The M.U.P.P.E.T. Manifesto

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The Maryland University Project on Physics and Educational Technology uses microcomputers in the classroom to teach physics

The introductory undergraduate physics curriculum has been very stable for almost thirty years, and is nearly uniform throughout the country. Despite the apparent stability, there are indications that three "drivers of change" are beginning to have an impact: (1) the explosion of new knowledge in physics and related fields of mathematics; (2) new insights into the process of learning gleaned from studies in cognitive psychology; and (3) the power and widespread availability of personal computers. These developments both challenge the traditional physics curriculum and offer new opportunities for introducing students to the excitement of a research career in basic or applied physics, and giving a preparation for that career which is both broader and deeper than we have been able to offer in the past.

Even though the examples and problems in the present generation of introductory physics texts appear to have been modernized, in fact, in most cases, even the modern-looking problems are simply resettings of problems that are largely taken from older texts. This is a clear consequence of the fact that the level of the material in the physics curriculum continues to be strongly limited by the mathematical preparation students are assumed to have. Less obvious is the fact that the mathematical preparation expected from the typical student has also largely determined both the organization of the material and the relative emphasis given the various topics.

What is missing from the introductory physics course is the art of analyzing real physical systems. This requires a variety of physical principles and a panoply of skills that are usually not introduced until graduate school or on the job. In the introductory course, the artificiality of the problems and the limited introduction to the broad set of professional skills presents a misleading picture. Even the brightest physics majors often have little or no idea what it is that professional physicists actually do.

Applied Computing

To remedy this situation, The Maryland University Project in Physics and Educational Technology (M.U.P.P.E.T.) was started some five years ago in discussions among a group of faculty who became convinced that the availability of powerful, inexpensive personal computers provide the means to make the education of physicists more effective and exciting. These computers, M.U.P.P.E.T.'s founders believed, could help by:

- reorganizing elements of the curriculum to emphasize the fundamental physics;
- broadening the course content to include more contemporary physics and to provide the student with more experience with complex systems;
- training the student's intuition through simulations;
- giving research experience

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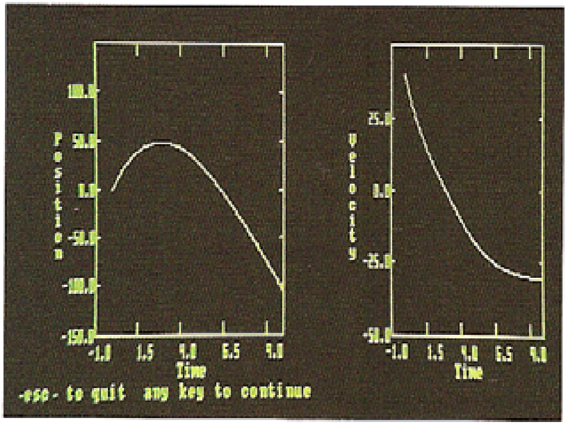
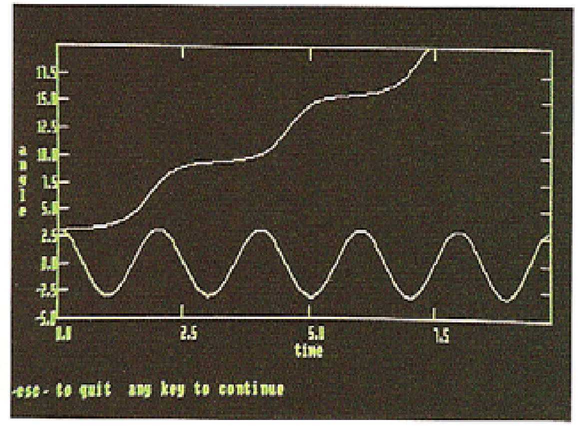


This screen from the M.U.P.P.E.T. program Project shows position and velocity of an object thrown upward from the top of a building. The effect of air resistance is included.



Angular displacement of a pendulum using the full equation (winding around) and the linear approximation (oscillating), from the M.U.P.P.E.T. program Pendulum.

through creative student projects.

M.U.P.P.E.T. has been guided by three important principles: we must rethink the curriculum entirely assuming the availability of the computer (what can we teach with it that we couldn't teach before?); the computer should not replace the teacher, the textbook, or the laboratory; and the student should run the computer, rather that the other way around.

The first point means that it is not sufficient to use the computer to illustrate examples in the current curriculum. We stress the second since the lecturer, the text, and the laboratory each has its own strengths and weaknesses. Rather than replacing any one of these, the computer can be used to empower the students by permitting them to solve large classes of problems that were previously inaccesible at the introductory level.

The third point requires that the students have the sense that they are in charge at all times. The students must therefore know what the computer is doing and not consider it to be a black box. This implies that the student will do some programming and that programs that are used in class will have an open and accessible structure. The materials developed in M.U.P.P.E.T. require the student to both read and write computer programs. Good programming practices (top-down design, structured programs, suggestive variable names, indentation, etc.) are emphasized to the students, and we require that all programs used or written in the course be easily read by other students and the instructor.

We began using the computer in the introductory physics courses at the University of Maryland in 1984 using personal computers provided under an IBM Corp./AEP grant. The development of materials using the computer in introductory physics courses began in earnest in 1985 under a grant from the Fund for the Improvement of Post-Secondary Education. Students have been taught to use the computer in the first semester of the introductory physics course, and its use has enabled us to explore ways of redesigning the curriculum to emphasize physical content and the skills appropriate for a professional physicist today.

It is not sufficient to use the computer to illustrate examples in the current curriculum.

Although we have used the computer in the laboratory as well as in the classroom, we will not discuss those methods here. There has been a long standing debate on the role of the laboratory in physics education with proposals ranging from replacing the lecture entirely by workshops or "discovery" labs to eliminating the laboratory entirely. A comparable debate on the role and content of the lecture course (especially with respect to the proper role of the computer in that course) does not exist. For this reason, in this article we limit our discussion to the lecture or classroom part of the introductory course for physics majors. We firmly believe in the importance of the laboratory as part of the education of a physicist and hope to address the role of the computer in the introductory laboratory in another article.

To begin our discussion of computers in the physics classroom, let's consider specific examples of the four techniques made possible with the computer: reorganizing, broadening, intuition training, and student projects.

Reorganized Curriculum

The ordering of the traditional course is largely controlled by the mathematical training we assume the student to have. Since discrete forms of a law are often much simpler conceptually than the continuous ones, the presence of the computer allows us to introduce physically important ideas at an earlier stage than is otherwise possible. This has consequences for the intellectual structure of the course and permits us to change the emphasis in a significant way.

Cognitive researchers studying the approach of naive students to physics have emphasized the importance of a hierarchical ordering of the material presented to students. One of the most difficult tasks for a beginner in any field is to decide what are the uses and relative strengths of the various concepts, principles, and techniques that are presented. We may identify three classes of methods: "gimmicks," "pocket tools," and "power tools." Gimmicks are derivative results, the special cases, and the interesting but inessential facts. Pocket tools represent convenient and important simple principles that can be easily pulled out and applied to a variety of problems to give partial answers or to evaluate the plausibility of results. These include the conservation laws, the uncertainty principle, and so on. Power tools are those methods which can lead to results of high accuracy in a very wide variety of systems.

Power Tools

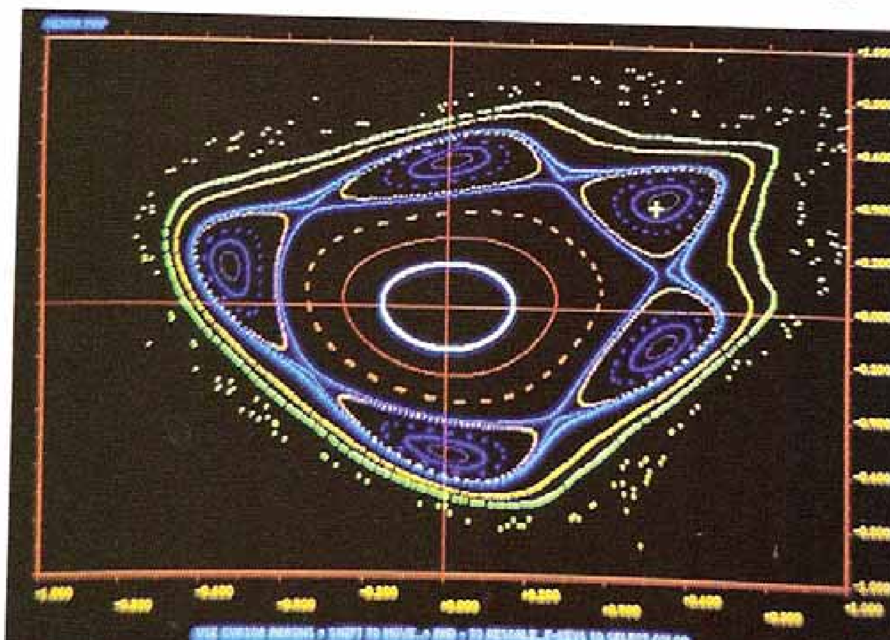
Students in the introductory physics course have a particularly difficult time deciding what is really important because the level of their mathematical skills prevent them from using power tools directly, except in a few very special cases. In mechanics, so much emphasis is placed on the gimmicks associated with a constant gravitational field ("flat-earth" gravity) that the student fails to learn how to use the real power tool, Newton's Second Law. Similarly, in electrostatics, Gauss' Law, which is an important pocket tool, is discussed at length and used to derive the electrostatic field in several special cases. But the student rarely learns to use the real power tools of electrostatics, the equations which can be used to find the electric field or the electrostatic potential surfaces for any arrangement of charges and conductors.

The computer reduces the limitations imposed by the mathematical preparation of students and allows us to present the material in a hierarchical order which emphasizes–and uses–the most important and powerful concepts and laws of physics. In the M.U.P.P.E.T. course, the power tools are not restricted to the formal level. The student is able to work directly with them to solve problems of considerable significance and interest.

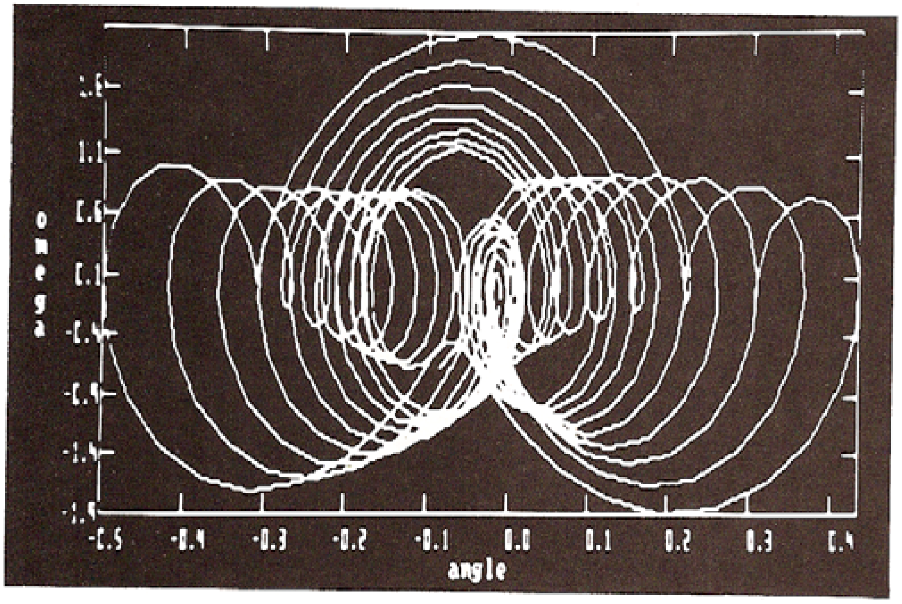
As an example, consider the way mechanics is presented in the usual introductory course for scientists and engineers. Almost every introductory physics text begins its presentation of mechanics with two or three chapters on motion in a uniform gravitational field before discussing Newton's Second Law. This is primarily because the former can be solved algebraically without differential equations and is an appropriate place to introduce the concept of derivative. The latter requires a more complete understanding of derivatives.

But from the point of view of both physics and cognitive psychology, this is highly inappropriate. The uniform gravitational field is a very special and peculiar case. Putting it first gives it a primacy which is both undeserved and misleading. It makes it difficult for the student to develop an appropriate concept of force and leads to confusion between force and acceleration. Often, the student fails to grasp the local character of Newton's law, is confused about what causes projectile motion, and overgeneralizes the independence of orthogonal motions.

After Newton's Laws are introduced, the student uses these equations to find the motion of objects under constant forces (or piecewise constant forces such as friction) and nothing further. Instead, chapters on conservation of energy and momentum follow immediately. These are fundamental laws, but their introduction at this point is really to allow some discussion of non-uniformly accelerated motion. Some of the difficulty that students have with these conservation laws can be traced to a lack of understanding of their proper position in the hierarchy of ideas. Much later, the student learns (read: is presented with) the solution for the harmonic oscillator. A few texts also go through the



Iteration of points in two dimensions using the Henon map, $(x,y) \rightarrow (x',y')$ with $x' = cx - sy + sx^2$, $y' = sx + cy - cx^2$ with $s^2 + c^2 = 1$, using the M.U.P.P.E.T. program Henon.



Phase space plot of a driven weakly damped pendulum, also from *Pendulum*.

solution to the Kepler problem in detail, but students taking calculus concurrently find this very heavy going. The student often leaves the introductory physics course with the impression that these are the only solvable cases. Even worse, many students believe that, in the world of physics, as opposed to the real world, the equations for uniformly accelerated motion, circles, or simple oscillations describe the motion of all objects.

In the M.U.P.P.E.T. physics course, the students are taught how to read, run, and write simple programs in the popular computer programming language Pascal, using class handouts that we have developed. Students use the computer to explore the relation between position, velocity, and acceleration using both the differential relations learned in calculus,

$$v = dx/dt$$

$$a = dv/dt \qquad (1)$$

and the approximate difference equations for these quantities at: $t_n = n\Delta t$:

$$v_n = (x_{n+1} - x_n)/\Delta t$$

$$a_n = (v_{n+1} - v_n)/\Delta t \qquad (2)$$

A simple plotting package called MUPgraph allows the student to write programs which display plots of x_n, v_n, and a_n in different computer windows. By working with the kinematical relations for a variety of cases, and using graphical displays, students gain an intuitive understanding of the relation between velocity and acceleration for many different functions $x(t)$. This is important because lack of an intuitive grasp of these relations is a major source of the difficulty students have with introductory mechanics.

This brief example provides just one case of how the computer can change the way we organize the curriculum by bringing the physically important concepts to the fore and by introducing the students to the power tools of physics. It can, of course, be carried through and applied to the rest of the introductory mechanics syllabus.

Broadening Scope

Many relevant and interesting problems are excluded from the standard curriculum even when the relevant physical concepts and equations are easily presented and understood, because their solutions are mathematically inaccessible at the introductory level. The computer allows us to broaden the standard curriculum to include many of these problems. This is important for a number of reasons: (1) we can do problems which are more realistic than before and which are closer to the student's experience; (2) we can introduce new ways of thinking about problems and extracting the physics from complicated systems–ways which are more in line with the way the professional physicist approaches realistic problems; and (3) we can introduce new physics of contemporary interest. We will discuss two examples from mechanics that illustrate these ideas: the large amplitude pendulum, and nonlinear (chaotic) dynamics.

Large-Amplitude Pendulum

The simplest example of a nonlinear system is the pendulum. The harmonic approximation is thoroughly discussed in every introductory text, and a few texts even discuss corrections to it. But they rarely note that the nonlinear term completely changes the qualitative character of solutions for large amplitude motion. The most obvious difference is that the harmonic solution

$$\Theta = \Theta_{max} \cos(\omega t + \delta) \qquad (3)$$

predicts oscillatory motion even when the initial velocity is so large that the maximum angular displacement exceeds 90°.

A less obvious difference is that the principle of superposition does not hold for large amplitude motion. The large amplitude solution of the exact equation is not equal to the sum of two independent solutions with coefficients determined by initial conditions.

Finding numerical solutions to the equation

$$d^2\Theta/dt^2 = -(g/l)\sin\Theta \qquad (4)$$

permits the student to learn the

distinction between the analytic solution to an approximate equation and the numerical solution to an exact equation. The transition from the linear behavior in the harmonic approximation to the nonlinear motion can easily be followed by plotting the trajectory in phase space. Not only are such plots valuable for studying any kind of nonlinear motion, but their introduction provides the basis for an introduction to the Bohr-Sommerfeld quantization rule.

Chaotic Dynamics

An example of broadening to include problems of contemporary interest is the inclusion of topics from the theory of nonlinear dynamics. These topics are of considerable current interest not only to scientists but also to the general public. For example, *Chaos* by James Gleick (Viking, 1987) is currently on the list of best-sellers (see *CIP*, Mar/Apr 1988, p. 40, for an excerpt from this book).

Students in our freshman physics majors classes have been excited to learn about modern topics such as chaos, period doubling, fractals, and basins of attraction. Simple systems provide examples of all these topics, which can easily be explored using personal computers. Many systems exhibit chaotic behavior at some level, and some systems can only be understood in terms of nonlinear equations.

The subject of chaos (or sensitivity to initial conditions) is actually much more important conceptually than simply an attempt to spice up a stale course with some hot topics. The standard introductory course includes a large block of material on classical mechanics. A major point of this block is predictability: given the starting positions and velocities of all the bodies and the laws of force between them, their motions are predictable (infer forever) using the laws of mechanics.

The standard introductory course also includes a large block of material on thermodynamics. Although this can stand by itself, it is often introduced in conjunction with some concepts of kinetic theory or statistical mechanics. This approach requires the description of mechanics in terms of probabilities, especially if the information theory definition of entropy is discussed. This procedure can be very confusing to the student, given the emphasis on predictability in the mechanics section. A barrier may be set up in the student's mind between mechanics and thermodynamics.

Many relevant and interesting problems are excluded from the current curriculum.

If we spend one week on nonlinear dynamics as an interpolation between mechanics and thermodynamics, we can improve the situation substantially. Many simple examples are available where the long term behavior is extremely sensitive to the initial conditions. Having introduced the phase plane, we can naturally introduce the concepts of preparation of states, ensembles, experimental uncertainty and repeatability, and averaging. Complex trajectories in phase space occur even in simple examples. The relation between a time average and an ensemble average then makes the basic idea of statistical mechanics plausible.

Intuition Training

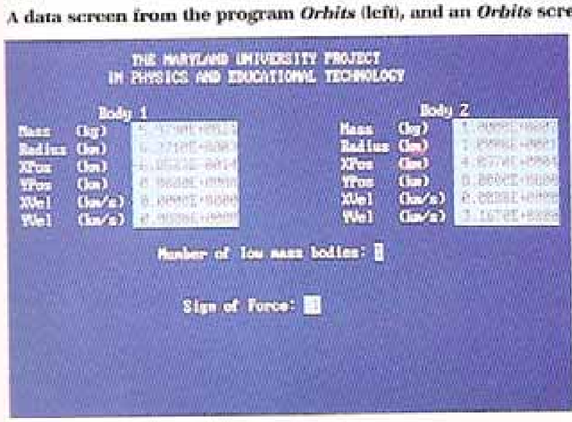
Dirac once said that a physicist does not understand a problem until he can "solve it without solving it," that is, until he has enough experience to judge which physical effects will be most important so that he can anticipate the solution without working out the details. This so-called "physical intuition" can only be gained by studying a large number of specific problems. Moreover, it requires experience with complex systems in which different physical effects interact.

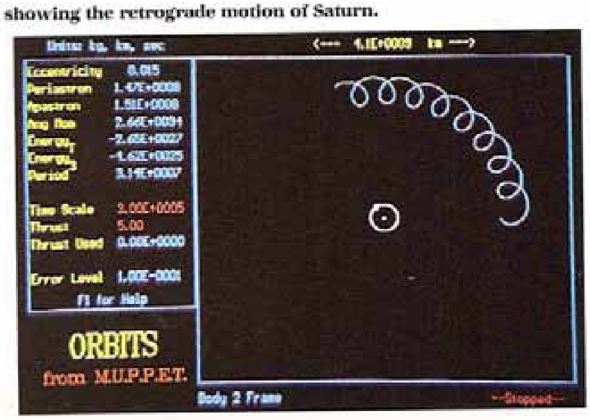
An example of such a problem is provided by the trajectories of shells from Big Bertha, the long range gun used to bombard Paris in the first World War, from a distance of nearly 75 miles. (See Problem 5.6-12, p. 217 of Bennett listed below in "For Further Reading.") The maximum altitude of these shells was so great that the variation of air density with altitude qualitatively changes the solution. The formula for air resistance given by:

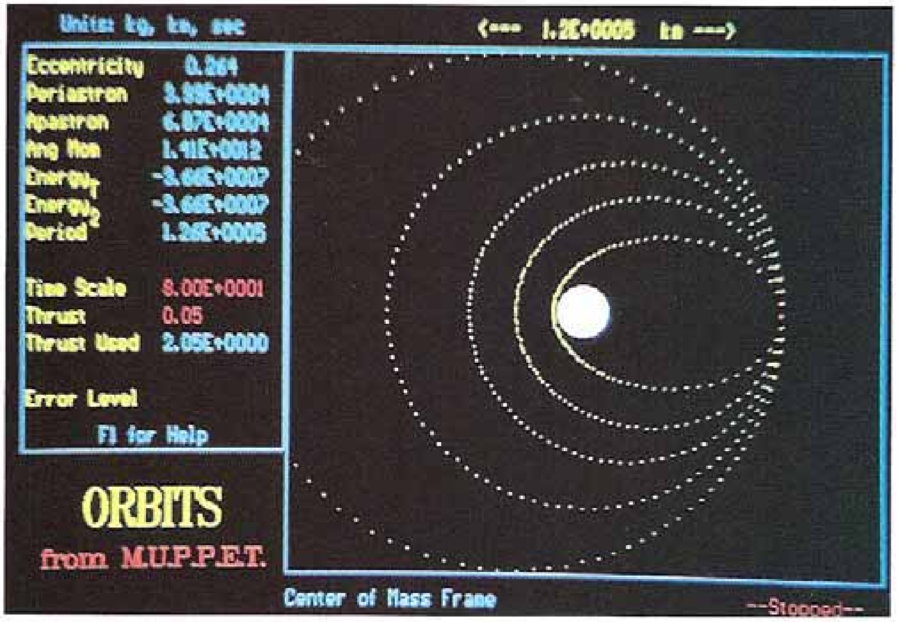
$$\mathbf{F}_T = -C_T A \rho |\mathbf{v}| \mathbf{v} \qquad (5)$$

shows that the resistance is proportional to the air density, and it therefore decreases with altitude. When the variation of air density with altitude is taken into account, the question can again be asked,

A data screen from the program *Orbits* (left), and an *Orbits* screen showing the retrograde motion of Saturn.







This *Orbits* screen shows a comparison of orbits of varying eccentricity.

"What angle of elevation of Big Bertha gives the maximum range?" Many physicists will guess that an angle greater than 45° will reduce air resistance along the trajectory and give greater range. But few will be confident until they have seen a solution to this problem, which can only be obtained by numerical integration. Most will also want to see whether the numerical results could have been anticipated by some approximate calculation.

Complex systems that require long or sophisticated programs can be investigated by students using Simulation Packages. These are programs that can solve a variety of problems associated with a given class of systems. An example is the program Orbits (see Harold in "For Further Reading" below), developed by the M.U.P.P.E.T. team. This program solves the restricted three-body problem of two heavy objects and a set of light ones which do not interact with each other. Up to five light objects can be considered. The program allows initial conditions to be specified on a "data screen," which can be saved as a scenario. Or one can load and run a previously saved scenario. The orbits are plotted and information about them is displayed. The student can choose to display the orbits in the center of mass frame or in the rest frame of one of the two heavy bodies. The student can deliver a vector velocity increment $\Delta \mathbf{v}$ to any of the objects using the cursor keypad.

The program can be used in a variety of ways. The professor may prepare a sheet of problems as a "microlab," which is a class period spent in a room furnished with microcomputers, with the students trying to solve a specified set of problems while an instructor is available to answer questions. The program can also be made available for students to use out of class to do homework assignments. Finally, the program is powerful and flexible enough for the students to use in a term project on the gravitational many-body problem.

Student Projects

The fourth way the computer can be used in an introductory course is to permit the students to do some independent projects and gain experience in how one does scientific research. In most versions of the current curriculum, the computational skills needed for research–understanding approximations and numerical skills–are left for graduate study. This can give students a distorted view of physics as an "exact" science, rather than as a science where we know the range of applicability of our equations. Large-scale problem-solving skills are rarely encountered in an undergraduate program unless the student does a senior thesis. This is particularly unfortunate, since the approach to a complex, open-ended problem (especially one where the answer is not known beforehand) is the fundamental skill of the professional scientist. The curriculum has become so standardized that it can appear exceedingly rigid. In the present curriculum a physics major can take two years of high school physics, four years of college physics, and two years of graduate physics without ever seeing a problem the teacher doesn't know the answer to! This very badly misrepresents the important role that creativity and independent thinking play in the day-to-day work of a professional scientist.

Our approach emphasizes the power tools of physics, introduces the students to numerical methods which can be used to solve rather complex problems, and gives them the experience of pursuing a variety of topics beyond the qualitative and approximate level to more complete and quantitative results. We find that even while working on specific homework problems, many students catch fire and begin to use the homework assignment as a springboard to pursue problems which interest them. The opportunity to do projects which take several weeks or more to complete was welcomed by most students, and they tackled a variety of exciting problems. Topics studied have included colliding galaxies, "shepherd" moons in the rings of Saturn, tethered satellites, the behavior of nonlinear oscillators, and the transfer of planets between colliding stars.

Students have approached the computations in a variety of ways including writing their own programs entirely from scratch, writing their own programs with the aid of the M.U.P.P.E.T. utilities and template programs, and using pre-prepared powerful tool programs such as Orbits to study a class of problems. The students have found this aspect of the course very successful and satisfying.

M.U.P.P.E.T.'s Environment

We have attempted to develop our materials and curriculum modifications so they can be used inexpensively and effectively in a variety of environments. Our own environment at Maryland is currently based on IBM XT and AT personal computers. A reasonable configuration for using our materials is an 8088 or 80286 IBM compatible with two floppy drives or one floppy and a hard disk. For the 8088-based machine (an IBM XT or clone), the 8087 coprocessor is highly recommended as is 640K of memory. All of our packages have been prepared to run with CGA or EGA graphics.

In our experience, one such machine suffices for every 8-10 students. We have two microlabs in the Physics Department: one with 16 machines, mostly XTs, networked with an AT master. The second lab is an overflow lab with a dozen machines, also networked to the same master. Our freshman physics majors classes, each with 10-20 students, meet there 3-4 times each semester for a 1-hour microlab session with

Our approach emphasizes the 'power tools' of physics and numerical methods.

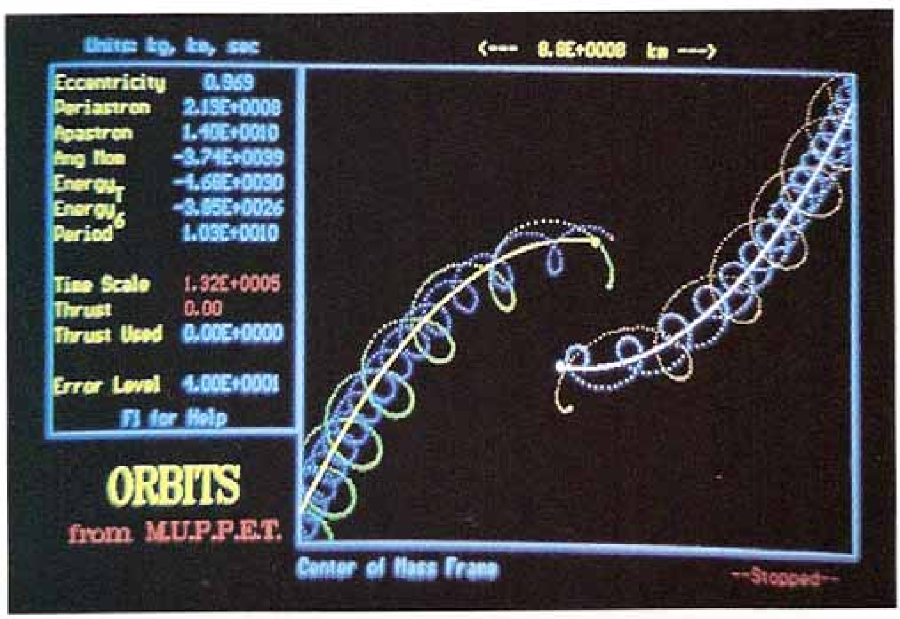
the teacher. Teaching assistants keep the lab open for eight hours a day on weekdays. Students make extensive use of the lab for computer homework assignments and their term projects.

The University of Maryland also provides a number of general purpose microlabs in libraries throughout the campus, and will begin to provide in-dorm computers next year as part of a major effort to expand computer availability.

We spent much of our first year in debate over the languages to use in M.U.P.P.E.T. We concluded that the appropriate language for freshman majors was Pascal. There are a number of reasons for this choice.

- Pascal encourages good programming habits. This results in programs that are easy for others to read and that provide the student with building blocks to use in increasingly ambitious projects.
- Pascal significantly reduces run-time errors. These tend to be difficult to analyze for the introductory student. They can be both frustrating and time consuming.
- Pascal has been standardized. Only minor differences occur in different implementations.
- Students who know Pascal find it easy to learn more powerful languages such as FORTRAN, C, and ADA.
- Pascal programming encourages an algorithmic approach to problem solving which cognitive scholars have found strongly advantageous in learning general problem solving skills.

Pascal is also widely favored as the language taught in introductory computer courses, even at the high school level. A large fraction of our beginning physics majors enter the course familiar with Pascal. Finally, an important financial consideration is that Pascal is available in an



Another *Orbits* screen shows the collision, in the CM frame, of each of two stars with two planets.

inexpensive version (available for students at the cost of a textbook) as Turbo Pascal from Borland International, Scotts Valley, Calif. Turbo Pascal conveniently combines editor and compiler, provides excellent syntax checking, and compiles very quickly.

In order to minimize the amount of programming we have to teach, we have developed class handouts which distill the basics of Pascal down to a few minimalist ideas. We have developed utilities which permit students and faculty to easily write programs with interactive input and simple multi-window graphics. Simple sample programs can be used interactively in microlabs to study complex phenomena and to serve as starter programs or templates from which other programs may be built. This makes it possible for students to learn to write useful programs very quickly.

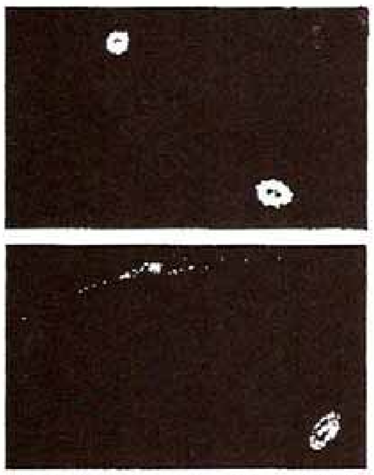
These materials also help resolve the problem of making the computer accessible to faculty who are not programmers or who program in a language that is too sophisticated for most freshman to use.

We currently refer to this collection of materials as "Freshman Physics with the Microcomputer." It is continually being modified and expanded as a result of feedback from students, faculty, and other users. The handouts and instructions can be obtained by writing to one of the authors. The programs and utilities are available through the AAPT/M.U.P.P.E.T. electronic bulletin board, which can be accessed by modem at (301) 454-2086.

The standard introductory physics course is so tightly packed with "absolutely critical" material that an introductory physics text is typically over a thousand pages long and can weigh 8 pounds. Teachers race through the material in order to "cover" as much as possible; complaints about the amount of material in the introductory course are a standard part of every public discussion about changes in the curriculum.

The question that then logically arises is how can we possibly expect to include more material in a modified curriculum? What has to be left out to make room for the computer? In our view, the current curriculum is badly unbalanced. The students wind up memorizing far too much material and thinking far too little. Something will certainly have to be left out, or at least postponed until a later point. A survey of majors' programs indicates that there is often room at the senior level. Many students use this as an opportunity to start grad courses early. A new curriculum design must look at the whole program. A much more coherent product can be produced by zero-basing the curriculum–reconsidering the value of all its elements–including ones currently present as well as those being proposed.

One modest proposal is to suppress rigid body motion, optics, and the properties of materials (including fluid dynamics) until the junior level. These topics could be treated in more depth at that level than is common in the current curriculum. Computer-based intuition training techniques could be particularly valuable in these subjects. In addition, students trained with the computer-assisted introductory course can be expected to have an increased sophistication and ability to deal with them more effectively.



These successive views of two colliding galaxies were produced by a freshman physics student for a term project at The University of Maryland.

The most significant change in the course arising from adding the computer is not the change in content. It is the change in the activities that students pursue outside the classroom. The number of plug-in homework problems is substantially reduced (although some are found on every assignment). They are replaced by computer associated homework problems that encourage thinking about the phenomena. These are not simply numerical problems: many of them are analytic, estimations, or qualitative analyses that are required before a problem can be brought to the computer. Having an independent project also tends to increase the student's involvement with the course and with the material.

In conclusion, M.U.P.P.E.T. has found that many changes are possible and that there are many elements of the traditional course that are unbalanced or inappropriate in a modern environment. The power of the computer permits us to address a number of these problems. Including the computer in the students' first physics course permits us to begin their training in skills normally neglected until graduate school; to introduce contemporary topics; and to let the students undertake creative, open ended investigations of interesting and unsolved problems, even at the freshman level.

FOR FURTHER READING

A partial list of some works the authors reflected upon during the preparation of this article follows:

1) Gordon Aubrecht, "Should There Be Twentieth Century Physics in Twenty-First Century Textbooks?", University of Maryland preprint, 1987.

2) William R. Bennett, Jr., "Scientific and Engineering Problem-Solving with the Computer," Prentice-Hall, 1976.

3) J.B. Harold, K.A. Hennacy, and E.F. Redish, "The Computer and Intuition Building: A Multi-Body Orbit Simulation," *AAPT Announcer*, 17, no. 2, May 1987, p.58.

4) J.H. Larkin and F. Reif, "Understanding and Teaching Problem Solving in Physics," *European Journal of Science Education*, 1, 191, 1979.

5) F. Reif, "Teaching Problem Solving–A Scientific Approach," *The Physics Teacher*, May 1981, p. 310.

6) Jack M. Wilson, "Microcomputers as Learning Tools," Inter-American Conference on Physics Education, Creating Physics Education Networks for the Americas, Oaxtepec, Mexico 7/20-24/87, proceedings to be published. ■