Computer-based instruction in physics

Students are learning physical principles from well-programmed computers, which engage them in dialog, allow them to display and manipulate physical laws and then diagnose their educational progress.

Alfred Bork

Until now, the computer has played only a minor role in the teaching of physics and other subjects. In the next few years we can expect this to change dramatically because of the development and profusion of relatively inexpensive personal computers and because of the growing pressure to streamline the educational system. In the future, computer-based instruction may make practical the organization of colleges in which almost all funds are used for the development of curriculum material and relatively little is spent per student for delivery.

The instructional capabilities of the computer give it several great advantages over many of the other educational media currently in use. A computer with a good instructional program in physics, for example, allows the student to engage in Socratic dialog about the details of the subject, to display the laws of physics graphically and to see the results of varying not only the initial conditions but even the laws themselves. Computers can let students cover course material at their own pace and can administer examinations, giving the student feedback after each test item. The advantages of computer-based instruction are particularly appropriate for dealing with a severe problem in education: teaching an increasingly heterogeneous group of students. We must create a learning environment in which a greater number of students, with a more pronounced mixture of backgrounds, can succeed. Our current physics classes fail many students.

In the past the teacher has almost always viewed this lack of success as a problem of the student. There is an increasing feeling in society, however, that students are not entirely to blame for their failures; our schools and our teachers are frequently called upon to bear a portion of the responsibility. There is a growing consensus in society that the schools need to be improved.

The first advantage of the computer is interaction. The computer allows every student to play an active role in the learning process, in contrast to the passive role that is characteristic (for most students) of lecture and textbook formats, particularly in large classes. It is difficult for one to appreciate just how interactive the computer can be without spending some time running good computer-based learning material. The student in such a situation is no longer a spectator, but is an active participant. (See figure 1.)

A second advantage of the computer is the possibility of giving the student individual attention. As soon as the student types a response to a question asked by the computer, the reply is analyzed by the program. The program makes many decisions, which are based not just on the student's last input, but on previous responses as well.

It is common knowledge among educators that students are different; not all students have the same backgrounds and not all students learn in the same way. But many of our conventional approaches to education use a lock-step procedure for all students and do not allow us to take these differences into account. An advantage of the computer is that with good material we can individualize instruction. Individualization can also be achieved if a single extremely good tutor works with a very small group of students, say no more than four. The classical model for such a tutor is Socrates. But this second way, although superior to anything we can attain with the computer, is impractical in our society, except in advanced graduate education. We have too many people to educate, not enough teachers and not

enough money to proceed in this fashion. The computer can give us some of the advantages of Socratic dialog, in an affordable manner.

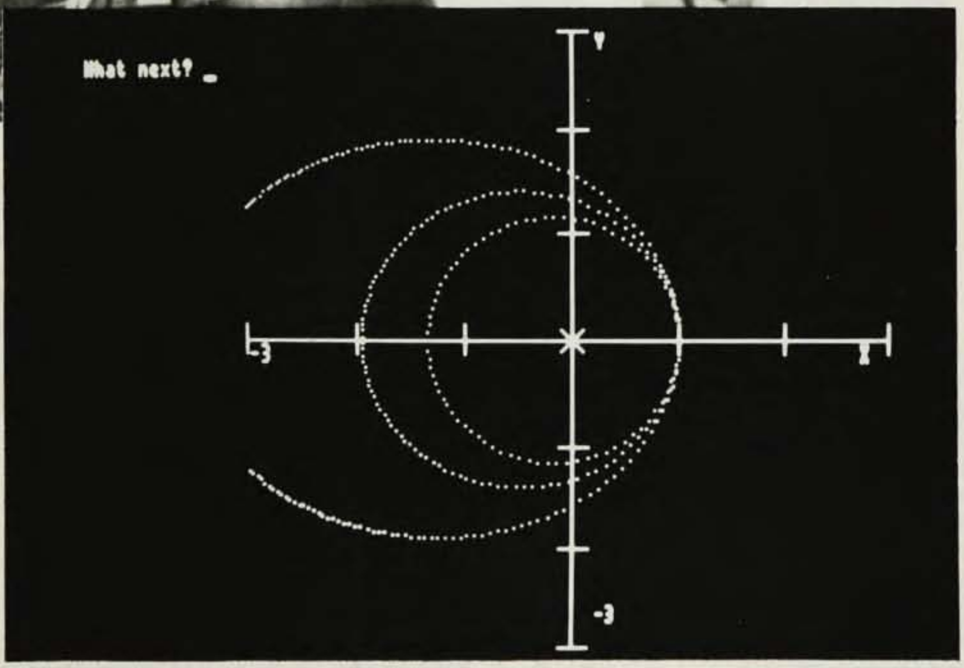
A third advantage is also related to individual differences among students. As all students do not learn at the same rate, it is important to give different students different amounts of time to go through the learning material. Computer-based instruction allows the student to control the pace of the individual learning sequence or unit and, in a "Keller plan" or other self-paced situation, to control the overall pace of the course. Another student choice that the computer can provide is a choice of content, even within a single course.

Computer-based learning

In the following examples we discuss four of the many ways we can use the computer to aid the physics student: the computer as an intellectual tool,

Alfred Bork is professor in the department of physics and the department of information and computer science at the University of California, Irvine, where he is director of the Educational Technology Center.

0031-9228 / 81 / 090024-07 / $00.50



Students at computer terminals at the Educational Technology Center, University of California, Irvine, using instructional programs. As a medium of instruction the computer has many advantages over the traditional textbook and lecture. For example, in computer-based instruction the student plays an active role rather than the traditional passive one. The increasing availability of "personal" computers such as the one shown here (left) will make computer-based instruction available on a much wider basis. The computer display (right) shows a scene developed by a student while using an instructional program. As part of a unit on planetary motion, the student puts planets into orbit around a fixed sun, varying the initial conditions at will. The student sees the orbits develop in time. Three orbits are shown here for the case of an inverse-square force law. Figure 1

the computer controllable world, the computer as a testing and diagnostic aid, and the Socratic dialog on computers.

Intellectual tool. In this context the computer is used to expand the user's mental capabilities and understanding. It often allows us different approaches to the content of physics. We consider the computer to be an intellectual tool when the student is a programmer. But the aim of the programming activity is to learn physics. Our students use a common standard programming language, usually APL or Pascal for beginning students.

The most well-developed example within physics of the intellectual tool use is in beginning mechanics. Here, students use the computer to study the laws of motion in a new way, differing significantly from the typical approach in the standard texts. Two physics texts, *Basic Concepts of Physics*[1] by Chalmers Sherwin, and the *Feynman Lectures on Physics*,[2] pioneered the notion, but without using computers. The basic concept is to approach problems involving $F = ma$ through numerical techniques for solving the differential equations, using simple methods that are easily understandable even at the high-school level.

The most widely used physics material of this kind, *Introductory Computer Based Mechanics*, is available through CONDUIT at the Computer Center, University of Iowa. This material is in the form of two units or modules, and is designed for supplementary use in physics classes. The first module[3] considers only one-dimensional systems. The second module[4] extends the notion to two-dimensional systems and considers auxiliary concepts such as energy. CONDUIT will soon issue a new version using the graphic capabilities of personal computers.

The basic ideas can be introduced in several ways. Richard Feynman approximates the derivatives of position and velocity as ratios of finite differences. In any approach the student is led to the following equations as the basis of the numerical method:

$$\mathbf{x}_{\text{new}} = \mathbf{x}_{\text{old}} + \mathbf{v}\Delta t$$
$$\mathbf{a} = \mathbf{F}/m$$
$$\mathbf{v}_{\text{new}} = \mathbf{v}_{\text{old}} + \mathbf{a}\Delta t$$

A significant aspect of this approach

is that it can lead to a quite different beginning quarter or semester in physics. Even the problems that students study are different. The traditional course tends to offer problems that can be solved by handling $\mathbf{F} = m\mathbf{a}$ algebraically. This restricts the user to a narrow range of problems: projectile motion, "block sliding down inclined plane," "rope over pulley."

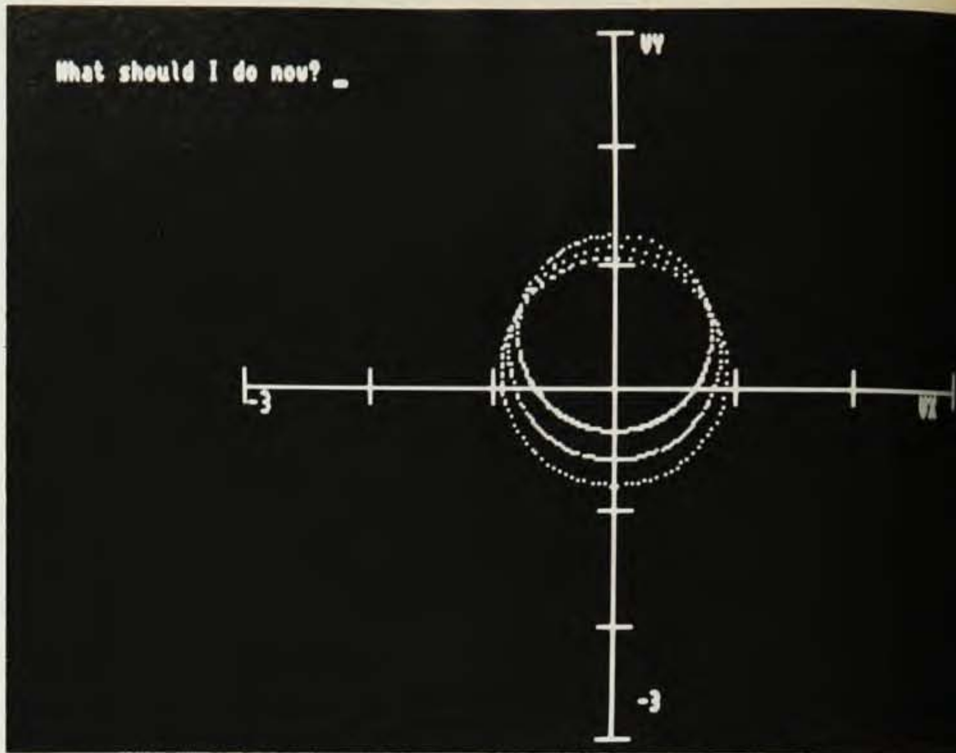
To give some idea of the flavor of the intellectual tool approach to beginning mechanics, here are several of the problems from module two of *Introductory Computer Based Mechanics.*

> Starting at (3,0) and moving initially upward, investigate the motion of a satellite for initial speeds between 0.4 and 0.8. Comment on the curves obtained.
>
> Suppose the gravitational force law was $F(r) = -1/r^{1.8}$
>
> (**a**) Run your program for a circular orbit.
>
> (**b**) Run your program for initial conditions which would provide an elliptical orbit for the inverse square law. In which direction is the precession of the orbit?
>
> (**c**) By using several exponents between 1.8 and 2.2 relate the precession of the orbit to the deviation of the power away from 2.
>
> Elliptical motion is still possible with two fixed force centers! Speculate as to how this could happen, and then experiment at the computer to verify or refute your speculation.

Controllable worlds. The second type of computer use in physics courses is directed toward building up a student's insight or intuition. This important goal is difficult to accomplish in traditional courses. Again, I will use an example from beginning mechanics. The basic notion is that we can help the student achieve better insight into physical problems by allowing the computer to simulate a great range of experiences and make them available to the student.

As an example, let us examine a unit that we developed, called NEWTON, on planetary motion in the ordinary inverse-square case. The student is allowed not only to examine in a free and easy fashion the usual spatial orbits but is introduced, even at the beginning physics level, to various abstract spaces.

Consider a planet moving around a fixed sun. This system is always discussed in physics classes, but no one has ever seen a planet move around the sun! Direct experience is not available. Hence, there is a certain abstraction to the results that are presented to the student; a student may not necessarily build up a feeling for the situation. In a program such as NEWTON, we can let the student in an easy and natural fashion begin by looking at several planetary orbits, simply picking slightly different initial velocities as in figure 1.

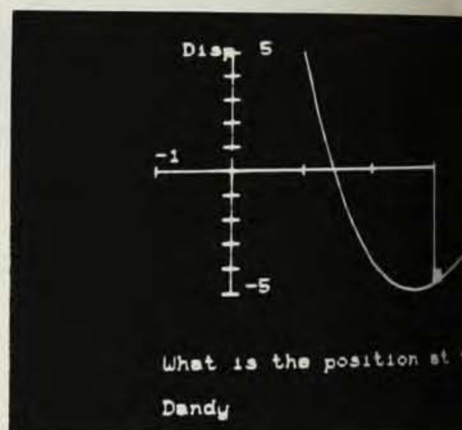


Velocity-space plots (above) of planetary orbits are as readily available to students as are the x-y plots seen in figure 1. Students discover that in velocity-space the orbits are circles. Figure 2

The figure does not show an important aspect of the display seen by the student—that the orbit develops in time. Thus, the type of motion that Kepler's second law tells us must happen is something the student experiences as an actual fact, not simply an abstract idea. The student "sees" phenomena not ordinarily seen.

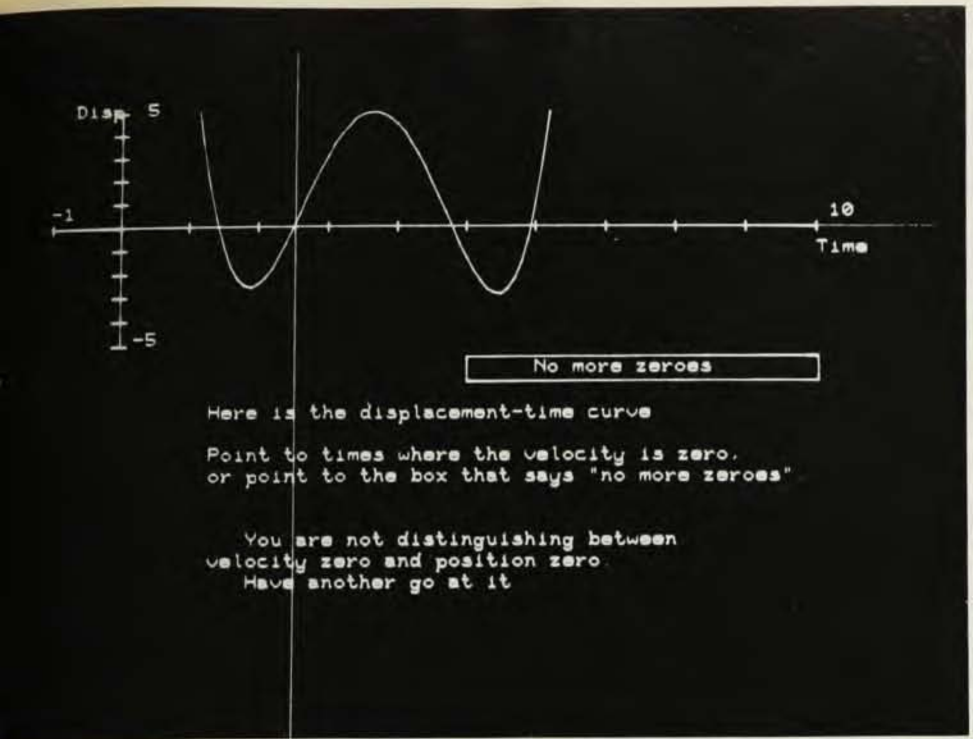
But the user does not need to stay in x–y space. The student might be asked to look at what happens for the same orbits, with the same initial conditions, but in velocity space, where the x component of velocity is plotted against the y component of velocity. Figure 2 shows the results. Looking at the figure, we see that the "orbits" in velocity space are circles, something not known to a great many physicists. This leads to some interesting views of what is happening; an approach to mechanics developed by Andrew di Sessa and others at MIT uses this as a way of attacking gravitational problems.[5]

The student can also easily view other aspects of gravitational motion. NEWTON allows us to plot any mechanical variable against any other mechanical variable and allows complete student control of initial conditions, constants in the equations, scaling details and other factors of the motion. In order to reach all students in a large class, auxiliary workbook material is needed; we are preparing such material with the CONDUIT group.[6]

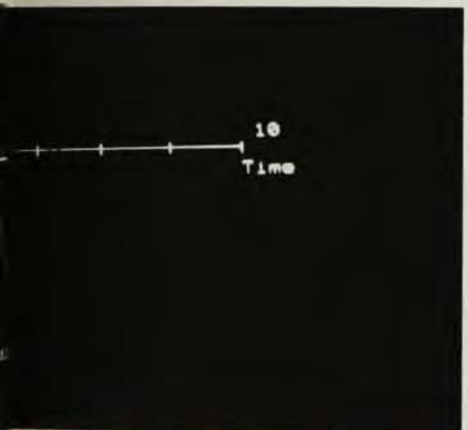


Testing and diagnostic aid. A third kind of computer usage, the testing of students, is something we are giving increasing attention to at the Educational Technology Center at Irvine.

The main advantage of testing via the computer is that we can give the student immediate feedback and aid. This stands out in contrast to normal testing, where often it is days or even weeks before the student receives any information on the difficulties encountered. From an instructional point of view such a delay is unfortunate because feedback is most effective at exactly the time the student is taking the test. It is then that students are most amenable to learning, particularly from material that points out just what kinds of difficulties occurred. Often it is possible to be very precise in this regard; good instructors know the typical errors made by students and write programs that check for such errors. On other occasions the aid will be more general, reviewing the student's problems.



Quiz item, student's incorrect answer (crosshairs) and program's response illustrate the ability of a good instructional program to anticipate a likely student error. Figure 4



Question presented by the computer (left) is part of a quiz designed to assess the beginning student's knowledge of graphs. The curve and the point of interest are different each time the computer gives the quiz. Here the student has given a correct answer. Figure 3

As an example, consider one of the early quizzes used in our beginning course, a course we will describe later in this article. The quiz is concerned with geometrical calculus as used in physics. Can a student seeing a position–time curve, for example, recognize the correct corresponding velocity–time curve?

The quiz starts by checking to see if the student has adequate background to read a graph and to place a point on the graph. While most of the students in the University of California can read graphs, a few can not. Hence, it is reasonable to find out early in the course that a student needs help in this regard. Figure 3 shows a situation in which a student correctly reads a point from the graph. The graph is different each time the quiz is given, as is the particular time the student is asked about. So we examine the students on their understanding of concepts, not their knowledge of particular examples of concepts.

In the next part of the quiz the student is asked where the velocity is zero, given a position–time curve. The student answers using the video display terminal's built-in pointer. Again, the curve will be different each time the program is run. Figure 4 shows a situation in which a student has pointed to a place where the position, rather than the velocity, is zero. Most of the feedback is self-explanatory. What is not shown is that the student has pointed several times and has received a number of different replies. The program was quite responsive in pointing out a likely student error, confusing the zero of position on the curve with zero velocity.

The next sequence of the quiz, one of the two main sequences, offers the student a position–time curve and velocity–time curve and asks whether they are a good pair or a bad pair. The position–time curve stays the same as various velocity–time curves are presented, but only one at a time. The student may see a matched pair right away or may go through five or so possibilities before that. Likely wrong answers are presented. Figure 5 shows a problem presented to the student. Again, the curves are different each time the program is run. Similar sequences of questions ask the student to match acceleration–time curves with velocity–time curves or present the student with a velocity–time curve and ask about position.

Unlike ordinary multiple-choice questions, this variant does not show the student all the possible responses, but makes the student accept or decline each possible answer. A large number of possible answers are available in the program, and these are picked at random for each student taking the quiz. This technique, developed by Stephen Franklin,[7] is widely used in our quizzes. Thus, we avoid one of the major disadvantages of ordinary multiple-choice questions: allowing the student to guess from a series of possibilities. We very seldom find it necessary or desirable to use the standard multiple-choice format in our computer-generated quizzes. If the student chooses an incorrect answer, the correct answer is displayed immediately.

Socratic dialog. The last type of computer usage that we will discuss is one in which the computer plays the role of an excellent tutor. The notion of Socrates teaching through a series of carefully chosen questions, responsive to the student's answers, has been well known for 2500 years. This procedure is very different from the typical lecture–textbook system of education, where the student is constantly being *told* things. Socrates very seldom gave any information to the student but tried to lead the student's thinking toward the critical ideas, through question after question.

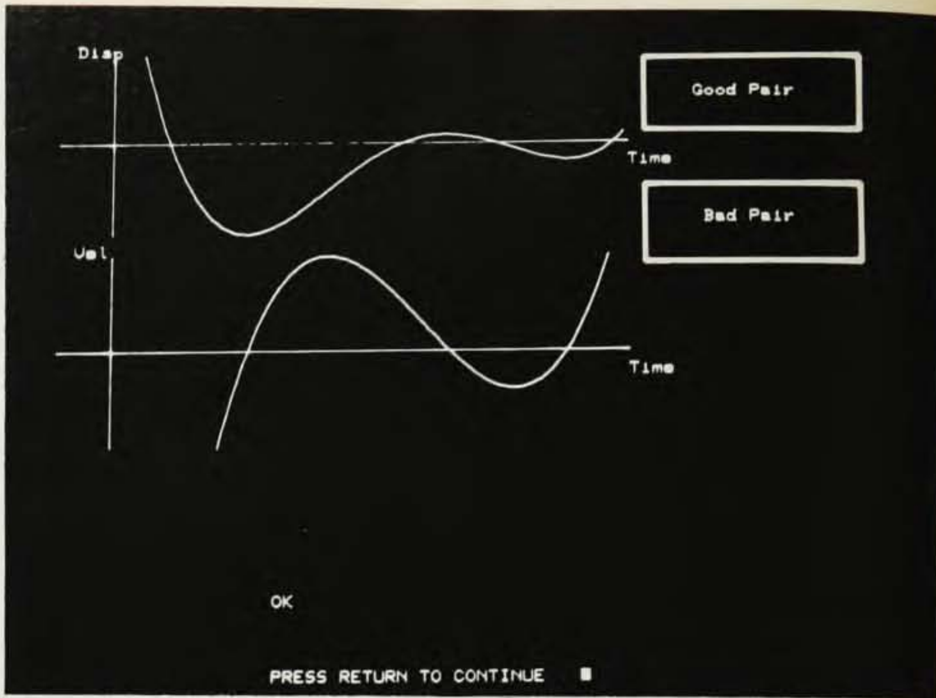
We will look at an example that was developed by Arnold Arons, Barry Kurtz, Stephen Franklin and myself with aid from Francis Collea. It is based on curriculum material first developed in the Elementary Science Study units. The immediate situation involves the use of batteries, bulbs and wires, but the emphasis in the material is not to teach the simple information involved but rather to lead the student, through questioning and empiricial investigations, to a satisfactory model of what happens in electrical circuits. Thus, the question of how we know what we know is very important.

This material was prepared for use in public libraries. The general subject of the modules is scientific literacy, bringing a wide variety of individuals to a better understanding of what science is all about. Figure 6 shows stages along the way. One can get some flavor of what is happening by looking at the questions the users are being asked.

The reader is reminded that the four computer uses we have discussed are illustrative rather than exhaustive. A full program can occupy several hours of student time.

An example at Irvine

I will now describe computer-aided physics instruction from a different



Two curves are generated and displayed by the computer and the student is asked whether or not they are mutually consistent. Using a variation of a multiple-choice format, a single position-time curve is displayed while various velocity–time curves are presented—but only one at a time. The student must accept or decline each choice that is displayed. Figure 5

point of view, that of a particular course. Physics 5A at the University of California, Irvine, is the first quarter of a calculus-based course taught primarily to science and engineering freshman.

On the first day of Physics 5A students are told that they have a choice among three different courses, all carrying the same credit. Course 1 is conventionally taught and graded; the computer plays no role except as a possible optional learning device. The second and third choices both heavily involve the computer and are based on the "Keller" or "Personalized System of Instruction" strategy.

Students move through courses 2 or 3 at their own pace. Before proceeding, they must demonstrate knowledge of a unit by passing a test or tests at essentially the 100% level. The personalized system of instruction has been well described in the literature, and has been shown to be an effective way of learning. What makes this particular course interesting is that the testing is all done directly on-line at the computer except for the final exam.

The two computer courses differ in content. Course 2 has the same content as course 1 and uses the same standard beginning textbook. Course 3 is based on a set of notes developed at Irvine. It makes use of the intellectual tool aspect of computers, presenting a quite different approach to $\mathbf{F} = m\mathbf{a}$, as discussed earlier. Courses 2 and 3 are quite different in content as demonstrated by the fact that there is very little overlap in their quizzes.

In the winter 1981 quarter approximately 450 students enrolled in Physics 5A. About three-quarters of these students chose the two computer tracks, a dramatic increase from the initial offering of the course, indicating a favorable reputation among the students. Students spend about three hours per week at the computer display screens. Each student takes about fifteen different quizzes, often taking a quiz several times until he or she demonstrates mastery of the material covered. We gave about 15 000 computer quizzes during the ten weeks of the quarter, providing immediate assistance when needed.

A full course management system on the computer backs up the course. As the students take quizzes, pass/fail information is recorded. The course management system also controls access to the quizzes. Students are not allowed to take quizzes in a unit until they have completed quizzes in all the previous units. If a quiz is not passed, twelve hours must elapse before the computer will allow the student to take the quiz again, emphasizing the need for additional study. If a student does not pass a quiz after four attempts, he or she must come in and see the instructor before being allowed to take the quiz again. Thus, the instructor sees each student in trouble individually, and the system assures that this will be the case for every student continuing in the course.

This is only one of many different courses that could be put together with the computer. Other uses in physics courses are described in the literature.

Writing computer-based text

So far we have been looking at existing courses and material. But very little in the way of good computer-based learning material exists at the present time. The past twenty years have been a period of experiment, where much of the effort (sometimes unknown to the developers) has gone into understanding the capabilities of the computer as a medium of instruction. Now we have a reasonable, but not perfect, understanding of these capabilities. The hardware has continued to decline in cost during this period, so that now, with the advent of the new personal computers (see figure 1) based on microcomputer chips, it is reasonable to plan large-scale production and use of computer-based learning material.

Earlier attempts at producing computer-based learning material tended to follow what might be described as the "coursewriter" strategy. The no-

Graphics and text appearing in a computer-based instructional unit on elementary electrical circuits, prepared for use in public libraries. The user of such a program plays an active role in the instructional process. Figure 6 tion of this strategy was that each author would develop a unique set of programming commands and use this as the basis for producing material; one person would do all the work. This is somewhat like requiring that an instructor who wants to write a textbook learn how to run a typesetting machine and a printing press.

At the Educational Technology Center at Irvine the process of producing computer-based course material begins with specification of the teaching strategies to be used for each concept. This requires extremely good teachers, who work in small groups with those who have knowledge of the computer's capability. The teachers do not need to know anything about computer programming, and most of those who work with us do not. They have complete freedom to make the best choices possible from an instructional point of view; they need not be concerned with the associated programming problems.

The second stage is that of visual and temporal design of material on the screen. Earlier computer material often paid no attention to screen layout, implicitly using the same strategies that are used in books. But more recently teachers have realized that the screen is a very different medium from the book with many different nuances. For example, diagrams and even text can be made to appear on the screen slowly in order to show a sequence of development; the screen can be cleared at will, without regard to conservation of paper as with the pages of a book.

A third stage is the actual programming. At Irvine the programming work is typically carried out by undergraduate students using powerful higher-level languages. Our recent activities employ Pascal, with various auxiliary software to aid the process.

A series of testing and revision stages follow. One of the advantages of computer-based teaching is that the instructional material itself can collect very detailed feedback on what happens when it is used. Then the material can and should be rewritten, perhaps several times, based on the information so obtained. The information received can be much more microscopic in detail than that concerned with students learning in lectures or from textbooks. At each stage we can record student responses to computer questions, and these answers can be analyzed to improve the program.

Future

The development of new computer-based instructional material, and the associated research, will have one interesting effect not directly associated with the material itself. We can expect to learn more about the way people learn. The computer is a unique tool for learning about learning, and has only recently become available for research in this area.

A second factor that is very important to remember is the continual evolution of computers themselves. Chip technology is still young and vigorous and is leading to better and less expensive machines. All indications are that this process will continue for a considerable period of time. New developments are continually extending the possiblities. Costs for equivalent computing power have gone down about 25% per year in recent years, and it looks as if this striking reduction will continue. The net effect is that we can expect more and more computers to be available for use in education. Economic factors are on the side of the computer.

Computers will also become better from an educational standpoint. We will have more memory, both fast memory and slower backup memory, at less cost. We will have faster and more sophisticated central processing units, a development already reflected in the newer chips such as the Intel 8086 or 432 and the Motorola 68 000. Graphic capabilities will improve considerably over what they are today, allowing better color, resolution, shading, and even full animation with much better treatment of three-dimensional aspects. Voice output is already practical, and there is the increasing possibility that within a decade we will see unconstrained voice input. So our capabilities will continue to grow.

Another continuing development with computers is the availability not only of better software but of more powerful programming tools with which to develop software. Newer languages such as Pascal and most recently Ada, were developed to meet the need for better programming techniques. With regard to the preparation of computer-based learning material, this gives us the ability to produce programs that will be easier to modify and use.

From the instructional point of view, however, the main interest will be the effects on courses and curricula. The computer will allow much more self-pacing, along the example of the course just described. For such courses the computer will present learning material, give unit tests with not only diagnostic value but with instructional value as well and manage the entire process. We will be able to break away from the notion that courses always have to begin and end at a certain time, or the notion that courses must have the same duration for all students, independent of the needs of the students.

But the greatest change will probably be in the quality of the courses. As courses are rethought, with the possibility of using an interactive and individualized learning medium, we can produce curriculum materials far superior to those currently in use. How this process will take place is not certain. One possibility is the formation of an American Open University, with the associated curriculum development activities.

Finally, we may see considerable changes in our institutions. Some of these changes will be made practical by the computer. The enrollment problems of the next fifteen years, universally predicted, may be a major stimulus. Although figures differ, in most parts of the country enrollments in universities can be expected to decline between 10% and 25%. The situation is much worse in the northeast and north central areas of the country than elsewhere. This demographic factor, combined with increasing public resistance to funding education, will increase greatly the external pressures for budget and personnel cuts in our institutions. Computers are one good possibility for accommodating these new and increasing outside pressures on education.

One interesting recent trend is the formation of a variety of nontraditional universities, universities which depart from the pervasive pattern of universities in the United States. Some nontraditional universities emphasize the notion that one can avoid constructing buildings. For example, Coastline College in Southern California is a community college that did not build a campus, but uses community buildings, television courses and other nontraditional techniques.

Another interesting new type of university is that connected with an industrial or commercial firm. Perhaps the most interesting recent example is the graduate school in computer science formed by Wang, a computer manufacturer.

Another new type of institution is exemplified by The Open University in England and to some extent by the University of Mid-America in this country. The notion is similar to that suggested by Coastline College, but in a direction that completely abandons the traditional campus. Almost all The Open University students work in their homes, coming only in a summer session to any central location. These summer sessions are held at universities all over the country, which are not in use then.

The most interesting aspect of The Open University from the standpoint of our current discussion is that it represents a very different balance of funding. The Open University puts almost all of its funds into *development* of curriculum material, using relatively little per student for *delivery*. Our traditional universities are based on almost the opposite balance. The Open University has proved successful, in terms of the quality of its students and in terms of its costs per student, a significant factor for us to consider for the future. The Open University does not use much computer material at the present time, but as the technology becomes more sophisticated, they and others will move further in this direction. If such universities develop in this country, there will be important consequences for both teaching and research.

* * *

The computer materials described in this paper were developed with support from the National Science Foundation and the Fund for the Improvement of Postsecondary Education.

References

1. C. Sherwin, *Basic Concepts of Physics*, Holt, Rinehart and Winston, New York (1961).
2. R. P. Feynman, R. B. Leighton, M. L. Sands, *The Feynman Lectures on Physics*, vol. 1, Addison-Wesley, Reading, Mass (1963–65), chapter 9.
3. A. Bork, A. Luehrmann, J. W. Robson, *Introductory Computer Based Mechanics I*, CONDUIT, University of Iowa, Iowa City 52242
4. A. Bork, D. Merrill, H. Peckham, W. Lang, *Introductory Computer Based Mechanics II*, CONDUIT, University of Iowa, Iowa City 52242.
5. A. Bork, *Learning with Computers*, Digital Press, Bedford, Mass. (1981), pages 83-97.
6. CONDUIT at the Computer Center, University of Iowa.
7. S. Franklin, J. Marasco, Journal of College Science Teaching **7**, September 1977, page 15.
8. Physics in the Irvine Educational Technology Center, in Computers and Education, An International Journal, **4**, D. F. Rogers, P. R. Smith, eds.; Alfred Bork, guest editor, Pergamon, New York (1980).