive to
points at which the student may en-
counter difficulty in learning. Such

COMPUTER SUMMARY of drill results
makes possible the analysis essential for as-
essment and revision of various study cur-
riculums. The results of 37 children's replies
to 20 questions designed to test elementary
arithmetic skills are summarized graphically
in this illustration. The most troublesome
question proved to be No. 7; not only did
it take the most time to answer but also 26
students failed to answer it at all and only
two answered it correctly. Although ques-
tion No. 9 is the exact reverse of question
No. 7, it received 13 correct answers. Evi-
dently obtaining an unknown quantity by
subtraction is harder than obtaining one by
addition, and the students found it harder
to multiply 12 by 6 than to multiply 6 by 12.
messages are the main help a good tutor gives his pupil; they are the crucial missing element in noncomputerized teaching machines. All of us have observed that children, especially the younger ones, learn at least as much by ear as they do by eye. The effectiveness of the spoken word is probably stronger than any visual stimulus, not only for children but also most of the time for adults. It is particularly significant that elementary school children, whose reading skills are comparatively undeveloped, comprehend rather complicated spoken messages.

A cathode ray tube, a keyboard and a loudspeaker or earphones therefore constitute the essential devices for computer-assisted instruction. Additional visual displays such as motion pictures or line drawings can also be useful at almost all levels of instruction. Ordinary film projectors under computer control can provide such displays.

So far three levels of interaction between the student and the computer program have received experimental attention. At the most superficial level (and accordingly the most economical

**GLOSSARY**

- α MOIST AIR RISES
- β MOIST AIR COOLS OR WILL COOL
- γ CLOUDS WILL FORM
- → FORMAL IMPLICATION
- ~ NOT

**RULES OF INFERENCE**

TRI TRANSVERSITY OF IMPLICATION
(FROM X → Y AND Y → Z, DERIVE X → Z)

IF MODUS PONENS
(FROM X → Y AND X, DERIVE Y)

CP CONTRAPOSITIVE
(FROM X → Y, DERIVE ~Y → ~X)

DNEG DOUBLE NEGATION
(FROM ~ ~X, DERIVE X)

RED CONTRADICTION OF CONSEQUENT
(FROM Y AND X → ~Y, DERIVE ~X)

**TUTORIAL EXERCISE** in mathematical logic is an example of a more complex variety of computer-assisted instruction. The student may proceed from a set of given hypotheses (top) to a given conclusion (bottom) by any one of several routes. Each of the illustrated downward paths represents a legitimate logical attack on the problem and each constitutes a unique sequence of inferences (see legend and statements in logical notation below each of the numbered verbal statements). Ideally a tutorial computer program will show no preference for one path over another but will check the soundness of each step along any path and tell the student if he makes any mistakes in logic.
one) are "drill and practice" systems. Instruction programs that fall under this heading are merely supplements to a regular curriculum taught by a teacher. At Stanford we have experimented a great deal with elementary school mathematics at the drill-and-practice level, and I shall draw on our experience for examples of what can be accomplished with this kind of supplementation of a regular curriculum by computer methods.

Over the past 40 years both pedagogical and psychological studies have provided abundant evidence that students need a great deal of practice in order to master the algorithms, or basic procedures, of arithmetic. Tests have shown that the same situation obtains for students learning the "new math." There seems to be no way to avoid a good deal of practice in learning to execute the basic algorithms with speed and accuracy. At the elementary level the most important way in which computer-assisted instruction differs from traditional methods of providing practice is that we are in no sense committed to giving each child the same set of problems, as would be the case if textbooks or other written materials were used. Once a number
Our key effort in drill-and-practice systems is being conducted in an elementary school (grades three through six) a few miles from Stanford. The terminals used there are ordinary teletype machines, each connected to our computer at Stanford by means of individual telephone lines. There are eight teletype systems in all, one for each school classroom. The students take turns using the teletype in a fixed order; each student uses the machine once a day for five to 10 minutes. During this period he receives a number of exercises (usually 20), most of which are devoted to a single concept in the elementary school mathematics curriculum. The concept reviewed on any given day can range from ordinary two-digit addition to intuitive logical inference. In every case, the teacher has already presented the concept and the pupil has had some

**PLEASE TYPE YOUR NAME**

DORIS VALIENTE

**DRILL NUMBER 604032**

**L.C.M. MEANS LEAST COMMON MULTIPLE**

<table>
<thead>
<tr>
<th>NUMBER</th>
<th>PERCENT</th>
</tr>
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<tbody>
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</tr>
<tr>
<td>WRONG</td>
<td>5</td>
</tr>
<tr>
<td>TIMEOUT</td>
<td>1</td>
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70% CORRECT IN BLOCK, 70% OVERALL TO DATE

GOOD BYE, 0 FEARLESS DRILL TESTER.
TEAR OFF ON DOTTED LINE

**DRILL-AND-PRACTICE EXERCISE**, shown in abbreviated form, is typical of a simple computer-assisted instruction program that is designed to be responsive to the needs of individual students. The illustrated exercise is one of five that differ in their degree of difficulty; when the student types his name (color), the exercise best suited to him on the basis of computer-memory records of his previous performance is selected automatically. The first three questions and answers exemplify the ways in which the computer is programmed to deal with various shortcomings. The student fails to answer the first question within the allotted 10-second time limit; the computer therefore prints **TIME IS UP** and repeats the question, which the student then answers incorrectly (color). A wrong answer to the next question causes the computer to announce the error and repeat the question automatically; a second chance again elicits a correct answer. A wrong answer to the third question is compounded by failure to respond to the reiterated question within the time limit. Because this question has now drawn two unsatisfactory responses the automatic **TIME IS UP** statement is followed by a printing of the correct answer. The question is now repeated for a third and last time. Whether or not the student elects to copy the correct answer (he does so in this instance), the computer automatically produces the next question. Only six of the 20 questions that comprise the drill are shown in the example. After the student's last answer the computer proceeds to print a summary of the student's score for the drill as well as his combined average for this and earlier drills in the same series. The drill-and-practice exercise then concludes with a cheery farewell to the student and an instruction to tear off the teletype tape.

Of study "tracks," representing various levels of difficulty, have been prepared as a curriculum, it is only a matter of computer programming to offer students exercises of varying degrees of difficulty and to select the appropriate level of difficulty for each student according to his past performance.

In the program we ran in elementary grades at schools near Stanford during the academic year 1965-1966 five levels of difficulty were programmed for each grade level. A typical three-day block of problems on the addition of fractions, for example, would vary in the following way. Students at the lowest level (Level 1) received problems involving only fractions that had the same denominator in common. On the first two days levels 2 and 3 also received only problems in which the denominators were the same. On the third day the fraction problems for levels 2 and 3 had denominators that differed by a factor of 2. At Level 4 the problems had denominators that differed by a factor of 2 on the first day. At Level 5 the denominators differed by a factor of 3, 4, 5 or 6 on the first day. Under the program the student moved up and down within the five levels of difficulty on the basis of his performance on the previous day. If more than 80 percent of his exercises were done correctly, he moved up a level. If fewer than 60 percent of the exercises were done correctly, he moved down a level. The selection of five levels and of 80 and 60 percent has no specific theoretical basis; they are founded on practical and pedagogical intuition. As data are accumulated we expect to modify the structure of the curriculum.
student results is available to the teacher. By typing in a simple code the teacher can receive a summary of the work by the class on a given day, of the class's work on a given concept, of the work of any pupil and of a number of other descriptive statistics I shall not specify here. Indeed, there are so many questions about performance that can be asked and that the computer can answer that teachers, administrators and supervisors are in danger of being swamped by more summary information than they can possibly digest. We are only in the process of learning what summaries are most useful from the pedagogical standpoint.

A question that is often asked about drill-and-practice systems is whether we have evidence that learning is improved by this kind of teaching. We do not have all the answers to this complex question, but preliminary analysis of improvement in skills and concepts looks impressive when compared with the records of control classes that have not received computer-assisted instruction. Even though the analysis is still under way, I should like to cite one example that suggests the kind of improvement that can result from continued practice, even when no explicit instructions are given either by the teacher or by the computer program.

During the academic year 1964–1965 we noticed that some fourth-grade pupils seemed to have difficulty changing rapidly from one type of problem format to another within a given set of exercises. We decided to test whether or not this aspect of performance would improve with comparatively prolonged practice. Because we were also dissatisfied with the level of performance on problems involving the fundamental commutative, associative and distributive laws of arithmetic, we selected 48 cases from this domain.

For a six-day period the pupils were cycled through each of these 48 types of exercise every two days, 24 exercises being given each day [see illustration on page 208]. No specific problem was repeated; instead the same problem types were encountered every two days on a random basis. The initial performance was poor, with an average probability of success of .53, but over the six-day period the advance in performance was marked. The proportion of correct answers increased and the total time taken to complete the exercises showed much improvement (diminishing from an average of 630 seconds to 279 seconds). Analysis of the individual data showed that every pupil in the class had advanced both in the proportion of correct responses and in the reduction of the time required to respond.

The next level of interaction of the pupil and the computer program is made up of "tutorial" systems, which are more complex than drill-and-practice systems. In tutorial systems the aim is to take over from the classroom teacher the main responsibility for instruction. As an example, many children who enter the first grade cannot properly use the words "top" and "bottom," "first" and "last" and so forth, yet it is highly desirable that the first-grader have a clear understanding of these words so that he can respond in unequivocal fashion to instructions containing them. Here is a typical tutorial sequence we designed to establish these concepts:

1. The child uses his light pen to point to the picture of a familiar object displayed on the cathode-ray-tube screen. 2. The child puts the tip of his light pen in a small square box displayed next to the picture. (This is the first step in preparing the student to make a standard response to a multiple-choice exercise.) 3. The words first and last are introduced. (The instruction here is spoken rather than written; first and last refer mainly to the order in which elements are introduced on the screen from left to right.) 4. The words top and bottom are introduced. (An instruction to familiarize the child with the use of these words might be: Put your light pen on the toy truck shown at the top.) 5. The two concepts are combined in order to select one of several things. (The instruction might be: Put your light pen on the first animal shown at the top.)

With such a tutorial system we can individualize instruction for a child entering the first grade. The bright child of middle-class background who has gone to kindergarten and nursery school for three years before entering the first grade and has a large speaking vocabulary could easily finish work on the concepts I have listed in a single 30-minute session. A culturally deprived child who has not attended kindergarten may need as many as four or five sessions to acquire these concepts. It is important to keep the deprived child from developing a sense of failure or defeat at the start of his schooling. Tutorial "branches" must be provided that move downward to very simple presentations, just as a good tutor will use an increasingly simplified approach when he re-

classroom practice; the computer-assisted drill-and-practice work therefore supplements the teacher's instruction.

The machine's first instruction—Please type your name—is already on the teletype paper when the student begins his drill. The number of characters required to respond to this instruction is by far the longest message the elementary student ever has to type on the keyboard, and it is our experience that every child greatly enjoys learning how to type his own name. When the name has been typed, the pupil's record is looked up in the master file at the computer and the set of exercises he is to receive is determined on the basis of his performance the previous day. The teletype now writes, for example, drill 604032. The first digit (6) refers to the grade level, the next two digits (04) to the number of the concept in the sequence of concepts being reviewed during the year, the next two digits (03) to the day in terms of days devoted to that concept (in this case the third day devoted to the fourth concept) and the final digit (2) to the level of difficulty on a scale ranging from one to five.

The real work now begins. The computer types out the first exercise [see illustration on opposite page]. The carriage returns to a position at which the pupil should type in his answer. At this point one of three things can happen. If the pupil types the correct answer, the computer immediately types the second exercise. If the pupil types a wrong answer, the computer types wrong and repeats the exercise without telling the pupil the correct answer. If the pupil does not answer within a fixed time (in most cases 10 seconds), the computer types time is up and repeats the exercise. This second presentation of the exercise follows the same procedure regardless of whether the pupil was wrong or ran out of time on the first presentation. If his answer is not correct at the second presentation, however, the correct answer is given and the exercise is typed a third time. The pupil is now expected to type the correct answer, but whether he does or not the program goes on to the next exercise. As soon as the exercises are finished the computer prints a summary for the student showing the number of problems correct, the number wrong, the number in which success of .53, but over the six-day period the advance in performance was marked. The proportion of correct answers increased and the total time taken to complete the exercises showed much improvement (diminishing from an average of 630 seconds to 279 seconds). Analysis of the individual data showed that every pupil in the class had advanced both in the proportion of correct responses and in the reduction of the time required to respond.

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alizes that his pupil is failing to understand what is being said. It is equally important that a tutorial program have enough flexibility to avoid boring a bright child with repetitive exercises he already understands. We have found it best that each pupil progress from one concept in the curriculum to another only after he meets a reasonably stiff criterion of performance. The rate at which the brightest children advance may be five to 10 times faster than that of the slowest children.

In discussing curriculum materials one commonly distinguishes between "multiple-choice responses" and "constructed responses." Multiple-choice exercises usually limit the student to three, four or five choices. A constructed response is one that can be selected by the student from a fairly large set of possibilities. There are two kinds of constructed response: the one that is uniquely determined by the exercise and the one that is not. Although a good part of our first-grade arithmetic program allows constructed responses, almost all the responses are unique. For example, when we ask for the sum of 2 plus 3, we expect 5 as the unique response. We have, however, developed a program in mathematical logic that allows constructed responses that are not unique. The student can make any one of several inferences; the main function of the computer is to evaluate the validity of the inference he makes. Whether or not the approach taken by the student is a wise one is not indicated until he has taken at least one step in an attempt to find a correct derivation of the required conclusion. No two students need find the same proof; the tutorial program is designed to accept any proof that is valid [see illustration on pages 214 and 215]. When the student makes a mistake, the program tells him what is wrong with his response; when he is unable to take another step, the program gives him a hint.

It will be evident from these examples that well-structured subjects such as reading and mathematics can easily be handled by tutorial systems. At present they are the subjects we best understand how to teach, and we should be able to use computer-controlled tutorial systems to carry the main load of teaching such subjects. It should be empha-

ESSENTIAL COMPONENTS that allow interaction of computer and student are grouped at this terminal console. The cathode ray tube (right) replaces the earlier teletypewriter roll as a more flexible means of displaying computer instructions and questions. Earphones or a loudspeaker reproduce spoken words that are particularly important in primary school instruction. Students may respond to instructions by use of the terminal’s keyboard or by use of a light pen (extreme right); programs that will enable the computer to receive and respond to the student’s spoken words are under study. Supplemental displays are shown on the screen at left.
sized, however, that no tutorial program designed in the near future will be able to handle every kind of problem that arises in student learning. It will remain the teacher's responsibility to attempt the challenging task of helping students who are not proceeding successfully with the tutorial program and who need special attention.

Thus a dual objective may be achieved. Not only will the tutorial program itself be aimed at individualized instruction but also it will free the teacher from many classroom responsibilities so that he will have time to individualize his own instructional efforts. At Stanford we program into our tutorial sessions an instruction to the computer that we have named TEACHER CALL. When a student has run through all branches of a concept and has not yet met the required criterion of performance, the computer sends a teacher call to the proctor station. The teacher at the proctor station then goes to the student and gives him as much individualized instruction as he needs.

At the third and deepest level of student-computer interaction are systems that allow a genuine dialogue between the student and the program. "Dialogue systems" exist only as elementary prototypes; the successful implementation of such systems will require the solving of two central problems. The first may be described as follows: Suppose in a program on economic theory at the college level the student types the question: WHY ARE THE ASSOCIATIVE LAWS APPLICABLE TO LINE 3. This program is perfectly practical with our present computer system as long as the commands are transmitted by typing a few characters on the keyboard. A major effort to substitute voice for the keyboard is planned for the coming year; our preliminary work in this direction seems promising.

But these are essentially technological problems. In summarizing some other problems that face us in the task of realizing the rich potential of computer-assisted individual instruction, I should prefer to emphasize the behavioral rather than the technological ones. The central technological problem must be mentioned, however; it has to do with reliability. Computer systems in education must work with a much higher degree of reliability than is expected in computer centers where the users are sophisticated scientists, or even in factory-control systems where the users are experienced engineers. If in the school setting young people are put at computer terminals for sustained periods and the program and machines do not perform as they should, the result is chaos. Reliability is as important in schools as it is in airplanes and space vehicles; when failure occurs, the disasters are of different kinds, but they are equally conclusive.

The primary behavioral problem involves the organization of a curriculum. For example, in what order should the ideas in elementary mathematics be presented to students? In the elementary teaching of a foreign language, to what extent should pattern drill precede expansion of vocabulary? What mixture of phonics and look-and-say is appropriate for the beginning stages of reading? These are perplexing questions. They inevitably arise in the practical context of preparing curriculum materials; unfortunately we are far from having detailed answers to any of them. Individualized instruction, whether under the supervision of a computer or a human tutor, must for some time proceed on the basis of practical judgment and rough-and-ready pedagogical intuition. The magnitude of the problem of evolving curriculum sequences is difficult to overestimate: the number of possible sequences of concepts and subject matter in elementary school mathematics alone is in excess of $10^{400}$, a number larger than even generous estimates of the total number of elementary particles in the universe.

One of the few hopes for emerging from this combinational jungle lies in the development of an adequate body of fundamental theory about the learning and retention capacity of students. It is to be hoped that, as systematic bodies of data become available from computer systems of instruction, we shall be able to think about these problems in a more scientific fashion and thereby learn to develop a more adequate fundamental theory than we now possess.

Another problem arises from the fact that it is not yet clear how critical various kinds of responses may be. I have mentioned the problem of interpreting sentences freely presented by the student, either by the written or by the spoken word. How essential complex constructed responses to such questions may be in the process of learning most elementary subjects is not fully known. A problem at least as difficult as this one is how computer programs can be organized to take advantage of unanticipated student responses in an insightful and informative way. For the immediate future perhaps the best we can do with unanticipated responses is to record them and have them available for subsequent analysis by those responsible for improving the curriculum.

The possible types of psychological "reinforcement" also present problems. The evidence is conflicting, for instance, whether students should be immediately informed each time they make a mistake. It is not clear to what extent stu-
Students should be forced to seek the right answer, and indeed whether this search should take place primarily in what is called either the discovery mode or the inductive mode, as opposed to more traditional methods wherein a rule is given and followed by examples and then by exercises or problems that exemplify the rule. Another central weakness of traditional psychological theories of reinforcement is that too much of the theory has been tested by experiments in which the information transmitted in the reinforcement procedure is essentially very simple; as a result the information content of reinforcement has not been sufficiently emphasized in theoretical discussions. A further question is whether or not different kinds of reinforcement and different reinforcement schedules should be given to children of different basic personality types. As far as I know, variables of this kind have not been built into any large-scale curriculum effort now under way in this country.

Another pressing problem involves the effective use of information about the student's past performance. In standard classroom teaching it is impossible to use such records in a sensitive way; we actually have little experience in the theory or practice of the use of such information. A gifted tutor will store in his own memory many facts about the past performance of his pupil and take advantage of these facts in his tutorial course of study, but scientific studies of how this should be done are in their infancy. Practical decisions about the amount of review work needed by the individual, the time needed for the introduction of new concepts and so forth will be mandatory in order to develop the educational computer systems of the future. Those of us who are faced with making these decisions are aware of the inadequacy of our knowledge. The power of the computer to assemble and provide data as a basis for such decisions will be perhaps the most powerful impetus to the development of education theory yet to appear. It is likely that a different breed of education research worker will be needed to feel at home with these vast masses of data. The millions of observational records that computers now process in the field of nuclear physics will be rivaled in quantity and complexity by the information generated by computers in the field of instruction.

When students are put to work on an individualized basis, the problem of keeping records of their successes and failures is enormous, particularly when those records are intended for use in making decisions about the next stage of instruction. In planning ways to process the records of several thousand students at Stanford each day, we found that one of the most difficult decisions is that of selecting the small amount of total information it is possible to record permanently. It is not at all difficult to have the data output run to 1,000 pages a day when 3,000 students use the terminals. An output of this magnitude is simply more than any human being can digest on a regular basis. The problem is to reduce the data from 1,000 pages to something like 25 or 30. As with the other problems I have mentioned, one difficulty is that we do not yet have the well-defined theoretical ideas that could provide the guidelines for making such a reduction. At present our decisions are based primarily on pedagogical intuition and the traditions of data analysis in the field of experimental psychology. Neither of these guidelines is very effective.

A body of evidence exists that attempts to show that children have different cognitive styles. For example, they may be either impulsive or reflective in their basic approach to learning. The central difficulty in research on cognitive styles, as it bears on the construction of the curriculum, is that the research is primarily at an empirical level. It is not at all clear how evidence for the existence of different cognitive styles can be used to guide the design and organization of individualized curriculum materials adapted to these different styles. Indeed, what we face is a fundamental question of educational philosophy: To what extent does society want to commit itself to accentuating differences in cognitive style by individualized techniques of teaching that cater to these differences? The introduction of computers in education raises this question in a new and pressing way. The present economics of education is such that, whatever we may think about the desirability of having a diverse curriculum for children of different cognitive styles, such diversity is not possible because of the expense. But as computers become widely used to offer instruction in the ways I have described here, it will indeed be possible to offer a highly diversified body of curriculum material. When this occurs, we shall for the first time be faced with the practical problem of deciding how much diversity we want to have. That is the challenge for which we should be prepared.

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