USING COMPUTERS IN TEACHING PHYSICS

Computers can revolutionize not only the way we teach physics but also what physics we teach.

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and Edward F. Redish

The computer has revolutionized the way we do physics, but surprisingly, it has not significantly altered the way we teach physics. Talks and papers on teaching with computers fill the meetings and journals of the American Association of Physics Teachers, and workshops on the topic abound, yet the real impact of computers in the classroom is slight. In physics research, change comes quickly, disseminates rapidly and is widely appreciated. In physics teaching, change evolves gradually, spreads slowly and frequently meets with resistance. On 6 June 1988 *The Wall Street Journal* published a story with the headline "Computers Failing as Teaching Aids." The reasons the *Journal* cited for this failure at the general pre-college education level apply equally well to physics teaching at the introductory college level: lack of access to computers, poor software and faculty members who are inadequately prepared to use computers effectively.

Failure is nothing new in this area. In 1970 Edwin Taylor of MIT wrote an article entitled "A History of Failure of Computer Interactive Instruction." Now, 18 years later, in spite of dramatic advances in capabilities, decreased costs, extensive familiarization programs and widespread availability, computers are still not in regular use in physics teaching. Part of the problem is that we are chasing a rapidly moving target. The goals of access, software and faculty familiarity are difficult to achieve because our ambitions are so much greater today than they were two decades ago.

Still, many wish to see the computer used more at all levels of physics instruction. For example, more than 300 physicists attended the Conference on Computers in Physics Instruction held in Raleigh, North Carolina, last August.[1] The past three conferences of physics department chairs have devoted considerable discussion to the role of the computer in teaching.[2]

Not only are physicists rethinking the role of computers in instruction; they are reevaluating the very content of physics courses. The Introductory University Physics Project[3], sponsored by AIP, APS and AAPT, and the Maryland University Project in Physics Educational Technology, or MUPPET,[4] are each studying the physics curriculum to determine how it might change to reflect physics as it is done today. As such studies bring up to date

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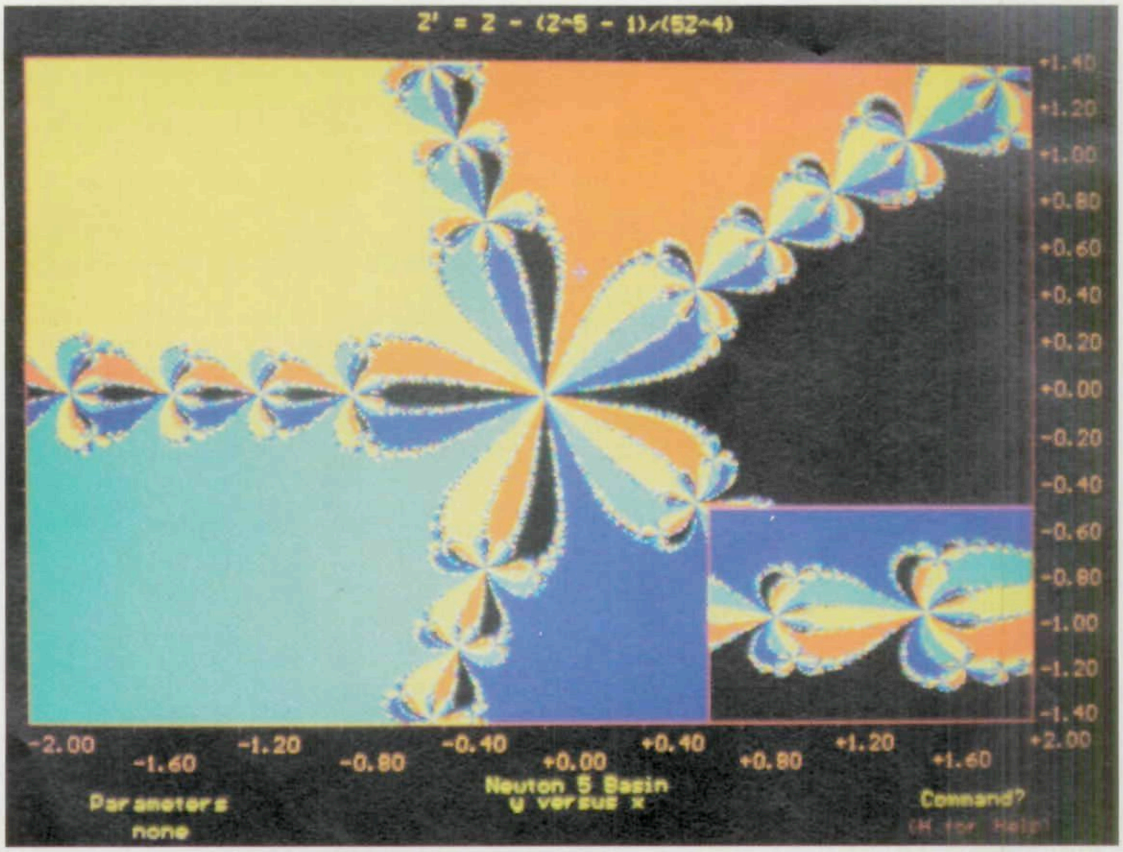


"Newton 5 Basin" is the plot of a nonlinear function projected onto the screen of a computer monitor. Software called "The Mapping Machine," which generated this figure, was written by James Harold, a graduate student at the University of Maryland. Such computer programs enable even introductory students to experience some of the excitement of current topics in physics. This photograph and the others that accompany this article were made by Harold. **Figure 1**

not only the topics to be taught but also the student skills to be developed in introductory courses, computers may find a natural niche as both a mathematical and a pedagogical tool. Along with the subject matter of physics, the methods of doing physics have changed greatly in recent years. Numerical approaches to problem solving are widely prevalent in research but are rarely taught to beginning students. Computers may allow us to introduce these approaches earlier.

We have not yet systematized and incorporated computers as mathematical and pedagogical tools in the way we have calculus and differential equations. Physicists are not alone in this quandary. Mathematicians have launched a national effort, "Calculus for a New Century," aimed at reforming calculus instruction in light of the tools that will be required of mathematicians and scientists in the 1990s. This interest and activity takes place against a historical background that is not completely encouraging.

Our MUPPET program at the University of Maryland is a collaboration of research physicists and physics educators. The thrust of this program is to reorganize and broaden the content of introductory physics courses. We feel that computers can help us to emphasize fundamental physics, include more contemporary physics, train student intuition, provide students more experience with complex systems and give them some research experience.

Computers have been put to a variety of uses in teaching physics. Among these are:
▷ drill and practice
▷ testing
▷ course management
▷ tutorials
▷ dialogue and artificial intelligence
▷ simulations
▷ instructional games
▷ laboratory data acquisition
▷ programming
▷ modeling physical phenomena.

A variety of software has been developed to serve these purposes. Physics instructional software is regularly reviewed by an evaluation project jointly sponsored by AIP, APS and AAPT and by an evaluation project at North Carolina State University. Some of these reviews appear in a monthly column in *The Physics Teacher.*

Each of these ways of using computers can contribute to learning, but the educational context of the use determines just how effective a particular tool can be. Over the years each has acquired some baggage of particularly poor applications that colors the acceptance of new materials. We review each of these uses below to develop a historical perspective for our discussion of today's activities. We will emphasize those current activities that seem to show particular promise for early application and for significant improvements in the physics curriculum.

Drill and practice, testing and course management are relatively straightforward uses of the computer that many physicists find practical but uninspiring. Each can and should be part of a physics instructional program, but they represent incremental improvements over traditional methods, not tools for restructuring pedagogical approaches or altering course content.

Tutorial materials

When physicists who are not involved in using computers to teach think of doing so, they often think first of tutorial programs. Ambitious efforts to create tutorials for physics, such as Control Data Corporation's Physics 1 Courseware known as PLATO and a project at the University of California, Irvine,[5] were undertaken in the 1970s. Tutorial materials have not received much acceptance in the physics community, and many question the educational philosophy behind tutorials, which are often characterized as "computers running students." Alfred Bork developed the best rationale for developing such materials in his 1978 Millikan lecture when he sketched a visionary view of tutorial materials that were much more interactive than what then existed.[6]

To produce tutorial materials one must have a model of how students think and must recognize the preconceptions students bring with them into the classroom. The author must anticipate likely mistakes and create scripts for dealing with those mistakes. Bork developed an extraordinarily sophisticated system for producing tutorials that involved experts in cognition, physics teaching, design and programming, but in spite of his best efforts few universities have adopted either his materials or his methods.

Others have tried to make it easier to produce tutorial materials by creating "authoring" languages that simplify the writing of software. The PLATO project, originally written for a mainframe computer, spawned the TUTOR authoring language, which eventually evolved, through development work at Carnegie Mellon University, into the microcomputer language CMU TUTOR (now known as cT).[7] The cT system enables even authors with no programming background to create quite sophisticated materials with graphics and mouse controls. The cT language includes a novel display editor for generating cT source code during interactive sessions with the author. This language works in a Unix environment, is based upon the C language system and is available for IBM and Macintosh systems as well as standard Unix systems. Bruce and Judy Sherwood of Carnegie Mellon are now working to remove limitations on string handling, color use, data types and file structures. David Trowbridge, also of Carnegie Mellon, used cT to create a program called "Graphs and Tracks," which was given an award in 1988 for best physics software and best integrated software under a program sponsored jointly by Educational Computing (EDUCOM) and the National Center for Research to Improve Post-Secondary Teaching and Learning (NCRIPTAL).

Artificial intelligence

Artificial intelligence techniques and expert systems are beginning to be used in physics,[8] but are little used in physics education. The SOAR system, a generalized artificial intelligence inference machine developed by Allen Newell of Carnegie Mellon,[9] looks particularly promising, but has thus far not been applied to teaching. Because the AI structures of rules, inference engines and learning by experience have parallels in research on physics education, the physics classroom appears to be a logical place for the future development of AI models.

Simulations

The development of simulations that can be used as lecture demonstrations has been increasingly popular in the past few years. Many institutions now have video projection systems that allow entire classes to follow graphic demonstrations; the systems represent great improvements over the lecturer's drawing skills. In the coming years we expect that more good materials will become available and that computers will be routinely used for visualization in lectures. Blas Cabrera of Stanford has produced a number of such simulations, which are now marketed commercially for the Macintosh computer.[10]

Students can also use simulations directly to explore the structure of physical models.[11] Taylor has produced "Spacetime Physics," a tool that takes students into the world of special relativity. "Spacetime Physics" is another EDUCOM/NCRIPTAL 1988 award winner, for best physics and best tool software.

MUPPET has also developed interactive tools that are based on simulations and can be used as class assignments in the introductory course. (These programs can be obtained from the authors.) Using the program "Orbits," for example, students explore the interactions of several bodies by controlling the number of bodies (up to five), their sizes and positions, and the type of central force law. (See the figure on page 41.) One assignment is disguised as a game whose object is to maneuver a rocket from one side of a planet to another in order to intercept another rocket in the same orbit.

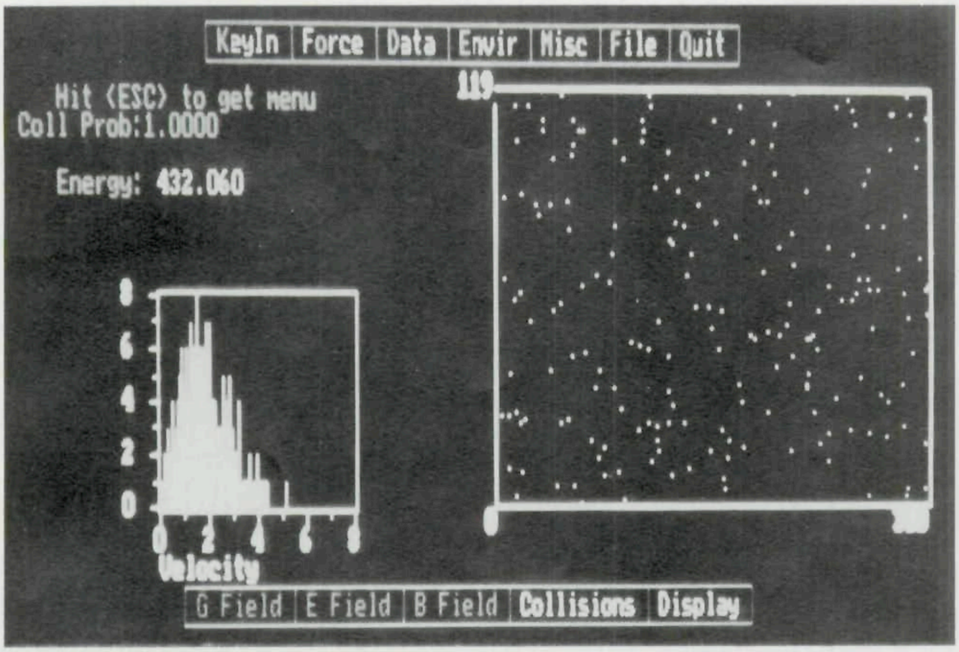
Another program, "Thermo," introduces students to a "microworld" inhabited by a large number of particles. (In a microworld only a handful of rules operate.) Students control the number of particles, the frequency of collisions among them, the types of interactions (gravitational, electric, magnetic and so on) and the initial conditions. In one part of the screen students can display the distribution of particle energies. The program illustrates the approach to equilibrium through collisions. (See the figure on page 37.)

"The Mapping Machine" allows students to explore nonlinear systems through one- and two-dimensional functional maps of several types, including the Mandelbrot set, the Henon map and Newton's-method maps of several orders and types. (See the figure on page 35.)

Each of these computer programs is accompanied by curriculum material to be used in the classroom. These special programs help students build intuition. Students seem to be particularly captivated by chaos and nonlinear dynamics, and they enjoy knowing they are exploring areas not well understood even by their professors.

Simulations also have been used in the laboratory to replace "hands on" student activity. This has a seductive appeal, considering the poor quality of most introductory physics laboratories and the expense of operating an effective laboratory program. The appeal should be resisted, however, since laboratory experience is an important and far too neglected part of the training of a scientist. Some have suggested guidelines that would restrict the use of computer simulations to those experiments that are too dangerous, too complicated or too expensive to be done routinely. However, we feel that these kinds of experiments are probably not suitable for introductory teaching laboratories in any case.

The computer is not a tool in search of a problem. It is better to start with a problem and then seek a tool than vice versa. Any of the thousands of graduate students teaching labs each year can identify common problems: Students come ill-prepared for the laboratory. They do not read through the materials ahead of time. Laboratories are considered boring. The students try to fit too much work in too little time. The objectives are rarely



Hit <ESC> to get menu
Coll Prob:1.0000

Energy: 432.060

Histogram of velocity distribution is displayed for colliding particles in a box by a MUPPET program called "Thermo." Students can specify the number of particles and types of interactions, and can watch as the system approaches equilibrium. **Figure 2**

well understood. Students can't make the equipment work properly. They rely on their partner to do the work, and they leave the lab with little understanding of what happened. In an attempt to remedy these problems the laboratory instructors give lengthy and detailed prelaboratory instructions that compound the time problems and seem to do little for student understanding.

A number of technological solutions to these problems have been attempted, with varying success. These include videotaped prelaboratory preparations, self-paced laboratories and computer-controlled videodisc prelaboratories. Each of these solutions has its own problems. The videotaped prelaboratories are totally noninteractive and can lead to a cookbook approach to the laboratory. Although videodiscs can be much more interactive, the interaction paths are few and must be decided ahead of time by the producer. The open and self-paced laboratories require extensive facilities and a well-managed system to cope with the complexity.

One approach to these problems involves the use of simulations as a required prelaboratory activity. We tried such an approach at the University of Maryland.[12] At the beginning of the semester, students were divided into "research teams." Each team was responsible for one of the 11 experiments in the class, including setting up and conducting the experiment a week before the rest of the class, working with the laboratory instructor during the laboratory, and summarizing the results of all students in a formal "thesis style" lab report. No student was admitted to the lab until he or she had successfully completed the simulation.

The program was evaluated by blindly grading laboratories from classes that used this system against those that used the traditional system. Students were also asked to complete a survey that recorded their perceptions on several items. The results were that the laboratory reports were significantly better; students spent more time working on the laboratory; and they found it more satisfying.

Computer data acquisition

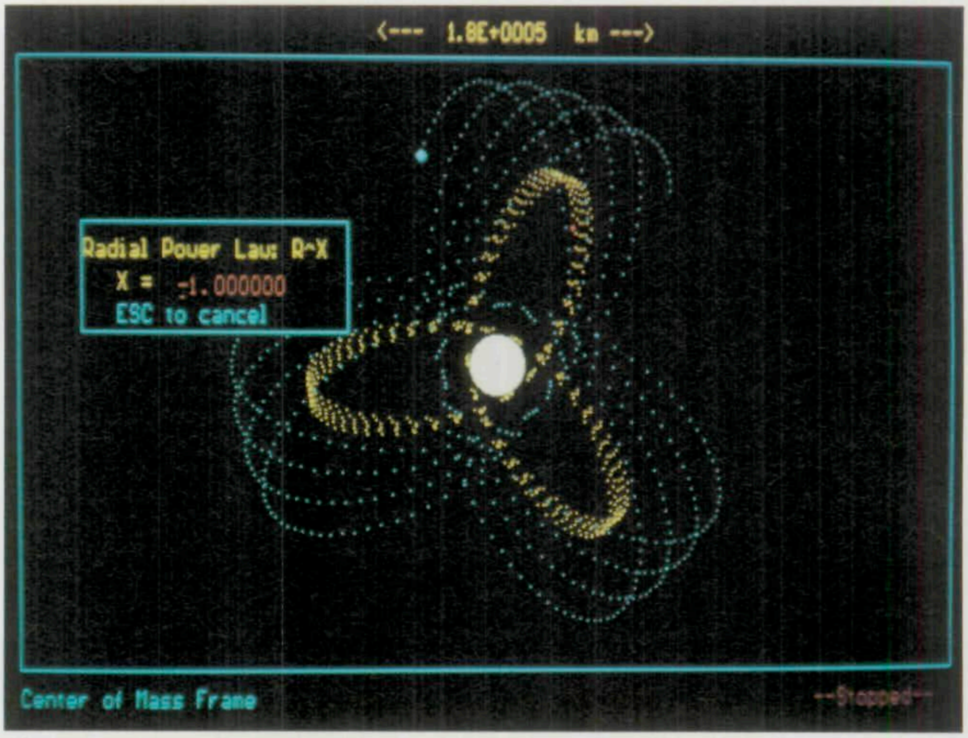
Computer data acquisition can also be used to improve lab experiences, but one must be careful to ensure that the computer doesn't become a "black box" that obscures rather than enlightens.[13] Robert Tinker[14] of the Technical Education Research Center, Cambridge, Mass., and John Layman[15] (University of Maryland) have pioneered the use of microcomputers as data acquisition devices in teaching labs Secondary and even elementary schools have been quicker to implement these microcomputer-based laboratories than have universities.

It is quite easy to set up a microcomputer to acquire data from input devices such as thermistors, photodiodes, pressure transducers and even ultrasonic rangefinders. Ultrasonic transducers have been used to measure the positions, velocities and accelerations of objects—including students! A group at the University of Munich has developed a simple interface that allows one to use a television camera to locate a single white object against a black background. Another group, at Dartmouth, has developed a more elaborate television system for Macintosh computers. With these systems, more complicated two-dimensional motions can be registered digitally. Thousands of people have participated in the AAPT workshops on interfacing microcomputers to laboratory equipment and have either built or bought data-acquisition systems. Used with the accompanying instructional materials, these devices have shown remarkable promise in helping students understand the concepts of velocity, acceleration, temperature and heat. Far from being "black boxes" that obscure the physics under investigation, these materials are powerful spotlights for illuminating topics that are often difficult for students when presented in more traditional ways.

Programming and modeling

Programming and modeling were among the earliest uses of computers in physics education, and yet they remain largely unexploited and potentially powerful tools. Physics students have been expected to program and develop computer models as they advance through the major, but courses at the introductory level have rarely included such work.

The selection of topics for introductory physics courses is often driven by the mathematical complexity of the techniques needed to study the topic. Many topics are



Radial Power Law: R^X

X = -1.000000

Trajectory of a single particle subject to a central force that varies as 1/r. This configuration is one of the possible phenomena a student can investigate with the MUPPET "Orbits" program. Students can thus build intuition about physical phenomena that are mathematically beyond their grasp. **Figure 3**

"off limits" because the students are not expected to have the requisite mathematical tools. As computing power becomes widely available in physics departments, a new set of tools becomes available for student use. Previously off-limits topics become easily accessible.

Consider the mathematical hierarchy of physics: algebra, geometry, trigonometry, calculus, differential equations, linear algebra, probability and statistics, and partial differential equations. The path through the mathematical hierarchy is generally a serial one. Linear algebra and probability are taught at various times in the sequence, but the remainder form a "lockstep" arrangement. In high school, students are generally expected to know trigonometry. For the introductory university physics sequence, students are expected to start with a little knowledge of calculus and to develop more proficiency as they advance through the sequence. Differential equations are rarely introduced until the first advanced courses after the introductory sequence, and partial differential equations appear in some junior and many senior courses. Topics from probability and statistics are often introduced in an *ad hoc* fashion as necessary. Linear algebra is often taught in different ways and at different levels. Numerical methods, if taught, usually come late in a student's studies.

Instructors often equate students' mathematical level with their level of conceptual development. Frequently topics are dimissed as "too abstract" when in reality they simply call for a higher level of mathematics. We have made a virtue of necessity by selecting a palette of topics that are mathematically accessible to students and then defining those topics as the ones necessary to the student's conceptual development.

The mathematical hierarchy given above is roughly the same as it was at the turn of the century. Certainly physics students need to know these topics, but for research physicists today these are not the only and probably not the most important topics in mathematics. Research physicists nowadays rely heavily on numerical and computational techniques for solving problems. A whole new area of physics—computational physics—has emerged in the last few years. In the more established fields of physics, such as condensed matter, nuclear physics, particle physics and astrophysics, both theorists and experimenters have become increasingly dependent on computational methods. Few interesting problems remain that rely solely on the old analytical techniques for their treatment. This is not to say that these techniques are no longer important. Analytical techniques are often used extensively for putting problems in a form that can be solved computationally, and it is surely an advantage for a physicist to recognize portions of problems that can be readily solved in closed form.

If one begins by assuming that students should learn something about numerical and computational methods as a prerequisite or corequisite for their physics courses, one reaches very different conclusions about which topics contribute most to the logical and conceptual development of physics. New topics become accessible, and old topics can be treated differently. Differential equations are replaced by difference equations. Although computational physics has its own set of advanced mathematical techniques that are perhaps even more opaque than some of the analytical techniques, much can be done with the Euler method or simple higher-order Runge–Kutta methods.

Making this assumption should lead one to question the conventional wisdom in topic selection, concept development and pedagogic approach. Consider, for example, the burgeoning cottage industry in identifying student misconceptions in physics. (See Lillian C. McDermott's article in PHYSICS TODAY, July 1984, page 24.) This work has helped us to better understand concept development by students and has led to some tentative efforts to improve science learning. Much of the attention has been directed toward mechanics. For some time quite a bit of the published literature dealt with the reconciliation of students' Aristotelian and teachers' Newtonian world views. Now we recognize the naiveté of referring to the various levels of concept development as Newtonian or Aristotelian. Some early computer programs presented students with the opportunity to explore these world views. One of the most popular simulated a track on which students could race cars by giving "kicks," or impulses, to each car at various times. Through experimentation students were to learn all about inertia and Newton's first law. The racetrack could operate under either Aristotelian or Newtonian rules. The only problem was that the simulation was so realistic that the Aristotelian interpretation agreed better with the students' own experiences than did the frictionless Newtonian world.

Classification of concepts as Aristotelian or Newtonian is one of those nonproductive exercises we should avoid. They are simply two different perspectives on the same world. One is more complete and consistent, but the other is often more useful to nonscientists as a working model!

If students approach physics through analytical techniques, they are barred from considering a consistent model of mechanics. Dissipative forces and nonlinear systems are simply beyond their mathematical ability. The frictionless Newtonian microworld they learn about is so different from the highly dissipative world they inhabit that it is no wonder many studies have shown that students divide things into "physics" and "the real world." We owe them a more consistent picture of the physics, and it is not that difficult to deliver.

Many groups are busily investigating which topics from modern physics might be included in an introductory course.[16] Of these groups, many equate the term "modern physics" with quantum mechanics, relativity and specific topics such as particle physics and superconductivity. Certainly modern physics includes these topics, but it also includes modern ways of approaching problems and thinking about the world. It includes probability, uncertainty, nonlinearity and complexity.

One aspect of modern physics that is almost totally missing at the introductory level is uncertainty—both that due to complexity and that due to quantum limitations. Teaching nonlinear systems helps students understand why the world is not as relentlessly deterministic as we might expect from Newtonian mechanics. Nonlinearity is certainly not the entire story, but it is an important untaught chapter. It has been the experience of the MUPPET collaboration that these topics are interesting and accessible to the students at the introductory level. We have introduced a number of these topics to students in the introductory course for physics majors. Among them are deterministic chaos, fractals, bifurcations, motion in the phase plane and strange attractors. Nonlinear phenomena are very popular when students choose semester projects in our courses (see the cover of this issue).

The curriculum is likely to change in an evolutionary rather than revolutionary way. Most of the traditional features will be retained, but certain items will be added: a stronger emphasis on units, dimensional analysis and scales; use of numerical techniques for problem solving; inclusion of programming as an integral part of learning physics (perhaps in a way analogous to the use of calculus); and the introduction of problems with more complexity than is found in most illustrative problems in current texts.

Complexity versus simplicity

Complexity versus simplicity is one of the most important and most controversial issues facing those of us in this field of physics education. Most physicists would agree that the ability to find a simple model in a complex situation is one of the greatest strengths of physics. Unquestionably, students should be taught to develop a simple model and solve it using traditional analytical techniques. But is it better to present the simplified model first and then add the complicating factors years later, or to present a problem with all of its "real world" complexity, solve it and then reduce it to the traditional simple model?

Prior to the use of computers in teaching, the first option was the only option. Students could not be expected to have the mathematical skills needed to solve the complex problems. Using numerical methods to solve complex problems, however, is fundamentally easier than the traditional analytical calculus approaches. The MUPPET collaboration feels it is much better to deal first with the realistic problem and then boil the problem down to the simple but powerful model that illustrates the essential features of the phenomena. Because this is the way physicists actually solve problems, why not introduce students to it right away? We do not have to give the students the impression that all problems in physics come already stripped of the interesting detail.

Consider the case of the simple pendulum. The usual classroom approach to describing its motion is to write down Newton's second law for a pendulum, make the approximation of small angles and then solve the resulting differential equation for the simple harmonic oscillator. What if a student asks what happens at large angles? What happens when a damping force is present? Or when a driving force is added? The teacher must evade the student's questions because the student does not have the necessary mathematical background to consider such complex problems. The answer is postponed until the student's mathematical skills develop. Actually, even the differential equation for simple harmonic motion taxes most students to the limit of their development.

Using numerical methods one can write a simple iterative program that solves it. The program could be written as a spreadsheet in which time, angle, angular velocity and angular acceleration are the columns and each row corresponds to a time some small interval later than the row above. Alternatively the program could be written in a language in which one could use the traditional FOR or DO loop structures to increment time by Δt on each iteration.

In the numerical approach, driving forces and damping forces are easily added through appropriate terms. The introductory physics student is able to consider the phenomena in all aspects while using mathematical tools at a level well below that of the traditional approach. The "step by step in time" approach is also a much more concrete—even transparent—approach to this problem. It is far less abstract than the traditional small-angle, differential-equation analysis.

The realistic approach to the pendulum has the additional advantage that students are able to explore new phenomena not previously accessible at the introductory level, in this case resonance and chaotic motion. Students quickly discover resonance as they adjust the frequency of the driving force and observe the response of the system. The approach to chaotic motion is somewhat more subtle.

As the amplitude of the driving term is increased, the pendulum may swing over the top and enter a new region of oscillation. This approach introduces students to a phase-plane analysis of the motion, a concept that will prove most useful in many later courses. The actual path of the pendulum is so critically dependent on the initial conditions that it is difficult to predict. This becomes an example of deterministic chaos.

At the University of Maryland, students have coupled computer modeling with data-taking using real pendulums.[17] We also have built a model of an inverted driven pendulum that demonstrates the presence of two basins of attraction. After showing this device to our students, we challenge them to make computer models that explain the behavior of this (very loud) physical system.[18]

Participants in the Conference on Computers in Physics Instruction held at North Carolina State University last August debated the role of complexity, among other pedagogical issues. One of the speakers, Arnold Arons (University of Washington), made the argument for simplicity: He felt it would be damaging to present students with too much complexity too soon. He also felt introducing modern physics too early would lead to rote learning of vocabulary rather than deep understanding of physics. Others felt that although this was a danger, just the opposite effect would prevail. Students would gain a deeper understanding of the physics because it could be coupled more realistically to their own environment.

The MUPPET project

One of the largest challenges facing the MUPPET group was the need to select a "language" for students to use in the numerical solution of physics problems. After considering many candidates we eventually settled on two possibilities, each of which has its advantages and disadvantages, its boosters and detractors. The two were a programming language (PASCAL) and a spreadsheet program. We were struck by the similarities between the techniques used in PASCAL programming and the hierarchical thinking advocated by Frederick Reif (see Reif's article in PHYSICS TODAY, November 1984, page 48) and others who have studied formal problem-solving skills.[19]

We selected a spreadsheet program because spreadsheets are widely used in business and are valuable in a variety of professions. Spreadsheets greatly facilitate data entry, data manipulation, programming and graphics output. They are particularly well-suited for the discrete mathematics found in the pendulum example. Because the spreadsheet language does not contribute to the further development of computing skills for physicists, many members of our project group feel that spreadsheets are best suited to working with nonmajors.

PASCAL provides an attractive alternative for teaching physics majors. It is widely used, quite powerful and inexpensive in several versions. Writing in PASCAL encourages good programming and problem-solving habits. In fact, a PASCAL program mimics the solution to simple physics problems. PASCAL forces students to identify the variables and constants in a program and to discover which are to be given and which to be found. They are made to think about data structures and about how to process those structures. Many schools and universities as well as the Educational Testing Service have adopted PASCAL as the introductory computer language. We expect the student to know PASCAL prior to taking the MUPPET physics class or to learn it concurrently with the class.

We have developed a tutorial computer program for the roughly half of our students who have not previously studied any programming. We present the physics applications concurrently with the PASCAL programming. As the semester goes on, both the physics and the programs become more sophisticated. Our approach to programming is not unlike the traditional approach to calculus and physics, in which the two topics are presented in parallel.

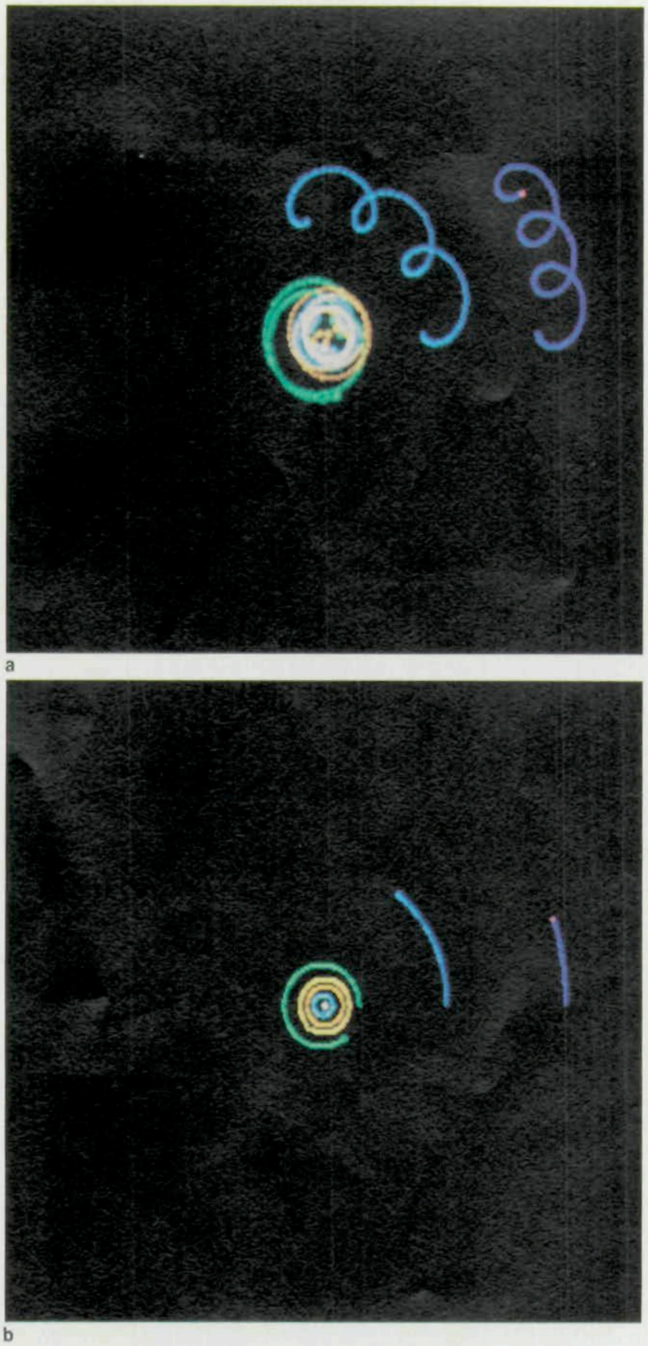
At the beginning of the semester, students are presented with rudimentary programs and asked to run them and make modifications. By the end of the semester, they are developing their own programs. In most classes students work on individual projects for completion by the end of the semester. Some of the students have worked out particularly elegant projects. These include models of waves on a hanging rope, the inverted pendulum, colliding galaxies, and sophisticated orbit programs using fourth-order numerical methods. About 80% of our students work adequately with the computers by the end of the semester. For the top 10–20% of our students, computational techniques open new vistas onto exciting and challenging problems.

To enable students to devote a minimum amount of effort to input and graphic output, we have developed a set of tools that simplify these tasks. The data-input tools allow the student to design a "form" to be displayed on the screen and to display and edit that form as a part of a program. We are also able to provide default responses, that is, a standard set of parameters that will allow the program to run, on these "screen forms." This helps get the student started with interesting and realistic situations.

The graphic tools allow students to plot data by issuing a single command. Scaling, clipping and adjustment to screen coordinates are done automatically. The more sophisticated student, on the other hand, can control the graphic environment with commands that override the simple default options.

Computers change the curriculum

Through the Introductory University Physics Project, MUPPET, the recent Conference on Computers in Physics Instruction, and local institutions, many physicists, some well-known research physicists among them, have been trying to explore the implications of the availability of computers for setting new directions for undergraduate and graduate physics programs. Often they begin by comparing what students are learning in physics with



Orbits of the solar system can be generated on the computer monitor both from the reference frame of the center of mass (**a**) and from that of one of the orbital bodies (**b**). In both photographs the outermost three bodies have not yet finished one complete revolution. In this simulation called "Orbits," developed by the MUPPET program, students can vary the number of bodies, their sizes and positions and the type of central force law. The monitor also displays the values of such parameters as eccentricity, periastron, apastron, angular momentum, energy and period (not shown). **Figure 4**

what physicists think they should be learning. Unfortunately, in our opinion most introductory physics courses teach students that physics is hard to understand, mathematically intricate, relentlessly deterministic and concerned with levers, inclined planes and projectiles. The body of literature on teaching physics tends to confirm this opinion.

At the University of Maryland, we saw introductory physics as the pivotal course in the curriculum. Improving this course is a prerequisite for improving both advanced courses and high school courses. The advanced physics courses are built upon the solid foundation of the introductory course, while the high school courses try to emulate the university introductory course. We felt that we were losing good physics majors because of the outdated and authoritarian curriculum. Students would major in physics in spite of the introductory course, not because of it. We also felt that the training was inappropriate for today's physics majors.

A student could probably study physics for eight years without ever seeing a problem the teacher can't solve. We must engage students in the intellectual process of modern physics much earlier in their training. The microcomputer can help bring this change about by permitting students to approach a wider variety of phenomena and problems than they can grasp with only analytic tools, and by enabling them to understand those phenomena on a deeper and yet more concrete level.

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References

1. J. Risley, E. F. Redish, eds., *Proc. Conf. on Computers in Physics Instruction, Raleigh, N. C., 1–5 August 1988*, Addison–Wesley, Reading, Mass., in press.
2. *Proc. Top. Conf. on Physics Department Chairs I* (J. M. Wilson, ed.), *II* (G. Aubrecht, ed.), *III* (M. McDermott, ed.), AAPT, College Park, Md. (1983, 1985, 1988).
3. J. Rigden, Am. J. Phys. **51**, 516 (1983).
4. W. M. MacDonald, E. F. Redish, J. M. Wilson, Comp. Phys. **1**, 23 (1988).
5. D. Kane, B. Sherwood, in *Computer Assisted Learning in Physics Education*, A. Bork, ed., Pergamon, Oxford (1980).
6. A. Bork, Am. J. Phys. **47**, 5 (1978).
7. J. N. Sherwood, B. A. Sherwood, *CMU Tutor: An Integrated Programming Language for Educators*, IBM, Milford, Conn. (1987).
8. T. Schwartz, Comp. Phys. **2**, 40 (1988).
9. M. M. Waldrop, Science **241**, 27 (1988).
10. B. Cabrera, "Early Experiences in Physics Simulations in the Classroom," in *Proc. Conf. on Computers in Physics Instruction, Raleigh, N. C., 1–5 August 1988*, Addison–Wesley, Reading, Mass., in press. J. S. Risley, 1988: Computers in Physics Instruction: Software, North Carolina State University, Raleigh, N.C. (1988).
11. L. D. Roper, "Physics Simulations for High Resolution Color Microcomputers," in *Proc. Conf. on Computers in Physics Instruction, Raleigh, N. C., 1–5 August 1988*, Addison–Wesley, Reading, Mass., in press.
12. J. M. Wilson, Am. J. Phys. **48**, 701 (1980).
13. D. A. Briotta, Am. J. Phys. **55**, 891 (1987).
14. R. Tinker, Phys. Teach. **19**(2), 94 (1981).
15. J. Layman, M. DeJong, Phys. Teach. **22**(5), 291 (1984).
16. G. Aubrecht, ed., *Quarks, Quasars, and Quandaries*, AAPT, College Park, Md. (1987).
17. J. M. Wilson, AAPT Announcer **17**(2), 47 (1987).
18. C. W. Misner, AAPT Announcer **17**(2), 47 (1987).
19. F. Reif, Phys. Teach. **19**, 310 (1981). ■