8 June 1984, Volume 224, Number 4653 SCIENCE

Computer-Based Instructional Dialogs in Science Courses

A. B. Arons

The personal computer offers new opportunities for the application of technology to instruction. Although a similar claim was made for television 25 years ago, the influence and utility of television as an educational tool have fallen far short of initial expectations. To some observers this is not surprising, because television addresses an essentially passive watcher, presenting material that, in many instances, elicits little thinking, however lucid the presentation.

Summary. The personal computer is opening the door to supplemental, essentially tutorial, modes of science instruction that, particularly at introductory levels, can significantly enhance understanding of science and develop abstract reasoning skills. Competently prepared and judiciously utilized materials have the potential to improve the education of science and engineering professionals, elementary and secondary teachers, and, to some degree, the public at large.

The computer is fundamentally different. When properly used as an interactive device, it demands intense intellectual participation rather than passivity on the part of the user. This alters the instructional context, opening the door to levels of effectiveness not obtainable through didactic presentation alone (*1*). In this article some promising uses of the computer in introductory science courses are discussed.

Current Uses

Drill. This is perhaps the least sophisticated mode intellectually. Nevertheless, efficient and well-planned drill, presented on an individual basis with immediate feedback reinforcing correct responses and correcting mistakes, is a powerful instructional device. It is important in helping the student build bases of vocabulary and factual knowledge that underlie subsequent thinking, reasoning, studying, and problem-solving. Drill has been shown, for example, to be effective in enhancing the numerical skills of elementary school children (*2*). In higher education drill can be used to build vocabulary in chemistry, geology, and biology; to perform exercises with chemical and nuclear reactions; to practice use of mnemonic devices; to practice operations that should become routine (for example, vector arithmetic, both graphical and numerical; balancing chemical reactions; and using exponential notation); and to perform certain numerical problems once underlying concepts have been learned (such as elementary kinematics and dynamics in introductory physics and stochiometric problems in chemistry).

Number crunching. Number crunching involves using the computer for numerical computations that are excessively time-consuming if done by hand (*3*). With this mode students who have not yet had calculus (or perhaps never will) can explore continuous change. They can examine the implications of fundamental differential equations (varying acceleration; simple, damped, and driven harmonic oscillation; central force motion with various force laws; and radioactive decay or monomolecular reaction) without recourse to standard closed-form solutions. Indeed, many students in introductory physics do not acquire an adequate grasp of the essential numerical meaning of velocity and acceleration (or the distinction between the two) until they are required to make step-by-step numerical calculations, even for the uniform acceleration case; in dealing with standard problems in kinematics they resort to manipulation of formulas without analysis, interpretation, or comprehension of the concepts or the end results. Many such computations can, of course, be done on a programmable hand calculator, but the graphic display of a personal computer can powerfully enhance the resulting insights by displaying graphs of pairs of variables.

Where extensive numerical computation is done without directing students' attention to analysis and interpretation of methods and results, the effort is largely wasted. In other words, the computer must be used judiciously even for numerical work.

Laboratory applications. The computer is being widely used in the laboratory for monitoring, on-line data recording, and data analysis (*4*). If the computer is used in such a way as to involve the student, and if it facilitates the making of measurements not obtainable by simpler and more transparent techniques, it can be beneficial. However, if it short-circuits insight, if it simply makes available end results for analysis or "confirmation," it is educationally sterile or even deleterious, particularly in introductory courses. A student in introductory chemistry should turn his own stopcocks, monitor titrations by eye, and make his own proportional computations quite a few times before having the processes obscured by a computer monitoring an electronic device and rapidly delivering the end result.

Simulations. Another double-edged

A. B. Arons is professor of physics emeritus at the University of Washington, Seattle 98195.

sword is that of simulation of physical phenomena on the computer. If the phenomena are directly accessible, then it is better to expose beginning students to the actual phenomena than to simulations thereof. Some of the effort being devoted to simulation is producing undesirable materials.

However, simulations are justified and useful (i) when the phenomena are not directly accessible at reasonable effort or cost, (ii) when extensive statistical trials might be involved, (iii) when it is desirable to help a student prepare for an experiment, particularly when safety is at issue (*5*), and (iv) when the phenomena have already been previously observed and the student now requires drill and guidance in analyzing various cases, registering conceptual schemes, or making predictions.

Self-paced courses. Personal computers, or terminals connected to central computers, are being used to monitor the progress of students taking self-paced courses; to administer the tests that, at the end of each unit, are used to ascertain whether a student is ready to proceed; and to provide tutorial help and drill, relieving instructors of this repetitive activity and freeing them for more sophisticated and less routine work with their students (*6, 7*).

A Current Misuse

The most gratuitous misuse of the computer is as a page turner of text presentations. Much commercially available "instructional material" is of this variety, particularly at the secondary school level. The computer screen presents a paragraph or two, and the student is then asked some vacuous questions that are answered either through multiple choice or by inserting phrases directly from the text.

It would be better if such materials were withdrawn. A book is a far handsomer and better purveyor of text than the computer screen, and it is unwise to lure students away from habitual use of books.

Instructional Dialogs

A less well known use of the computer, but one that has particularly high educational potential, is that of instructional, or Socratic, dialog. The term "Socratic dialog" is used here in its classical sense of using a series of questions to lead a student through lines of reasoning to insights and conclusions. Exemplars of effective Socratic dialogs for computers are not numerous and not widely known. The ones with which I am acquainted (and some of which I have collaborated in writing) have been generated at the Educational Technology Center, directed by Alfred Bork, at the University of California, Irvine.

The dialogs are not, in general, conducted through a sequence of multiple-choice questions or yes-no answers. Most questions require response in words, symbols, or numbers chosen by the student. The computer recognizes a verbal response by searching for specified combinations of key words or phrases. Graphic displays are used throughout: graphs are formed and interpreted; objects move across the screen; flashlight bulbs light with various degrees of brightness; the student uses the built-in pointer to point to places in diagrams in answer to some of the questions or to indicate how to construct appropriate graphs.

Analysis of verbal responses is prepared for in the writing and editing of the dialog. Real person-to-person dialog is used to anticipate the general course of the dialog; additional unanticipated answers are collected and edited into the program through trial runs. A correct answer allows the student to continue in the main sequence; an incorrect answer is dealt with in a remedial sequence. Dialogs usually end with a test, a number of questions being chosen randomly from a large bank of questions, and the student is given an assessment of his performance. From the user's point of view these dialogs are, in some ways, similar to expert systems (*8*), which can, for example, lead a medical student through symptoms and test results to diagnosis of an illness. In this case, however, the intelligence of the expert teachers who design the dialog is reflected in the sequence of questions rather than by any intelligence built into the program.

Key word analysis, although powerful when the questions are well phrased and student response well anticipated, does not allow much freedom. Future developments in parsing sentences and understanding natural language may improve this situation considerably. So will the advent of the "intelligent" video disk (*9*).

Here are some examples of existing dialogs:

LUNA. LUNA (*10*) is a dialog that exploits graphics to lead a student to form a mental picture of the configurations assumed by the sun, moon, and earth and to use the model to answer questions such as, Would you expect to see a full moon rising at midnight? Why or why not? At what time of day or night would you expect to see a new crescent moon setting? A half-illuminated moon crossing the local celestial meridian?

TERRA. This dialog (*10*) provides remediation for users of LUNA who fail to exhibit adequate comprehension of the meaning of terms such as north, south, noon, midnight, vertical, horizontal, latitude, longitude, terrestrial and celestial poles, equator, and so forth.

HEAT. Many college students, even those in technical courses, use "heat" and "temperature" synonymously and show little or no awareness of the operational distinction between them. The HEAT dialog (*11*) is designed to lead students to an operational definition of "transfer of heat." It starts with acceptance of the thermometer and its readings as primitives. It then leads the student to articulate everyday experience with the trend to thermal equilibrium between bodies initially at different temperatures. The thermometer in a pan of hot water placed in a room eventually drops to the same reading as the wall thermometer; the thermometer in a pan of cold water rises to the same level. The same temperature changes take place more slowly if the water samples are in Thermos bottles. Since the rates of change are altered without alteration of any thermometer readings, the interactions apparently involve a process that the thermometer readings alone do not reveal.

Other familiar situations reinforce this perception. Two different quantities of water, each heated from 20° to 80°C over identical burners, require different amounts of time and fuel—both larger for the larger mass of water. As ice cubes melt in a beaker of water, a change is continually taking place, involving interaction with warmer air in the room, without any change at all in the thermometer in the beaker. In each case we encounter additional evidence of a process of interaction that the thermometer readings alone do not reveal. Having articulated awareness of such a process, we call it transfer of heat. The dialog then goes on to complete the operational sequence by leading the student to measurement of the quantity of heat transferred through observation of temperature changes occurring in the mixing of known masses of water.

The preceding is an outline of the logical flow of the dialog. Since one is, in this case, organizing familiar experience into synthesis of a new concept, the sequence is relatively linear and there is little branching for remedial purposes.

After the student has correctly indicated that, given passage of time, pans of hot and cold water will end up with thermometer readings equal to the reading of a thermometer measuring the constant temperature of the room, the computer says

Again, take containers of hot and cold water, each at the same initial temperature as before.

(Pans of hot and cold water, with thermometers in them, are then sketched on the screen.)

Now we put the same amounts of hot and cold water into Thermos bottles.

(Thermos bottles labeled cold and hot are sketched on the screen.)

Now insert thermometers through each stopper.

(A thermometer is added to each Thermos.)

What is the difference between this situation and the previous one in which the water was in ordinary pans rather than Thermos bottles? How do the thermometers behave in this case as compared to their behavior in the previous one?

The computer now awaits a response, and the student is free to respond in single words, phrases, or sentences. The computer then searches the response for the following key words in the sequence listed: (i) *slow*, (ii) *same* or *similar*, (iii) *rapid* or *fast* plus *not* or *less*, (iv) *rapid* or *fast*, and (v) *change*.

If the computer finds (i), it responds

Very good. The temperature changes much more slowly.

and goes on to the next question or statement in the main sequence.

If the computer does not find (i) but finds (ii), it responds

The thermometers do approach room temperature in both situations, but what is the difference in their behavior?

The computer then waits for a new input from the student and reexamines the input in the same sequence.

If the computer fails to find (i) or (ii) but finds (iii), it responds

Yes. The temperature changes much more slowly.

and rejoins the main sequence following response (i).

If the computer fails to find (i), (ii), or (iii) but finds (iv), it responds

No. The temperature changes much more slowly.

and rejoins the main sequence (no effort is made to remediate this very rarely given incorrect answer).

If the computer fails to find (i), (ii), (iii), or (iv), but finds (v), it responds

How does the rate of change compare with the previous rate?

and returns to reexamine the new input.

If the computer fails to find any of combinations (i) through (v), it responds

Think about why we put hot or cold liquids in Thermos bottles. Try again to tell us how you expect the thermometers to behave.

On the second go-around, the student receives a "yes" or "very good" reinforcement for a correct answer or, if the response is still incorrect or unintelligible, is simply put back into the main sequence with the statement, "The temperature changes very much more slowly."

BATTERIES AND BULBS. In this dialog (*12*), the computer screen presents fairly realistic pictures of a flashlight bulb, battery, and two wires. The student is asked to use the pointer to show where the ends of the wires should be connected in order to light the bulb. The computer draws the wires between the points indicated. The bulb remains dark if the correct connections, to the battery terminals and tip and screw base of the bulb, are not indicated. If the correct connections are indicated, the bulb "lights." Note that the bulb does not light unless the "two-endedness" of the battery and the bulb is exploited to form a closed loop. Such a closed loop is identified as a "circuit."

The circuit is "opened" by showing a gap in one of the wires. Various familiar objects (a coin, a pencil, a key, a shoe, and so forth) are then shown inserted in the gap in simulated experiments. Objects that allow the bulb to light are classified as conductors and the others as nonconductors, and a growing list is retained on the screen. The student is led to observe that air is present in the gap in the absence of other objects and thus must be classified as a nonconductor. The student is then led to recognize that the conductors are all metallic.

The mental picture of an invisible flow or current within the circuit (terms such as charge and electrons are not introduced and are set aside if the student volunteers them) is now synthesized by appeal to the preceding observations and additional simulated experiments: bulbs do not light and wires do not get hot unless the two-endedness of the source and each object is exploited to form a continuous closed loop. When wires glow (as they do in stove elements and toasters), they glow uniformly from one source terminal to the other. A bulb connected to the battery glows equally brightly whether the connecting wires place it near one battery terminal or the other. All these observations combine to suggest an invisible flow that continues uniformly around the system without being "used up" and that is interrupted by any nonconducting break in the loop. (Many students, including those in technical courses, have a misconception that current is "used up" in an electric circuit and decreases from one terminal to the other. They are not distinguishing between current and energy transformations.)

Simulated experiments then show that the brightness of a bulb decreases as additional bulbs are inserted end to end, that is, in series. This observation is reinforced by exhibiting increasing and decreasing brightness of the bulb as the length of a "special" (Nichrome) wire is decreased or increased in series with the bulb. The student controls the length of wire by moving the pointer, showing where connection is to be made. The brightness of the bulb increases or decreases accordingly.

The observation that the brightness of the bulb decreases as additional material is inserted in series is used to suggest that the bulb might be used to measure the intensity of the current and that such material offers an obstacle to the flow. This leads the student to the concept of resistance.

The dialog then elaborates the concepts of current and resistance into a model with predictive capacity. Combinations of resistors in series are shown to lead to lower brightness of a bulb used as an indicator of current intensity and to slower "running down" of a battery. Combinations of resistors in parallel are shown to run a battery down more rapidly and to produce higher brightness of the indicator bulb. The student is led to articulate the physical conclusion (without formulas) that effective resistance increases in series combinations and decreases in parallel ones. Many students, including those in technical courses, fail to comprehend the latter idea regardless of the formulas with which they are supplied and the numerical problems they "solve" in exercises.

The short circuit and the fuse or circuit breaker are introduced in further simulated experiments. Toward the end of the dialog, the student deals with various new series and parallel configurations of several identical bulbs connected to a battery. He is asked to use the current-resistance model to predict the initial brightness of the bulbs; to predict what will happen to the remaining bulbs if one is removed; and to predict what will happen to the bulbs and to the current at some indicated point if a wire is connected between two arbitrarily specified points in the system. Figure 1 shows the logical flow of questions and responses in such circumstances.

OBSERVATION AND INFERENCE. This dialog (*13*) begins with the presentation on the screen of the following statement:

> In one of the Sherlock Holmes stories by Arthur Conan Doyle, Holmes and his brother Mycroft are watching a man dressed in black with several packages under his arm. Mycroft says:
> "Of course, his complete mourning shows that he has lost someone very dear. The fact that he is doing his own shopping looks as though it were his wife. He has been buying things for children. There is a rattle, which shows that one of them is very young. The wife probably died in childbirth. The fact that he has a picture book under his arm shows that there is another child to be thought of."

The computer then draws a box around the phrase "dressed in black" and classifies it in the category "Mycroft sees." The phrase "lost someone very dear" is classified under "Mycroft reasons." A few more phrases are classified, and the student is then asked to classify the remaining phrases and is corrected if he makes mistakes. If several mistakes are made, the student is given an exercise in which the distance of a lightning stroke is determined by measuring the time between the flash and the thunder and applying the known velocity of sound. The process is then examined to classify observations and inferences. From this branch the student rejoins the main sequence which is being followed by those who made very few mistakes in analyzing the original passage.

The screen shows a sketch of a rectangular field teeming with grasshoppers (represented by dots). The problem is to estimate the number of grasshoppers in the field. The computer zooms in on a 1-square-meter patch in which grasshoppers come and go. The student must watch the patch and estimate the average number of grasshoppers occupying it. The lengths of the sides of the field are then estimated and the number of grasshoppers in the field is calculated. Steps of the sequence are classified as observations or inferences. The opportunity is also taken to comment that estimating, in science, is not a matter of wild guesswork but is a matter of careful reasoning, however imprecise the results.

AREA. This dialog leads the student to articulate the operational definition of area as a counting of unit squares in a figure of arbitrary shape and provides some exercises in such counting, including estimating fractional squares around the periphery. (This may strike readers as a trivial matter. However, many college students, when asked what area means or how it is assigned numerical values, respond with "length times width" rather than with a meaningful operational definition.)

The dialog leads the student to derive formulas (shortcuts to counting of unit squares) for simple figures like rectangles, parallelograms, and triangles. The sequence then addresses the scaling of areas when a figure is increased or decreased by a given length factor in both dimensions, develops an operational definition of volume, and administers exercises in scaling both area and volume. This dialog is important because most college students have great difficulty with such ratio reasoning when they do not have formulas into which to substitute actual dimensions (*14*).

Other dialogs in existence or in preparation at the Irvine Educational Technology Center deal with matters such as discrimination between position and velocity and between velocity and acceleration in rectilinear kinematics (*15*), forming and interpreting position-time and velocity-time graphs for rectilinear motions, and enhancing understanding of the law of inertia. A system for generating such dialogs, coding them, and making them operational is described elsewhere (*9*).

Requirements for the Generation of Effective Instructional Dialogs

To write an effective instructional dialog, the author or authors must have a clear perception of the basic reasoning processes that will be cultivated in the dialog. The logical structure of the subject matter must be thoroughly thought through at the particular level of instruction. Motivation and plausibility must be carefully built in. The learner's prior experience must be evoked as much as possible. Much writing of dialogs is undertaken without this sort of preparation, and the result is usually ex cathedra presentation, as in most textbooks, rather than a genuine Socratic dialog.

The authors must have knowledge of student difficulties both with the subject matter and with the types of abstract reasoning entailed. Such knowledge is not acquired simply through goodwill, lecturing, or conjecture, but only through personal dialogs with students and through the careful examination of responses on well-designed test questions that probe for lines of reasoning and for understanding rather than for calculational procedures or end results.

Most of my conjectures as to how students will answer a particular probing question (in a field I have not previously explored) are wrong. The answer, if incorrect, is usually plausible, however unanticipated. Its roots and origins can be traced, and remediation, through Socratic questioning, can be provided.

It is easy to anticipate the right answers. The real problem is to provide effective remediation for the wrong ones, and this is possible only if the wrong answers are properly anticipated and their origins understood.

Thus the writer of instructional dialogs must acquire substantial empirical knowledge of student responses. [The results of modern cognitive research (*15–19*) should be very helpful in this respect.] Although the acquisition of the necessary empirical knowledge will require time and effort on the part of authors, the saving grace is that every individual is not in fact different from every other individual. Incorrect responses to a particular Socratic question are frequently given in almost identical words.

It is preferable to have two or three individuals working together and checking each other than to write alone. The solo author may overlook errors in the logic of the instructions to be programmed into the computer, ambiguities, and alternative interpretations of his phraseology (the phraseology must be debugged as carefully as ordinary test and examination questions).

Finally, the authors must have an excellent command of the English language, the lucid and precise framing of questions being critical for the extraction of fruitful responses from the student.

Potential Educational Impact of Instructional Dialogs

Up to three-quarters of college students perform poorly on rudimentary tasks of abstract logical reasoning, such as ratio reasoning, solving arithmetic problems involving division, controlling variables, forming and understanding simple propositional statements and one- and two-step syllogistic statements, doing elementary correlational reasoning, and translating symbols into words and words into symbols (*14, 20–22*). There is reason to believe that such basic skills can be enhanced in many individuals (*22, 23*) given sufficient repetitive practice in a wide variety of contexts. Few individuals who have difficulty with such kinds of reasoning benefit significantly, however, from exposition, illustration, and explanation imparted by a text or teacher while they remain passive readers or listeners. These individuals do show significant progress over a series of episodes if they are led to articulate explanations and reasoning in their own words through Socratic dialog. There are too few teachers to reach huge numbers of students in such one-on-one dialog, but the availability of numerous computer dialogs designed to provide the necessary practice could make a significant impact on what is a serious national problem. (This problem could, of course, be removed from the realm of higher education if adequate instruction and help of the same variety were provided in earlier schooling. I hope that the shift will eventually be made, but, nevertheless, for some time we shall need such materials at the college level.)

Much of the weak performance in introductory science courses stems from failure to grasp concepts and lines of reasoning at crucial early points. Again, many students break through to grasp these issues only if they receive the help of timely one-on-one dialog. Availability of appropriate dialogs at early stages in these courses could be of substantial benefit.

The past decade saw the emergence of vigorous studies of cognitive processes associated with the learning and understanding of specific areas of scientific subject matter (*24*). Such studies deal directly with preconceptions, misconceptions, and impediments affecting students' penetration and mastery of abstract scientific concepts, models, and principles. The insights being gained are not rapidly assimilated into textbooks, and even if they were, few of the learning difficulties lend themselves to remediation through didactic presentation to a reader. The most effective pathway for many learners is that of articulation through Socratic dialog. Thus, appropriately designed dialogs offer a promising avenue to rapid incorporation into day-to-day instruction of the best insights being gained in current cognitive research.

The generation of such dialogs is at present very costly. Writing out the logical flow of a sequence that will require approximately 1 hour of student time at the keyboard takes two people about 50 hours. This is the input required from expert teachers, and it is unlikely that this time segment will be reduced. Coding and debugging of this written material (verbal and graphic) then requires 500 to 600 hours on the part of programmers. Increasingly sophisticated software may reduce this programming time.

Other Benefits

A particularly important cognitive process with which students receive little help under conventional instruction is that of hypothetico-deductive reasoning (visualizing, in the abstract, the consequence of a change imposed on some existing system). Not only is this mode of thinking essential to the grasp and effective use of scientific models, laws, and principles, it is necessary to many other disciplines. It also arises in duties of citizenship: one should be able to make plausible, reasoned judgments as to the possible outcomes of social, political, or economic actions. Hypothetico-deductive thinking can be practiced and cultivated through instructional dialog.

Another intellectual process in which most college students exhibit great weakness is the ability to recognize gaps in available information—gaps that must be closed by plausible assumptions or by additional data if an inquiry is to be pursued. Instructional dialog can confront students with the necessity of identifying and recognizing such gaps and thereby supply essential exercises rarely made available in conventional courses. In everyday life we are frequently confronted with the necessity of making

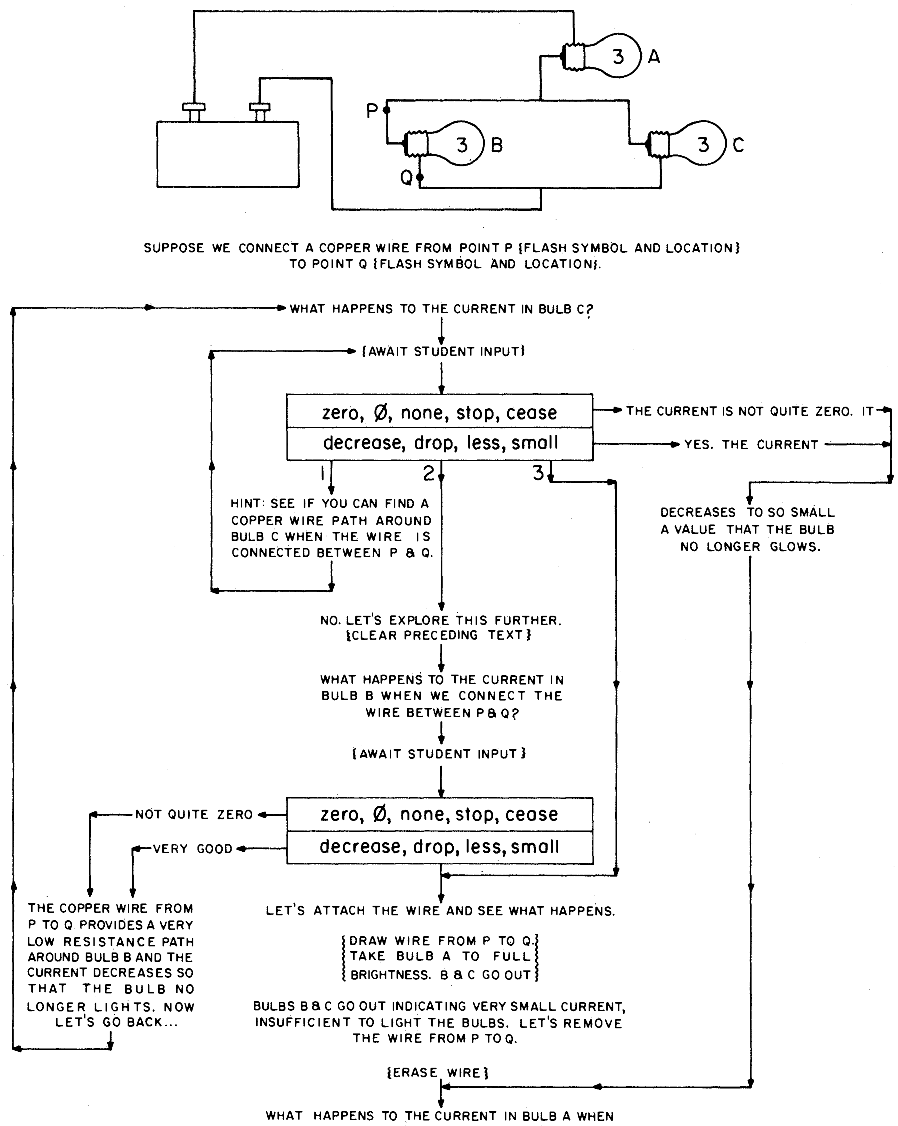

Fig. 1. Excerpt from dialog in which student predicts what will happen when an alteration is imposed on a circuit. Unbracketed statements appear on the screen. Statements within curly brackets are directions to the coder. Key words in boxes are those for which the computer searches the student response. An exit to the side shows the computer response if the key word is found. An exit from the bottom of the box shows the computer's response if none of the boxed responses is recognized.

decisions in the face of incomplete and inadequate information.

There are numerous other cognitive skills common not only to study of the sciences but to study of any discipline that involves forming concepts and using them in abstract logical reasoning. Students would benefit from dialogs that provide exercise in dealing with evidence; using propositional statements and syllogisms; translating words into symbols and symbols into words; traversing a more or less familiar line of thought in reverse direction to ensure a more secure grasp of the thinking; and making decisions as to what might be calculated, analyzed, or otherwise extracted from a situation that is presented without statement of a specific problem.

At present only a few instructional dialogs have been generated and used as part of course work. Before the effectiveness of this mode can be adequately tested, a much wider range of dialogs (in both level and subject matter) will have to be made available to the academic community.

Limitations

Although I am optimistic about the potential of computer-based instruction, I am not taking a position of unbridled evangelism. There are limitations and even dangers in these instructional techniques if they are overused or misused.

The principal function of higher education, in an age in which it is impossible to teach students all they need to know, is to teach them how to learn. Only then can they proceed to master new abstractions without perpetual formal instruction. Although many students can initially benefit greatly from the detailed guidance of Socratic dialog, the use of such materials in a student's education should eventually be tapered off. The last thing we want to do is cultivate dependence on the reinforcement supplied by computer instruction. Rather, we want to cultivate the skills underlying genuinely independent study: asking one's own probing questions; tracking down asymptotic cases; checking one's own reasoning for internal consistency; inventing simpler problems or special cases related to the more difficult one initially posed and working step by step to a deeper grasp; and being conscious of one's own thought processes. Once a student has had the opportunity to ask his own questions as an extension of a line of inquiry already begun, and once he has seen a perspective fall into place as he pursues the answer to his question, he will never be quite the same again. The computer can help many students to the threshold of these higher intellectual skills.

The sociology and human contacts of the classroom are basic to the mechanisms of intellectual growth. The classroom provides an opportunity for vivid, clarifying, motivating demonstrations. It gives the student contact with distinguished intellects, allows discursive presentation of intellectual perspectives that can be only cryptically outlined in an introductory text, and encourages conversation, argument, and discussion. Displacement of the classroom by computers would be a disaster.

Certainly, correspondence courses and "open universities," in which computer-based instruction plays an increasingly important role, are valuable supplements to the conventional system. They provide opportunities and options to individuals who might otherwise be barred from higher education. Still, computer-based instruction, although a powerful supplement to human instruction, would make a feeble substitute.

Scientific Literacy

There is much concern about our system of education in general (*25*) and about science education in particular (*26*). Both the preparation of scientists and engineers and the cultivation of scientific literacy in the public are at issue. That we have not achieved general scientific literacy is due in part to the illusion that such literacy can be generated by the "stream of words" technique—precipitating technical vocabularies and findings on listeners to lectures in introductory courses.

Words can do almost anything except define themselves. Meaning is attained not through passive listening to words and end results but through intellectual participation in the shared experience of ideas for which the technical terms are shorthand.

Researchers in cognitive development describe two principal classes of knowledge: figurative or declarative and operative or procedural (*27*). Declarative knowledge consists of knowing "facts" (the earth revolves around the sun); operative knowledge involves understanding the sources of such declarative knowledge (how do we know the earth revolves around the sun?). Operative knowledge further implies the capacity to use, transform, or recognize the relevance of the declarative knowledge in new or unfamiliar circumstances.

Meaningful scientific literacy cannot be attained through inculcation of declarative knowledge alone; operative knowledge must also be cultivated. This will never be achieved in the widely prevalent "stream of words" courses. Not only must we slow the pace and reduce the volumes of coverage imposed on students in science courses, we must also make room for philosophical, historical, and societal issues (*28, 29*).

Computer-based instruction will never, by itself, solve the major educational problems to which I have alluded. However, with the availability and the judicious use of perceptively prepared software, it can enhance the effectiveness of instruction at introductory levels, allowing teachers to devote more time to the development of operative levels of understanding.

References and Notes

1. A. M. Bork, *Am. J. Phys.* **41**, 5 (1979).
2. P. C. Suppes and M. Morningstar, *Computer-Assisted Instruction at Stanford, 1966–68: Data, Models, and Evaluation of the Arithmetic Programs* (Academic Press, New York, 1972).
3. R. P. Feynman, R. B. Leighton, M. Sands, *The Feynman Lectures on Physics* (Addison-Wesley, Reading, Mass., 1963), vol. 1; R. M. Eisberg, *Applied Mathematical Physics With Programmable Pocket Calculators* (McGraw-Hill, New York, 1976).
4. R. F. Tinker, *Phys. Teach.* **19**, 94 (1981).
5. S. G. Smith and B. A. Sherwood, *Science* **192**, 344 (1976).
6. S. V. Klester, *Change* **10**, 56 (1978); A. Bork, *Comput. Educ.* **4**, 37 (1980).
7. D. Kane and B. Sherbood, *ibid.*, p. 15.
8. R. O. Duda and E. H. Shortliffe, *Science* **220**, 261 (1983).
9. A. Bork, *Learning with Computers* (Digital Press, Bedford, Mass., 1981), p. 247.
10. _____, *ibid.*, p. 98.
11. _____, *ibid.*, p. 131; *Comput. Educ.* **4**, 51 (1980).
12. A. Arons, A. Bork, S. Franklin, B. Kurtz, F. Collea, *Science Literacy in the Public Library: Batteries and Bulbs* (Weeg Computing Center, University of Iowa, Iowa City, 1981).
13. A. Bork, D. Trowbridge, A. Arons, *Observation and Inference: A Computer-Based Learning Module* (IEEE Computer Society Press, Silver Spring, Md., 1983).
14. A. Arons, *Phys. Teach.* **21**, 576 (1983).
15. D. Trowbridge and L. C. McDermott, *Am. J. Phys.* **48**, 1020 (1980); *ibid.* **49**, 242 (1981).
16. J. Minstrell, *Phys. Teach.* **20**, 10 (1982).
17. R. Gunstone and R. White, *Sci. Educ.* **65**, 291 (1981).
18. M. McCloskey, A. Caramazza, B. Green, *Science* **210**, 1139 (1980).
19. J. Clement, *Am. J. Phys.* **50**, 66 (1982).
20. E. L. Chiappetta, *Sci. Educ.* **60**, 253 (1976).
21. A. B. Arons, *Am. J. Phys.* **44**, 834 (1976).
22. _____, *Phys. Teach.* **22**, 21 (1984); *ibid.*, p. 88.
23. A. E. Lawson, *Sci. Educ.* **64**, 95 (1980).
24. L. B. Resnick, *Science* **220**, 477 (1983).
25. National Commission on Excellence in Education, *A Nation at Risk* (Government Printing Office, Washington, D.C., 1983).
26. National Science Board Commission on Precollege Education in Mathematics, Science, and Technology, *Educating Americans for the 21st Century* (National Science Foundation, Washington, D.C., 1983).
27. A. E. Lawson, *Sci. Educ.* **66**, 229 (1982).
28. A. B. Arons, *Daedalus (Boston)* **112** (No. 2), 91 (Spring 1983).
29. _____, *J. Coll. Sci. Teach.* **13** (No. 4), 210 (1984).