Project Summary

The teaching of mechanics and motion in introductory physics has produced disappointing results that imply that most students leave the course with only a primitive understanding of the motion of objects. We propose to use recently developed video technology in an inquiry-based, laboratory-lecture format to improve our students' learning of the fundamental ideas of Newtonian mechanics. The students will record the trajectory of an object with a low-cost video camera, digitize and record the data on a computer, and then analyze the observed motion frame-by-frame to 'discover' the features of the observed phenomenon. This procedure will directly confront the students' preconceptions about motion, it will measure the same quantities that are used to describe motion in the classroom such as the time-dependent position of a projectile, and it will make new and challenging phenomena accessible in the introductory physics laboratory. Before now, the methods employed in this project were too costly to allow students to collect and analyze their own data in an introductory physics laboratory. In addition, the method is flexible and easy to use, an essential practical ingredient in an inquiry-based laboratory.

The audience targeted in this project are all students who take introductory physics. They are from all scientific disciplines (physics to sport science) and from all classes (first-year to seniors).

The project will implement the use of these video technologies in an environment where the students are involved in both recording the video and analyzing it. The students can investigate a variety of phenomena that because of technical or cost barriers cannot be addressed in the traditional undergraduate laboratory. The results of the project will be evaluated with a battery of tests including pre- and post-examinations of student understanding. All of these results will be the subject of journal articles.

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Results From Prior NSF Support

The Physics Department at the University of Richmond received funding for an Instrumentation and Laboratory Improvement grant from the National Science Foundation for the proposal entitled "New Teaching Technologies in Physics" submitted in 1991. The award (grant # USE-9250502) was for $24,907 from NSF with matching funds from the University. The grant period started May 1,1992 and the funds are nearly exhausted ($679 remains). The grant period runs until December, 1994.

The rapid development of computer power is shifting the focus of undergraduate science teaching away from reproduction of prescribed procedures to observing, investigating, and even "discovering" physical laws. The project uses the analytical tools that were once available only to the research scientist, but can now be used by undergraduates to visualize data and mathematical functions, to broaden the range of problems accessible to them, and to develop model-building and simulation skills. Also, the computer has itself become an integral part of nearly all scientific instrumentation and its use is now included in our physics curriculum.

The project was implemented by developing a computing laboratory for upper division courses using the software packages *Mathematica* (for visualization and computational power), LabView (a data acquisition and analysis code), and LogicWorks and PSPICE (electronics simulation codes). The codes run on Macintosh IIci computers using computer interfaces and associated hardware from National Instruments.

The Department of Physics of the University of Richmond has applied these new technologies and this project extended their use to our upper division courses. Quantum mechanics is one of most mathematically foreboding courses undergraduates face. The new laboratory enables students to experiment graphically and symbolically and to investigate the science more deeply. We incorporated modern simulation and data acquisition and analysis techniques into our two-semester electronics sequence. The students learn to transform physical measurements into electrical signals, process the signals, and collect them with the computer. They use simulation software to design, develop, and test circuits.

All of the goals of the project have been reached. Computational laboratories for Quantum Mechanics I and II have been developed that use *Mathematica* 'notebooks' on the Macintosh computers. The visualization capabilities of *Mathmatica* are used as an 'electronic chalkboard' to plot functions, test hypotheses, and even make movies to illustrate concepts. The symbolic reasoning capabilities have opened the door to new problems and new approaches to old ones. These inquiry-based exercises are done in class or as homework assignments (see list below). The response of the students as measured by student ratings and interviews is very positive. One of the students in quantum mechanics (an exchange student from Germany who was taking courses for one year at the University) requested via electronic mail more materials and texts on *Mathematica* after his return to Germany because he wanted to continue using the package at his home institution. Copies of the notebooks were requested and are being used at two other sites (James Madison University and Oregon State University). A paper describing one of the projects entitled "A New Teaching Approach to α Decay" has been submitted to the journal *Mathematica* in Education.

Our two-semester electronics course has been modified to make optimum use of the computer hardware and software purchased through the ILI grant. This course is designed to provide students with a basic working understanding of the electronics used in scientific instrumentation, and features a series of 26 laboratory exercises (see list below) followed by an instrumentation project. The circuit simulation software is used throughout the course to design and test circuits before they are constructed in the laboratory. The LabView instrumentation software and data acquisition hardware is used for measurement, analysis, and presentation, and students gain valuable computer-interfacing experience with this equipment.

During the final month of the second semester, the students perform a project that requires their new skills. Each student chooses a project from a list provided by the instructor or based on their own interests. A typical project might include the development of a transducer to perform a measurement, the design of a circuit to condition the signal from the transducer, and the development of software to read, analyze, and present the data. Some of the results of these projects are now used as demonstrations and laboratory exercises in the introductory physics course; providing a cohesiveness across our physics curriculum.

Computational Laboratories in Quantum Mechanics

1. Traveling Waves
2. Orthonormality of Wave Functions
3. Matter Waves and Fourier Series
4. Superposition of Waves
5. One-Dimensional Nuclear Fusion
6. Time Development of a Gaussian Wave Packet
7. The Correspondence Principle
8. The Baryon Mass Spectrum
9. The Square Barrier
10. A One-Dimensional Model of a Solid
11. α Decay Using Transfer Matrices
12. A Particle in a Square Well
13. Quantum Interference in 3D

Laboratory Exercises in Electronics

1. DC Measurements and Instruments
2. DC Circuits
3. Thevenin's Theorem
4. The RC, RL, and LRC Circuits
5. The LRC Series Circuit
6. Low Pass and High Pass Filters
7. Band Pass and Band Rejection Filters
8. Diode Characteristics and Applications
9. The Zener Diode
10. Rectification
11. Filtering and Regulation in Power Supplies
12. Common-Emitter Amplifier
13. Operational Amplifiers I
14. Operational Amplifiers II
15. Basic Logic Gates
16. De Morgan's Theorem
17. Half and Full Adders
18. Flip-Flops
19. Digital Counters
20. Synchronous Counter and Timer
21. Shift Registers
22. A Serial Adder
23. Op Amp Comparators and the Schmitt Trigger

Narrative

The Current Situation

The University of Richmond is a comprehensive private institution committed to the liberal arts tradition of teaching. It enrolls approximately 2,800 undergraduate students in its arts and sciences and business programs and is among the few institutions to have gained dramatically in selectivity during the past decade. Average S.A.T. scores have increased from 1050 to over 1200 during this period. There were about 5,000 applications for 750 undergraduate openings last year.

The Department of Physics at the University of Richmond is staffed by five full-time faculty members (all with doctorates) and a full time laboratory director who maintains the Department's teaching laboratories. The Department awards the B.S. and B.A. degrees and a minor in physics. There are currently six physics majors and six minors in the junior and senior classes. The Department teaches a two-semester, introductory physics with calculus sequence for science majors. Usually more than 90 students from all levels are enrolled in several sections.

The Department has research programs in nuclear and particle physics and has a significant computational component in its undergraduate curriculum. A network consisting of two VAXstations (3100 and 3200), a Hewlett-Packard 715/75, nineteen Macintoshes, and numerous terminals is used exclusively by the students and faculty of the Department. The equipment is maintained by our laboratory director and the University's computing division. There are also public computing facilities available in the science building and nearby.

The Department is now in the midst of a significant reform of its curriculum. One component of the reform is to inject an element of inquiry-based learning at all levels. 'Capstone' experiences (*i.e.*, end-of-the-semester projects) are now required in several upper-level courses and a senior seminar requires each graduating senior to investigate some physics topic, write a paper on that topic, and present the results to the Department. Some courses (*e.g.*, quantum mechanics) now use 'hands-on' computational laboratories instead of the usual lecture approach. In the fall of 1994 we opened a section of introductory physics that uses the workshop physics format, requiring students to take a more active role in this integrated, laboratory-lecture environment. The workshop physics approach is described in Reference 1.

The second component of our reform is to use state-of-the-art tools so our students will be prepared for the technical environment beyond the University's walls. In 1991 the Department began developing a computer-based, introductory physics laboratory to improve and modernise this part of the curriculum. In 1992 the symbolic mathematics package, *Mathematica*, was introduced in upper-level courses with computer-based data acquisition and simulation. The equipment and software for this project were purchased in part with an ILI grant from the National Science Foundation (see 'Results From Prior Support').

The traditional methods of teaching introductory physics (*i.e.*, several hours of lecture each week accompanied by a laboratory) have often produced dismal results. Few students are drawn into the discipline by their experience in the introductory sequence. The United States graduates only about 5,100 students a year with bachelors degrees in physics (among more than 3,000 four-year institutions).[2] Only about 5% of the students that take the introductory course go on to take more physics courses. Even worse, there is evidence that despite the most elegantly crafted lectures the introductory sequence often has little effect on learning. One study revealed that after a year of introductory physics the number of students that had a true 'Newtonian' understanding of mechanics only increased from 20% to 25%.[3]

We propose to use newly available video technologies in an inquiry-based laboratory to improve our students' learning of Newtonian mechanics. We have already begun using the inquiry-based format with our current equipment. In the new experiments the students will record the motion of an object with a video recorder and the images will be digitized and stored on a computer. Each student can then quantitatively analyze the movie frame by frame. This technique promises to be a powerful learning tool because the 'data' are closely linked to the students' experience. They are analyzing what they see with their own eyes. In addition, they will measure the same quantities that are discussed in class, the time-dependent position of an object. This will enable us to confront many preconceptions our students have about mechanics that hinder their learning.[4] For example, consider the independence of the vertical and horizontal components of the motion of a projectile. Many students fail to understand this notion despite lectures, homework assignments, demonstrations, and traditional laboratories. In many laboratories the students merely confirm the theory rather than discovering it. In our inquiry-based laboratory the student will record the time-dependence of the position of a projectile, analyze the results, and reveal to themselves this feature of projectile motion (see below). Recent studies in the literature bode well for the success of this combination of video technology and inquiry-based learning.[5,6]

Video techniques will also enable us to investigate new phenomena (and new applications of Newtonian mechanics) in our introductory laboratory. Many introductory texts discuss the effect of air friction or drag. To understand air drag the students must confront the idea that the net force on an object can vanish even when the individual forces are large and the object is moving at high speed (*i.e.*, at terminal velocity). This phenomenon can't be readily studied now even with our computer-based, introductory physics laboratory, but one can investigate it rather easily with the techniques proposed here (see below). Finally, video technology is flexible and easy to use. A broad range of inquiry-based experiments can be performed with these techniques and after a few laboratories the students will be using familiar equipment and software. This attribute is an important, practical ingredient to an inquiry-based approach where the students may perform experiments almost every class meeting. A list of possible experiments is shown in Appendix V.

We have already begun development of this project. We have purchased a single video board for digitizing the images recorded with a borrowed video camcorder. We have obtained copies of a software package for analyzing the movies. Our staff has gained experience with these technologies and we have completed a technical feasibility study of several experiments. The results of that study are presented below. We have also used the analysis software in our section of workshop physics with 'canned' movies the students did not record themselves. We note here that this last approach is a useful one for studying motion with our current equipment, but the analysis of prepared data does not have the same impact as the analysis of data the students collect themselves. The students are not required to design and set up experiments to test their ideas, a procedure we want to follow in the inquiry-based laboratory.

The Development Plan

We propose to introduce video technology into our two-semester, introductory, general physics with calculus sequence for science majors to improve our students' grasp of the concepts of Newtonian mechanics. This technology closely couples the measurements made in the laboratory with the students' experience and with the topics covered in class. Low-priced video cameras from Polaris Industries will be used to record movies that will be digitized and stored on our Macintosh computers with video boards from SuperMac. Our current Macintosh IIci's are too slow to do this adequately so they will be upgraded to Quadras. The '2D Video QT!' software developed at Dickinson College with Fund for the Improvement of Postsecondary Education support will be used to analyze the video images. Finally, the spreadsheet Excel from MicroSoft will be used to manipulate the data and make plots. The '2D Video QT!' software can store the positions extracted from each video frame directly into Excel.

These new methods will enable us to teach more effectively many concepts that are now part of the curriculum. In our pilot study we investigated several candidate experiments to test their feasibility with the equipment requested in this proposal. Consider the study of projectile motion. An essential point in the theory describing it is the independence of the vertical and horizontal components of the motion. In our current laboratory the students determine the speed of a ball rolling on a flat table with a photogate that measures the time it takes for the ball to pass through the gate. This procedure is done just before it leaves the table and falls to the floor. They record the range of the ball and use the equations introduced in class to predict the range from the measured initial velocity. They can then compare the predicted range with the measured one. The notion of the independence of the motion in the two horizontal and vertical planes is obscured by the calculations and the students are not explicitly confronted with the quantities used in class, namely the time dependence of the components of the position vector.

In the new laboratory the students will record a movie of a ball tossed in the air by pointing and clicking with Macintosh's mouse. The file containing the movie is saved. The '2D Video QT!' software is then used to open the movie file. Each student sees the first frame of the movie and when the mouse is moved over the image it changes into a cross hair. Placing the cross hair on the center of the projectile and clicking records the position of the ball in memory. The student then clicks on a control button to advance to the next frame. Data collection is fast and easy. Once completed, the points (consisting of frame number, horizontal position, and vertical position) are stored in an Excel file. Here the frame number can be converted to a time and the positions can be converted to the desired units (one can also calibrate the distance scales directly in '2D Video QT!'). The data can then be fitted with an appropriate expression the students discover themselves. Figure 1 in Appendix IV shows some of the results we obtained during our pilot study. The vertical position as a function of time is shown in the upper panel and the horizontal position as a function of time is displayed in the lower panel. The data in the upper panel clearly have a quadratic time dependence and the coefficient of the quadratic term is within 4% of the expected value of g/2 where g is the acceleration of gravity. In the lower panel the data fall very close to a straight line; dramatically different from the motion in the vertical plane. A close examination reveals a small non-linear dependence that can be identified as the effect of friction. An old, underinflated, basketball that induced a non-negligible amount of drag was used in this experiment. These results point to the effectiveness and the precision of these methods in exploring projectile motion.

Simple harmonic motion is another component of our introductory sequence. In the past our laboratories asked the students to measure the period of oscillation of simple pendulum with a stop watch and confirm the equations from the text or from class. The situation improved with the introduction of force transducers that could measure the force exerted by a simple pendulum swinging from the transducer arm. However, in both cases the students do not measure directly the quantities discussed in class, the time dependence of the angle the pendulum makes with the vertical. In the new approach the students would record the position of a ball swinging on the end of a string along with the position of the pivot. With these data stored in the Excel spreadsheet they can calculate the angular position of the pendulum as a function of time. The data can then be fitted with different functions to reveal the sinusoidal time dependence. An example of the results one obtains is displayed in Figure 2 of Appendix IV. The angle of the pendulum with the vertical is shown as a function of time. The solid curve is a fit to a sine function the students will discover.

Video technology will enable our students to investigate a wider range of phenomena and to encounter new applications of Newtonian mechanics that were inaccessible before. The effect of air drag on the motion of a projectile is familiar to our students and is discussed in most introductory texts. It can be used as a vehicle to confront our students with the notion that an object moving at high speed (terminal velocity) and with large forces acting on it (gravity and air friction) can have a net force and acceleration of zero. These students can analyze a real-life situation where friction is not neglected and the effect can be an introduction to velocity-dependent forces that will be met later in electromagnetism.

In our pilot project we found that terminal velocity could be reached in a laboratory by using an air-filled balloon. A wire is wrapped around the base of the balloon and fashioned into a hook to hold weights (metal washers). One student holds the balloon high and releases it while his or her partner films the motion. The position of the balloon is recorded frame by frame at a rate of about 30 frames/second. The vertical position as a function of time is shown in the top panel of Figure 3 in Appendix IV. The balloon quickly reaches terminal velocity and moves at a constant speed. A linear fit to the data (excluding the first few points when the balloon was accelerating) determines the terminal velocity. The forces on the balloon are gravity and air drag so

$$\boldsymbol{F}_{total} = (-mg + F_{drag})\boldsymbol{j}$$

where m is the total mass of the weighted balloon, g is the acceleration of gravity, F_{drag} is the magnitude of the air drag, and $\boldsymbol{j}$ is the unit vector pointing in the upward direction. At terminal velocity $\boldsymbol{F}_{total}$ vanishes so

$$F_{drag} = mg \quad .$$

Hence, one can determine the drag force at terminal velocity. In the lower panel of Figure 3, the drag force is plotted as a function of the measured terminal velocity and the plot shows it is linearly proportional to the velocity. The result is reasonable for slow-moving objects like the balloon here where the air flow is not turbulent.[7]

Another phenomenon that is accessible with these methods is deterministic chaos displayed by a coupled pendulum.[8] It is a special topic that extends ideas already developed in the analysis of the simple pendulum and introduces the students to a topic of considerable interest in a variety of fields beyond physics and in the popular press. In this experiment the students film the motion of a coupled pendulum that consists of metal bars connected by an axle and suspended from a second axle (see Figure 4 of Appendix IV). Each bar is free to rotate through the full angular range. The apparatus is allowed to swing freely after being pulled upward to some large, initial angle. After filming the motion of the pendulum the students extract the trajectory of the end point of the lower pendulum. By repeating this procedure the students observe the two trajectories quickly diverge and soon bear little resemblance to each other. They discover the extreme sensitivity of the trajectory of the coupled pendulum to small differences in the initial angular position. This sensitivity to initial conditions is the hallmark of chaotic motion and implies the distance between trajectories of systems with similar initial conditions grows exponentially. Quantitatively, the measure of 'chaos' is known as the Lyapunov exponent, λ, defined as[9]

$$\lambda = \frac{1}{d_N - d_1} \sum_{i=1}^{N-1} log_2 \left[\frac{d_{i+1}}{d_i} \right]$$

where d_i is the distance between points on two different trajectories at the same time after release, N is the number of data points, and the sum is over all the data points. In other words, one records two trajectories of the pendulum that start from nearly the same initial angle. The position of the endpoint of the lower bar in the first frame after release in each of the two films is determined and the distance between these points is calculated (this value should be small since they were released from nearly the same angular position). The same quantity is extracted from the second frame after release of each film. The distance between the endpoints of the two trajectories in the second frame after release is divided by the result for the first frame. The same process is done for the second and third frames after release of the pendulum and added to the previous result and so on for the entire data set. The process for each data point is a repetitive task that benefits from a spreadsheet to do the calculation in a timely fashion. If the Lyapunov exponent is positive, then the system exhibits deterministic chaos. If it is zero or negative, the system is not chaotic.[9] The results of our pilot study are displayed in Figure 4 of Appendix IV. In the upper panel on the right the distance, d_i, between two trajectories of the coupled pendulum is shown as a function of time (these are the same quantities used to calculate the Lyapunov exponent). The two trajectories started from the same, large initial angle. The value of λ for this data set is $+0.733 s^{-1}$ implying the system is chaotic. In the lower panel the results for the same pendulum are shown for the case of small initial angles. The distance between the two trajectories does not grow as large as in the previous case (the vertical scales differ by a factor of ten). The value of λ is found to be $-0.076 s^{-1}$ implying non-chaotic behavior. Hence, in a comparatively straightforward manner, our students will be able to investigate this new and fascinating phenomenon.

The experiments described above and those listed in Appendix V will use video technology to improve our students learning of Newtonian mechanics in an inquiry-based environment. Some of the traditional topics covered in introductory physics will be addressed as well as new ones like chaos. The project will extend the use of video technologies to these new topics and will encourage students to design experiments and collect and analyze their own data. The laboratories developed in this project will be readily portable to sites beyond the local setting.

Equipment

(1) The Equipment Request

We request funding for ten video cameras, eight video boards for installation into our existing Macintosh computers, eight upgrades of these existing machines to Quadras, and eleven copies of the spreadsheet, Excel for the Mac.

The video cameras are made by Polaris Industries and were chosen because they are small, rugged, give excellent, black-and-white video quality, and are inexpensive (only $160 each). The evaluation kit includes items like mounting hardware, a power supply, and other items that are needed to assemble the pieces into a functioning camera. The associated materials are for metal boxes to mount the cameras and cabling. We wish to equip the eight existing computer stations in our introductory physics laboratory plus one development station in another laboratory (for a total of nine). Polaris offers a discount for the purchase of ten or more cameras so it is cheaper to buy ten cameras than nine. The video boards are from SuperMac and were chosen for their low cost and functionality. We have already used one of the boards in our pilot study and found it adequate for our purposes. Eight boards plus the one already purchased will equip the introductory physics laboratory and the development station. We note again the importance of the students designing their own experiments and collecting their own data rather than receiving 'canned' movies, hence the need to equip all the stations in our introductory physics laboratory.

We also request upgrades of our current Macintosh IIci's to Quadras. The Macintosh IIci's we acquired two years ago are simply too slow for data acquisition by the students in the laboratory. When we tested the SuperMac video board with one of our current computers the machine could only collect about 10 frames/second. This is inadequate. A film recorded at this rate of a ball dropped from a height of two meters would only have about four usable frames of the ball in motion. The data do not clearly map the time dependence of the position. We have tested the same board in our lone Quadra and found the rate improved to 30 frames/second, the maximum rate for standard video. The memory upgrades are necessary to run the software we now use. We also considered the new PowerPC from Apple, but it is not compatible with our existing system.

The spreadsheet Excel will be used for data manipulation, plotting, and some fitting. The video analysis software, '2D Video QT!', (obtained free of charge from Dickinson College) can write the position of an object determined by a mouse click into an Excel file for analysis. This will make data collection and analysis fast and easy. With the educational discount the price of Excel is competitive with other spreadsheets for the Macintosh. We request copies for the eight machines in the introductory laboratory, the development station, and two faculty workstations that will be used for development.

The other items needed for experiments are on hand or can be purchased within the constraints of our regular equipment budget.

(2) Equipment on Hand for the Project

The Department of Physics at the University of Richmond maintains a large inventory of equipment for use in its introductory physics laboratory. Major equipment on hand that could be used in this project include an introductory laboratory equipped with Macintosh IIci computers, the '2D Video QT!' video analysis software from Dickinson College, data acquisition boards from National Instruments, associated cabling and materials, and LabView data acquisition and analysis software. The LabView software can be used for some of the data analysis associated with this project, but it is not easy for introductory students to program with this language(hence, the need for a spreadsheet like Excel). The materials needed for the experiments are already in hand or can be purchased within the constraints of the Department's equipment budget.

(3) Equipment Maintenance

Each item requested has a warranty. The Academic Computing Center at the University of Richmond supports all computers on campus with two full-time computer maintenance personnel on the staff. The maintenance and care of the other laboratory equipment will be performed by the Laboratory Director. The University provides the Department with funds for equipment maintenance in the yearly budget.

Faculty Expertise

Dr. Gilfoyle is a tenured, associate professor who has been at the University since 1987 and will serve as the project director. He has experience with developing experiments using our computerized data acquisition and analysis and performed the pilot study discussed here. He has taught the introductory physics sequence many times. He is an experimental nuclear physicist with experience in detector and software development both for data acquisition and for analysis. His current research interests are in electro-nuclear physics and he is actively involved in the development of the Continuous Electron Beam Accelerator Facility (CEBAF) Large Acceptance Spectrometer or CLAS. He served as project director for the project described in the section entitled 'Results From Prior Support'.

Dr. Vineyard is a tenured, associate professor who has been at the University since 1986 and is a co-project director. He is an experimental nuclear physicist with experience in electronics, detector development, and computing. He developed the computer-based introductory physics laboratory using the software system mentioned in this proposal, LabVIEW. He has taught the introductory physics sequence many times and is currently developing a workshop physics approach in one section of our introductory physics sequence. His current research interests are in electro-nuclear physics and he is actively involved in the development of the CLAS.

Dr. Rubin joined the faculty as an assistant professor in 1993 and is a co-project director. He is an experimental particle physicist active in research and also has considerable experience with computing and electronics design and construction. He has been involved in the development of new experiments in the introductory physics sequence and in the equipment development for the workshop physics. He is currently teaching one section of our traditional-format, introductory physics with calculus sequence. His current research interests are in electro-nuclear and particle physics and he is actively involved in experiments at Brookhaven and in the development of the CLAS.

Dissemination Plan

Evaluation of the impact of the project will be done with standardized tests and student ratings. An exam to test students' understanding of Newtonian mechanics will be administered at the beginning and at the end of each semester. We are already using such tests in our workshop physics section and in our traditional-format sections of introductory physics.

In order to communicate the results of the project to the scientific and engineering community an article will be prepared for publication in a physics education journal such as the American Journal of Physics or Computers in Physics and a presentation will be made at a meeting of the American Association of Physics Teachers. Students will be encouraged to present their research work at the University's annual undergraduate research symposium.

References

1. P.Laws, Physics Today. 44(12), 24-31(December, 1991).
2. SPS Newsletter, 25 (4), (March, 1992).
3. A.van Heuvelen, Bull.Am.Phys.Soc. 36, 1359 (April, 1991).
4. A.Arons, *A Guide to Introductory Physics Teaching*, Wiley, New York, 1990
5. D.A.Zollman and R.G.Fuller, Physics Today, 47 (4), 41-47(April, 1994).
6. B.Thacker, E.Kim, K.Trefz, and S.M.Lea, Am.J.Phys. 62, 627-633(1994).
7. R.P.Feynman, R.B.Leighton, and M.Sands, *The Feynman Lectures on Physics*, Addison-Wesley, Reading, Massachusetts, 1963.
8. T.Shinbrot, C.Grebogi, J.Wisdom, and J.A.Yorke, Am.J.Phys. 60(6), 491-499 (June, 1992).
9. F.C.Moon, *Chaos and Fractal Dynamics*, Wiley, New York, 1992.

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1993-present - Associate Professor of Physics, University of Richmond
Summer, 1988 - Visiting Professor, University of Pennsylvania Tandem Accelerator Laboratory
1987-1993 - Assistant Professor, University of Richmond
1985-1987 - Postdoctoral Research Fellow, Nuclear Structure Laboratory, SUNY at Stony Brook
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Phi Beta Kappa
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Grants:
1993-present - Department of Energy ($284,000)
1992 -present - National Science Foundation ($49,813)
1990-1993 - Department of Energy ($287,000)
1989-1991 - Research Corporation($26,000)

Publications:

1. J.Boger, J.M.Alexander, G.Auger, A.Elmaani, S.Kox, R.A.Lacey, A.Narayanan, M.Kaplan, D.J.Moses, M.A.McMahan, P.A.DeYoung, C.J.Gelderloos, G.Gilfoyle, "Light Charged Particle and Intermediate Mass Fragment Emission in the Reaction 640 MeV ^{86}Kr + ^{63}Cu", Phys.Rev. C49, 1576 (1994).

2. M.F.Vineyard, S.E.Atencio, J.F.Crum, G.P.Gilfoyle, B.G.Glagola, D.J.Henderson, D.G.Kovar, C.F.Maguire, J.F.Mateja, R.G.Ohl, F.W.Prosser, J.H.Rollinson, R.S.Trotter, "Light-Particle Correlations with Evaporation Residues in the ^{40}Ca + ^{12}C Reaction at E(^{40}Ca) = 450 MeV", Phys.Rev. C49, 948 (1994).

3. R.A.Kryger, J.J.Kolata, W.Chung, S.Dixit, R.J.Tighe, J.J.Vega, P.A.DeYoung, C.Copi, J.Sarafa, D.G.Kovar, G.P.Gilfoyle, and S.Sigworth, "Neutron-Charged Particle Correlations in the 3.8 MeV per Nucleon ^{16}O + ^{27}Al and 13.4 MeV per Nucleon ^{16}O + ^{27}Al Reactions", Phys. Rev., C46, 1887 (1992).

4. G.P.Gilfoyle, M.S.Gordon, R.L.McGrath, G.Auger, J.M.Alexander, D.G.Kovar, M.F.Vineyard, C.Beck, D.J.Henderson, P.A.DeYoung, D.Kortering, "Heavy Residue Production in the 215 MeV ^{16}O + ^{27}Al Reaction", Phys. Rev., C46, 244(1992).

5. M.D.Mestayer, C.L.Tam, K.Wang, H.Baghei, S.Christo, S.A.Dytman, G.P.Gilfoyle, J.D.Hewitt, F.W.Hersman, R.S.Hicks, R.A.Miskimen, R.Schumacher, and M.F.Vineyard, "Effects of Non-parallel Magnetic Fields on Hexagonal Cell Drift Chambers", IEEE Transaction on Nuclear Science, 39 (1992).

17 more journal articles and 31 abstract of papers presented at meetings.

Undergraduate Advisees (5): Amy S.Snyder, Carlos Cardounel, Michael McGehee, Michael Nimchek, Steven Sigworth

Collaborators (in addition to those listed above): W.Chung, S.Dixit, R.J.Tighe, J.J.Vega, C.Copi, J.Sarafa, D.J.Moses, C.J.Gelderloos, D.Kortering, J.Sarafa, K.Zienert, B.J.Fineman, X.Lu, R.L.McGrath, D.M.de Castro Rizzo, L.C.Vaz

PostDoctoral Advisor: Robert L. McGrath; Physics Department, SUNY, Stony Brook

Graduate Advisor: H.T. Fortune; Physics Department, University of Pennsylvania

Michael F. Vineyard

Department of Physics
University of Richmond, Virginia 23173
(804) 289-8257

9802 Mosswood Road
Richmond, Virginia 23236
(804) 330-2620

Personal: Born January 2, 1953 in Vineland, New Jersey; Married with two children

Education: Ph.D., Physics, Florida State University, 1984 ("A Study of Inelastic Scattering and Excitation of ^{6}Li" K. W. Kemper, advisor)
M.S., Physics, Florida State University, 1981
B.S., Physics, Stockton State College, 1978

Experience: 1992-present - Associate Professor of Physics, University of Richmond
1993-1994 - Visiting Scientist, Continuous Electron Beam Accelerator Facility
1987 (Summer) - Visiting Scientist, Argonne National Laboratory
1986-1992 - Assistant Professor of Physics, University of Richmond
1984-1986 - Research Associate, Argonne National Laboratory
1979-1983 - Research Assistant, Florida State University
1978-1979 - Teaching Assistant, Florida State University
1977-1978 - Physics Laboratory Assistant, Stockton State College

Societies: American Physical Society, Sigma Xi, Council on Undergraduate Research, Society of Physics Students, Sigma Pi Sigma

Grants: 1993-1996 - U. S. Department of Energy ($286,000)
1992 - ILI Program of the National Science Foundation ($49,813)
1990-1993 - U. S. Department of Energy ($284,000)
1988-1990 - U. S. Department of Energy ($63,000)
1990 - University of Richmond Research Grant ($4,000)
1986 - University of Richmond Research Grant ($1,495)

Publications:

M. F. Vineyard, S. E. Atencio, J. F. Crum, G. P. Gilfoyle, B. G. Glagola, D. J. Henderson, D. G. Kovar, C. F. Maguire, J. F. Mateja, R. G. Ohl, F. W. Prosser, J. H. Rollinson, and R. S. Trotter, "Light-particle correlations with evaporation residues in the ^{40}Ca+^{12}C reaction at E(^{40}Ca)=450 MeV", Phys. Rev. **C49**, 948 (1994).

M. F. Vineyard, J. F. Mateja, C. Beck, S. E. Atencio, L. C. Dennis, A. D. Frawley, D. J. Henderson, R. V. F. Janssens, K. W. Kemper, D. G. Kovar, C. F. Maguire, S. J. Padalino, F. W. Prosser, G. S. F. Stephans, M. A. Tiede, B. D. Wilkins, and R. A. Zingarelli, "Energy dependence of fusion evaporation-residue cross sections in the $^{28}Si + ^{12}C$ reaction", Phys. Rev. **C47**, 2374 (1993).

M. F. Vineyard, "Using LabVIEW Instrumentation Software", Council on Undergraduate Research Newsletter, Vol. XIII, Num. 3, 36 (1993).

M. D. Mestayer, C. L. Tam, K. Wang, H. Baghaei, S. Christo, S. A. Dytman, G. P. Gilfoyle, J. D. Hewitt, F. W. Hersman, R. S. Hicks, R. A. Miskimen, R. Schumacher, and M. F. Vineyard, "Effects of Non-Parallel Magnetic Fields on Hexangonal Cell Drift Chambers", IEEE Transactions on Nuclear Science **39**, 690 (1992).

M. F. Vineyard, J. S. Bauer, J. F. Crum, C. H. Gosdin, R. S. Trotter, D. G. Kovar, C. Beck, D. J. Henderson, R. V. F. Janssens, B. D. Wilkins, C. F. Maguire, J. F. Mateja, F. W. Prosser, and G. S. F. Stephans, "Fusion evaporation residue cross sections for $^{28}Si+^{40}Ca$ at $E(^{28}Si)=309$, 397, and 452 MeV", Phys. Rev. **C45**, 1784 (1992).

20 other journal articles and 33 abstracts of papers presented at conferences and workshops

Collaborators (in addition to those listed above): J. Cook, V. Hnizdo, M. N. Stephens, H. Ikezoe, G. Rosner, K. T. Lesko, K. E. Rehm, J. Kolata, R. Vojtech, C. N. Davids, L. A. Lewandowski, R. L. Stern, F. D. Becchetti, T. Casey, J. W. Janecke, P. M. Lister, W. Z. Liu, R. W. Phillips, I. Tserruya, V. Steiner, Z. Fraenkel, P. Jacobs, W. Henning, S. J. Sanders, W. C. Ma, T. F. Wang, P. Chowdhury, W. Kuhn, J. D. Hinnefeld, P. A. DeYoung, C. J. Gelderloos, D. Kortering, J. Sarafa, K. Zienert, M. S. Gordon, B. J. Fineman, X. Lu, R. L. McGrath, D. M. de Castro Rizzo, J. M. Alexander, G. Auger, S. Kox, L. C. Vaz, A. van den Berg, L. L. Lee, F. Videbaek,

Undergraduate Advisees: Jenifer Bauer, Craig Gosdin, Richmond Trotter, Shawn Atencio, James Rollinson, Raymond Ohl, Jason Crum, Ben Sabloff, Brian McKeever, Leith Kuhn, Mark Cheatham

Graduate Advisor: K. W. Kemper

PostDoctoral Advisor: D. G. Kovar

Philip D. Rubin

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8 Bostwick Lane
Richmond, VA 23226
(804) 282-1941

Citizenship: U.S.A.

Degrees:
Ph.D. Physics, UCLA, 1989
M.S. Physics, UCLA, 1986
M.A. Sociology, UCLA, 1980
A.B. Sociology, University of Pennsylvania, 1976

Experience:
1993-present - Assistant Professor of Physics, University of Richmond
1992-1993 - Research Assistant Professor, College of William and Mary
1989-1992 - Research Associate, Syracuse University
1986-1989 - Research Assistant, UCLA
1978-1986 - Teaching Assistant, UCLA

Organizations:
American Physical Society
Sigma Xi, the Scientific Research Society
CEBAF Users Group

Grants: 1994-present - Research Corporation ($28,000)

Publications:

1. K.Arisaka, *et al.* (BNL E791), "Improved Sensitivity in a Search for the Rare Decay K_L^0 -> e^+e^-", Phys.Rev.Lett., 71, 3910 (1993).

2. D.Cinabro, *et al.* (CLEO), "Limit on the Tau Neutrino Mass", Phys.Rev.Lett., 70, 3700 (1993).

3. A.Bean, *et al.* (CLEO), "Search for Exclusive b->u Semileptonic Decays of B Mesons", Phys. Rev.Lett., 70, 2681 (1993).

4. K.Arisaka, *et al.* (BNL E791), "Improved Upper Limit on the Branching Ratio B(K_L^0 -> $\mu^{+/-}e^{-/+}$)", Phys. Rev.Lett., 70, 1049(1993).

5. R.Balest, *et al.* (CLEO), "Measurement of the τ-lepton mass", Phys.Rev., D47, 3671(1993).

17 more journal articles and 31 abstract of papers presented at meetings.

Undergraduate Advisees (3): Mark McCaskill, Jeffrey Kushinka, Mark Esbenshade

Collaborators (in addition to those listed above): CEBAF Hall B, Brookhaven Experiment 871, CLEO, Brookhaven Experiment 791

PostDoctoral Advisor: Marvin Goldberg, Nahmin Horwitz, Giancarlo Moneti, and Sheldon Stone; Department of Physics, Syracuse University.

Graduate Advisor: William E. Slater; Department of Physics, UCLA

DETAILED BUDGET

Item (Descriptive name, probable brand and model)	How Many?	Unit Price (List)	Unit Price (Discounted)	Total Cost (Discounted)
(1) Scientific and Computing Equipment				
Student workstations				
Polaris Industries MB-812A Camera	8	$160	$160	$1,280
Polaris Industries Evaluation kit	8	20	20	160
Associated Camera Materials	8	15	15	120
SuperMac Video Board	8	429	429	3,432
Quadra 630 CPU	8	1,031	1,031	8,248
Memory upgrade to 8 MByte	8	183	183	1,464
2D Video QT! Video Analysis Software	8	0	0	0
Microsoft Excel	8	295	72	576
Student Workstations Sub-Total	8	2,133	1,910	15,280
Faculty workstations				
Polaris Industries MB-812A Camera	2	160	160	320
Polaris Industries Evaluation kit	2	20	20	40
Associated Camera Materials	2	15	15	30
2D Video QT! Video Analysis Software	3	0	0	0
Microsoft Excel	3	295	72	216
Faculty Workstations Sub-Total		490	267	606
Scientific and Computing Equipment Sub-total				$15,886
(5) Shipping Costs				0
			Total Project Cost:	$15,886
			Non-NSF contribution (including any overmatch):	$7,943
			NSF request:	$7,943

Appendix I.

Current and Pending Support

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Gerard P. Gilfoyle

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Nuclear Physics at the University of Richmond

Source of Support: Department of Energy

Award Amount (or Annual Rate): $ 284,000 Period Covered: 1993-1995

Location of Project: University of Richmond

Person-Months Committed to the Project. Cal: 4 Acad: 2 Summ: 2

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: New Teaching Technologies in Physics

Source of Support: National Science Foundation

Award Amount (or Annual Rate): $ 49,913 Period Covered: 1992-1994

Location of Project: University of Richmond

Person-Months Committed to the Project. Cal: 0 Acad: 0 Summ: 0

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: Acad: Summ:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: Acad: Summ:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Michael F. Vineyard	Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support

Project/Proposal Title: Nuclear Physics at the University of Richmond

Source of Support: Department of Energy

Award Amount (or Annual Rate): $ 284,000 Period Covered: 1993-1995

Location of Project: University of Richmond

Person-Months Committed to the Project. Cal: 4 Acad: 2 Summ: 2

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support

Project/Proposal Title: New Teaching Technologies in Physics

Source of Support: National Science Foundation

Award Amount (or Annual Rate): $49,913 Period Covered: 1992-1994

Location of Project: University of Richmond

Person-Months Committed to the Project. Cal: 0 Acad: 0 Summ: 0

Support: [ ] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: Acad: Summ:

Support: [ ] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: Acad: Summ:

Support: [ ] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: Acad: Summ:

---

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Philip D. Rubin

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support

Project/Proposal Title: Studies of Two Mesons which Contain Strange Quarks

Source of Support: Research Corporation

Award Amount (or Annual Rate): $ 28,000 Period Covered: 1994-1995

Location of Project: University of Richmond

Person-Months Committed to the Project. Cal: 4 Acad: 2 Summ: 2

Support: [ ] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: Acad: Summ:

Support: [ ] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: Acad: Summ:

Support: [ ] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: Acad: Summ:

Support: [ ] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Appendix II

Major equipment available to undergraduates

The Department of Physics at the University of Richmond maintains a large cumulative inventory of equipment, old and new, which runs to over sixty pages and lists more than 3000 items. Listed below are the most expensive items.

Item	Model	Year Purchased	Cost
SuperMac Video Board	VideoSpigot NuBus	1994	$429
Data Acquisition Computers(14)	Macintosh IIci and Quadras	1991-1994	$70,000
HP Computer System	HP 715/75	1993	20,000
LeCroy Oscilloscope	LeCroy 2248	1993	9,144
CAMAC Crate	BiRa	1993	3,480
Crate controller	Kinetic Systems	1993	2,475
Physics Simulation Software	Interactive Physics II	1993	299
Symbolic Mathematics Package	Mathematica	1992	3,000
Smart Pulley(12)	Pasco Smart Pulley	1991	948
Force Transducers(6)	Pasco Transducers	1991	1,350
Data Acquisition Software(14)	LabVIEW 2	1991	2,750
Networking System	Timbuktu	1991	349
Data Acquisition Hardware(14)	National Instruments Lab-NB board	1991	5,139
VAXstation Computer System	DEC VAXstation 3100 & 3200	1990	80,000
Graphics Terminal (2)	HDS 3200 Model 10 w/ Mouse	1989	1,52
Oscilloscope	Tektronix 2467B	1991	12,000
2 Watt Argon laser	Spectra-Physics 2000	1986	20,000
30 mW HeNe laser	Jodon HN-20G	1989	4,500
1 mW HeNe lasers (16)	Spectra-Physics155	1974	4,800
Mossbauer Spectrometer	Elscint et al.	1975	15,000
Assorted NIM Modules (22)	Ortec	1978-90	15,000
Oscilloscope	Tektronix 7613	1981	7,500
Oscilloscopes (16)	Kibusui 5020	1986,87	9,600
Oscilloscopes (5)	Phillips 3215	1984	6,000
Function Generators (16)	VIZ - 504B/44D	1983	2,400
Function Generators (6)	Wavetek 188	1984	2,100
Function Generators (3)	H.P. 3310A(2), 3311A	1974,81	1,450
X-Ray Diffraction machines (2)	GE XRD-5	1965,76	N/A
Ion Gauge and Electrometer	Keithley	1977,90	2,000

Appendix III

Catalog Description of Courses Directly Affected by the Project

131-132 General Physics With Calculus. Calculus-based introductory course. Mechanics, heat, sound, magnetism, electricity, and light. Includes laboratory. *Prerequisites*: Math 211 (or 111)-112 (may be taken concurrently). Physics 131 is a prerequisite to 132. A student may not receive credit for both Physics 131 and 101, nor for Physics 132 and 102. *4-4 sem. hrs.* (131 or 132, FSNP).

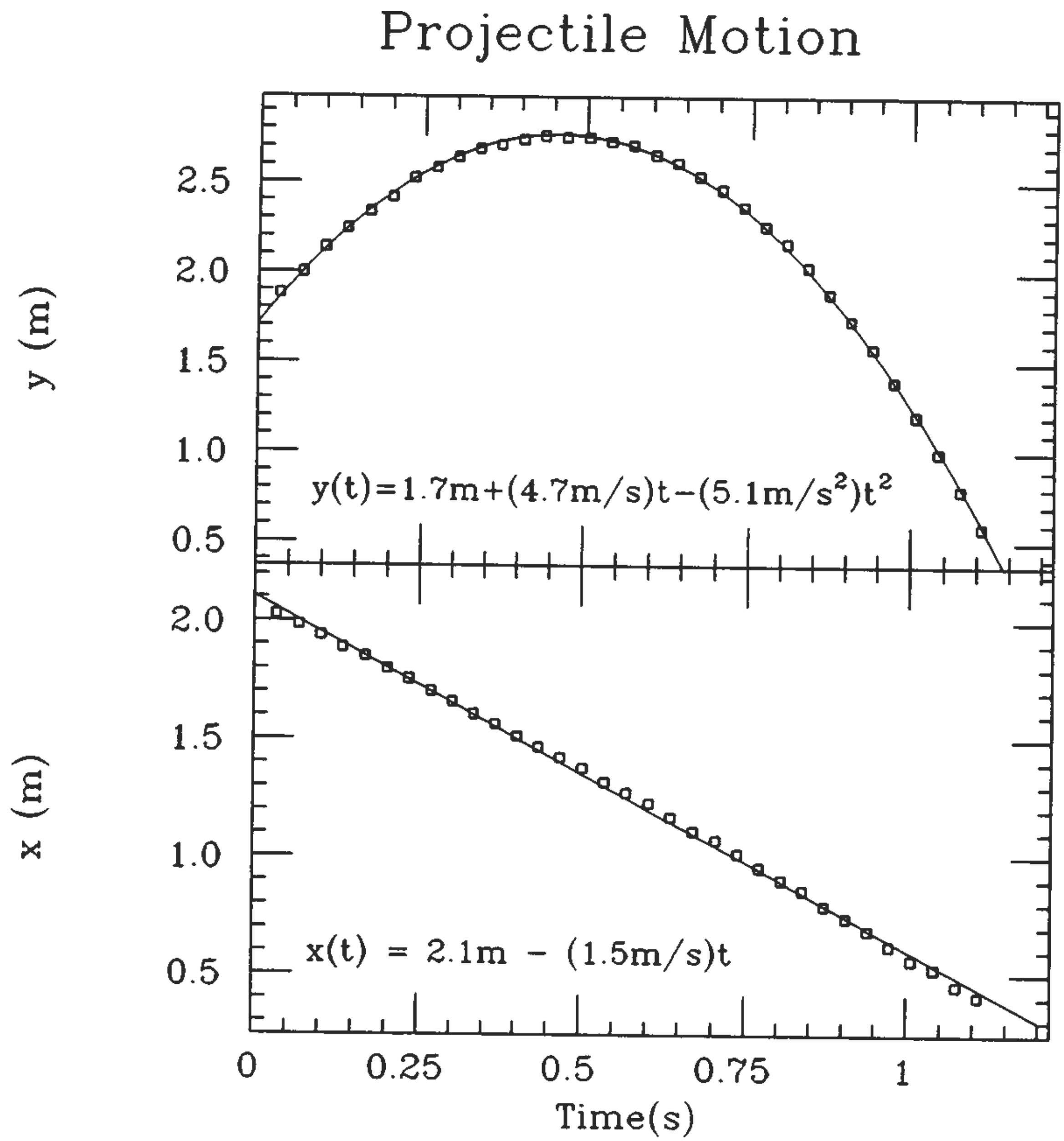
Frequency: every academic year
Enrollment: about 90
Required of physics majors

101-102 General Physics. Basic course without calculus. Mechanics, heat, sound, magnetism, electricity, light, and modern physics. Includes laboratory. Physics 101 not prerequisite for Physics 102. *Prerequisites*: Algebra and trigonometry. A student may not receive credit for both Physics 101 and 111, or 101 and 131. *4-4 sem. hrs.* (101 or 102, FSNP).

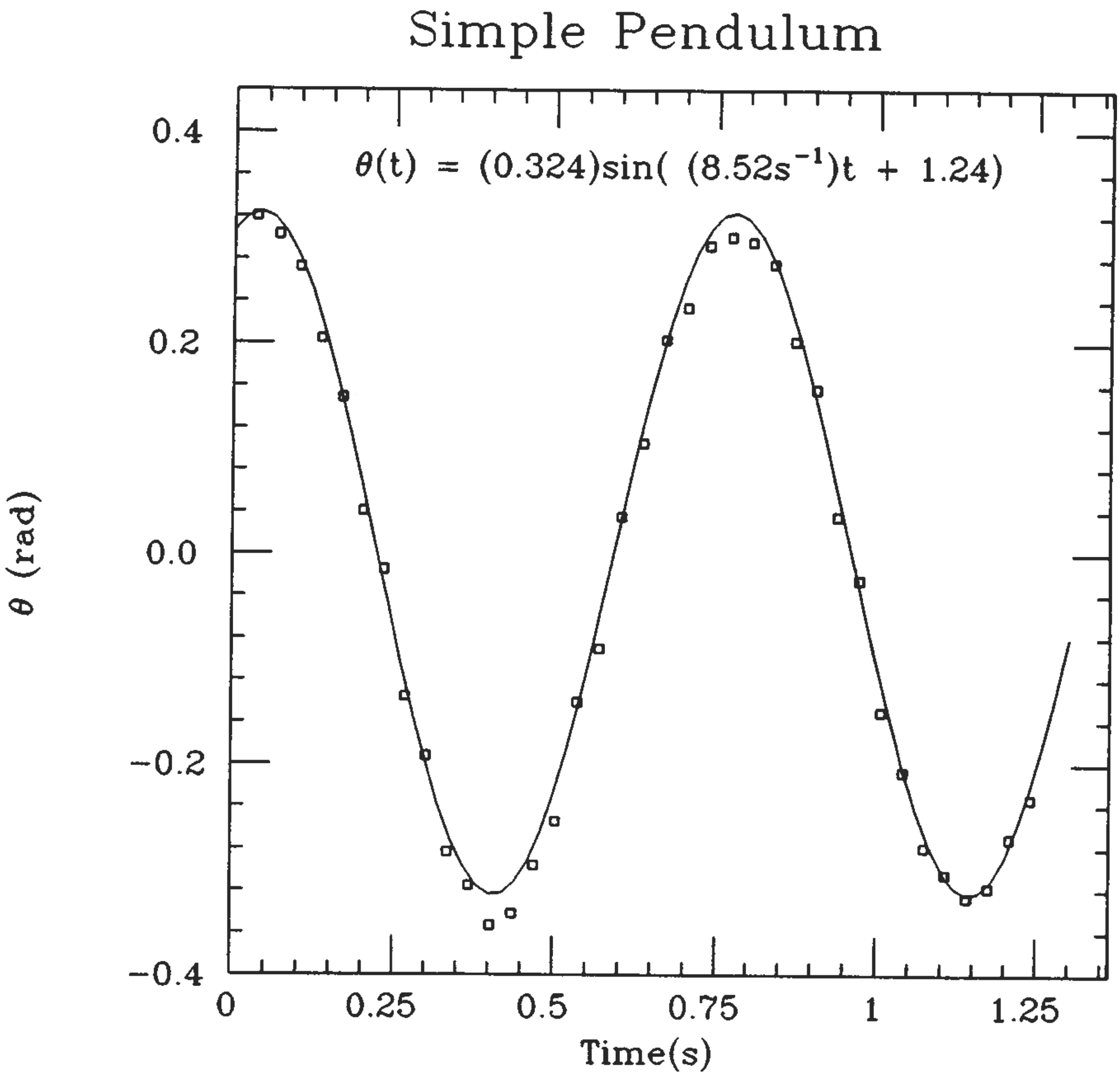
Frequency: rarely, most of our students have the mathematics background appropriate for our Physics with Calculus course.
Enrollment: about 20
Satisfies the requirement for the physics major

Appendix IV

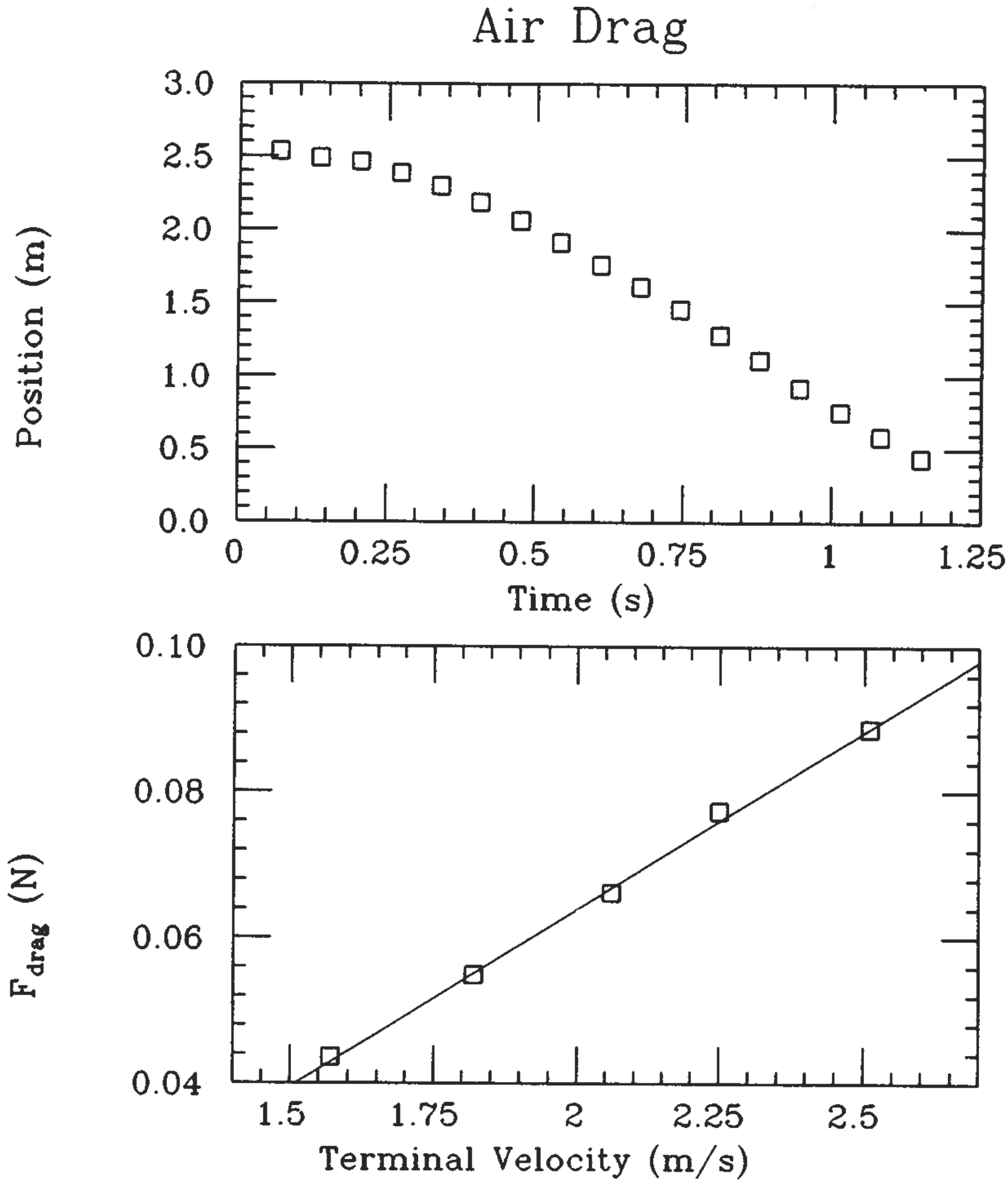
Figures



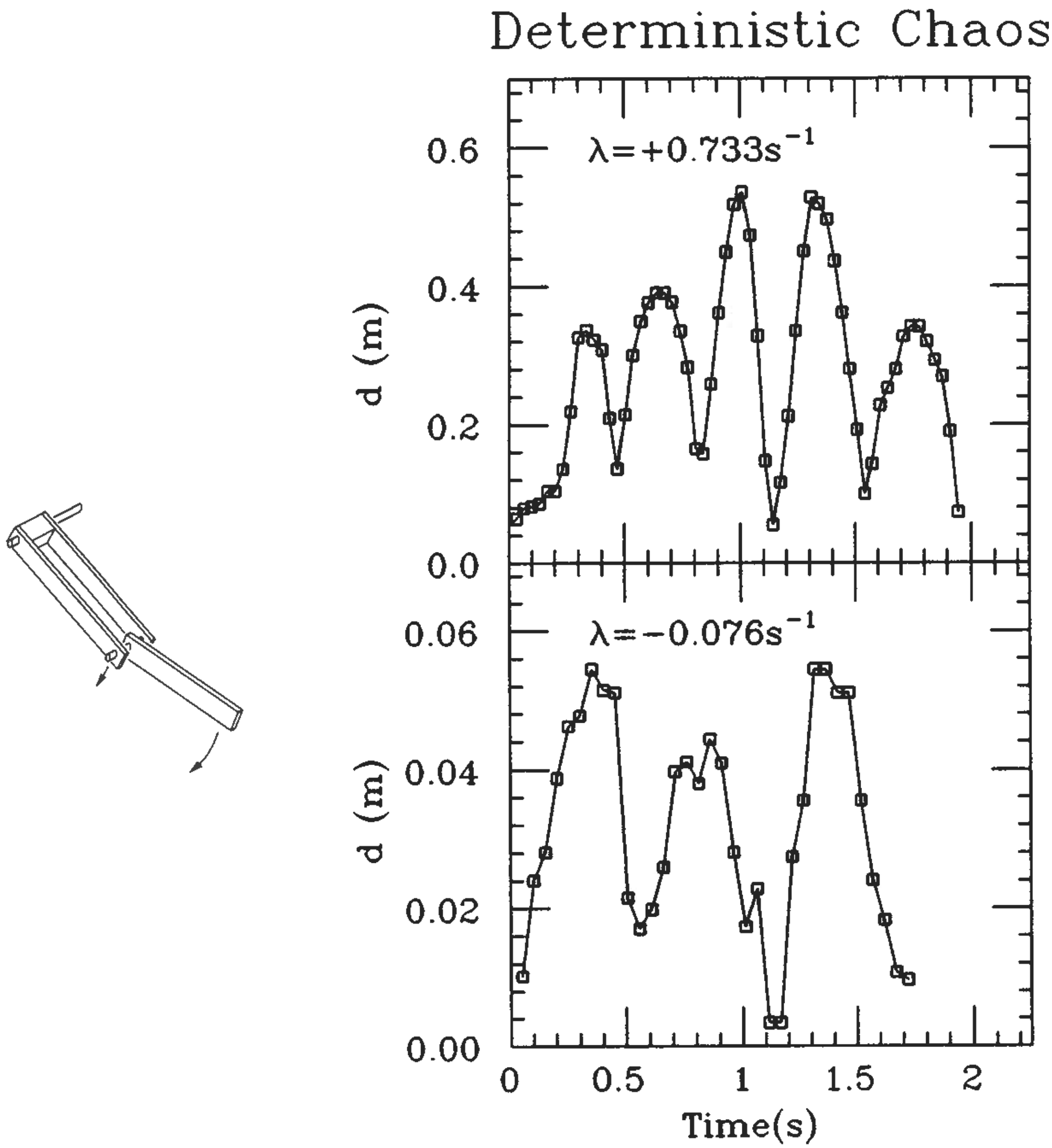
1. The data from a study of projectile motion are shown. The upper panel is the vertical position as a function of time. The lower panel is the horizontal position as a function of time. The curves are quadratic and linear fits to the data respectively.



2. The time dependence of the angle between the string of a simple pendulum and the vertical is displayed. The solid curve is a fit to a sine curve.



3. The results of an investigation of air drag are shown. The time dependence of the vertical position of a falling, weighted, balloon is shown in the upper panel. The dependence of the drag force on terminal velocity is displayed in the lower panel.



4. A sketch of the coupled pendulum is shown on the left-hand side of the figure taken from Reference 8. The time dependence of the linear distance between two different trajectories of a coupled pendulum is shown in each panel on the right. The data in the upper panel are for two trajectories that started from nearly the same, large initial angle. In the lower panel the same procedure was followed except the initial angle for each trajectory was small (about 20°). Note the scales for the two panels differ by a factor of ten.

Appendix V

Proposed Introductory Physics Laboratories

The following list describes briefly experiments that are candidates for introductory physics laboratories. It includes existing topics that will benefit from the video technology discussed in this proposal and new topics that are currently inaccessible.

1. Falling bodies; accelerated motion in one dimension.

2. Projectile motion (see discussion in narrative).

3. Falling bodies with friction; object moving at terminal velocity with zero net force; velocity-dependent force (see discussion in narrative).

4. Uniform circular motion; a metal weight attached by a hinged rod to the shaft of a motor is rotated at constant speed; force components are determined by the speed of rotation and the angle of the rod to the horizontal.

5. Center-of-mass motion; a ball-and-stick model is tossed in the air; the motion of its center of mass is recorded and compared with the results from projectile motion.

6. Rolling; disks are rolled down an inclined plane; the rotational and linear motion is recorded and analyzed.

7. Collisions; one and two dimensional collisions on a flat surface are recorded and analyzed.

8. Simple harmonic motion; the motion of a mass on a spring or a simple pendulum is studied (see discussion in narrative).

9. Deterministic chaos; the motion of a coupled pendulum is investigated qualitatively and quantitatively (see discussion in narrative).

10. Damped oscillations; a pendulum is immersed in water and its motion recorded.

11. Waves; wave speed is measured for an extended, plucked spring; the properties of standing waves on a spring are determined.

Product	Description	CPP 1 Price
MACINTOSH QUADRA CPUs		
All Quadra CPUs include System Software and a mouse. Display and keyboard sold separately. Quadra CPUs include 1MB VRAM, Ethernet and FPU unless otherwise noted.		
M3491LL/B	Macintosh Quadra 630 4MB Hard Disk 250 CPU (without Ethernet)	1031.00
M6710LL/A	Macintosh Quadra 950 8MB 1FD CPU	2466.00
M6720LL/A	Macintosh Quadra 950 8MB Hard Disk 230 CPU	2883.00
M6735LL/A	Macintosh Quadra 950 8MB Hard Disk 500 CPU	3334.00
M6780LL/A	Macintosh Quadra 950 16MB Hard Disk 1000 CPU	4167.00
POWER MACINTOSH™ CPUs		
All Power Macintosh CPUs include System Software and a mouse. Display and Keyboard sold separately. Includes Ethernet. Floating point is built into all PowerPC 601 processors.		
Display adapter included with non-AV 6100/60 CPUs.		
M3576LL/B	Power Macintosh 6100/60 8MB Hard Disk 250 CPU	1457.00
M1878LL/B	Power Macintosh 6100/60 8MB Hard Disk 250 CPU w/CD-ROM	1625.00
M3586LL/B	Power Macintosh 6100/60 16MB Hard Disk 350 CPU w/SoftWindows	2001.00
M3589LL/B	Power Macintosh 7100/66 (1MB VRAM) 8MB Hard Disk 500 CPU	2322.00
M3590LL/B	Power Macintosh 7100/66 (1MB VRAM) 8MB Hard Disk 500 CPU w/CD-ROM	2490.00
M3591LL/B	Power Macintosh 7100/66 (1MB VRAM) 16MB Hard Disk 500 CPU w/SoftWindows	2738.00
M2836LL/C	Power Macintosh 7100/66AV (2MB VRAM) 16MB Hard Disk 500 CPU w/CD-ROM	2963.00
Power Macintosh 8100/80 & AV CPUs include 2MB VRAM & 256K Cache.		
M3587LL/B	Power Macintosh 8100/80 8MB Hard Disk 500 CPU	3332.00
M2284LL/B	Power Macintosh 8100/80 16MB Hard Disk 500 CPU w/CD-ROM	3803.00
M2293LL/B	Power Macintosh 8100/80AV 16MB Hard Disk 500 CPU w/CD-ROM	3970.00
M2297LL/C	Power Macintosh 8100/80 16MB Hard Disk 1000 w/CD-ROM CPU	4218.00

The Univeristy of Richmond
Jerry Gillfoyle 804 ~~249-5800~~ 289-8482

Model	Description	Qty	Unit	Extended	Delivery*
M3651LL/A	Macintosh 4MB Memory Expansion Kit (1-4MB SIMM) Quadra/Performa 63X,	1	$183.00	$183.00	6 weeks

* Delivery quotes are for orders placed during the week of quotation
PLEASE NOTE FUNDING DEADLINES CLEARLY ON PURCHASE ORDER

11/4/94
1:33 PM

Apple Computer Inc.
2420 Ridgepoint Drive
Austin, TX 78754
512 919-2973 (fax)

Shipping charges paid by Apple
FIN # 94 240 4110
Payment Terms: NET 30

TOTAL P.03

SUPER**FACTS** SYSTEM

ID #	Document Name	Part #	SRP	Pgs.
232	E-Machines E20	EMD01T20	$1,899	2
301	SuperMatch Display Calibrator			4
	SuperMatch Display Calibrator Pro	C5555	$799	
	SuperMatch Display Calibrator	C5000	$399	
	ProofPositive Color-Printing Systems			
351	ProofPositive 2.0 Family			4
	Full-Page Color-Printing System	PTR120-2.0	$7,999	
	Two-Page Color Printing System	PTR220-2.0	$14,999	
	Full-Page Digital-Imaging System	PTR130-2.0	$6,999	
	Two-Page Digital-Imaging System	PTR230-2.0	$12,999	
	Adobe v2.0 PostScript Level 2 Rip, Full Page	PIF040-2.0	$1,499	
	Adobe v2.0 PostScript Level 2 Rip, Two Page	PIF050-2.0	$2,499	
	PostScript v2.0 Software/Hardware Upgrade Kit	PIF020U-2.0	$999	
	PostScript v2.0 Software-Only Upgrade Kit	PIF040U-2.0	$99	
	Digital-Video and Multimedia Solutions			
401	DigitalFilm			4
	DigitalFilm	DV2050	$3,799	
	DigitalFilm Player	DV2010	$1,999	
402	VideoSpigot			2
	VideoSpigot NuBus	DV1030	$429	
	VideoSpigot LC	DV1050	$279	
406	Cinepak Compression Accelerator Kit			2
	Cinepak Compression Accelerator Kit	DV3230	$1,499	
	Cinepak Software-Only Upgrade	DV3230-U	$499	
407	Spigot II Tape	DV1530	$999	2
	Mobile Computing and Presentation Graphics			
503	E-Machines Presentor	5008-PLP	$499	2
504	E-Machines EtherDock	5008-PLD	[illegible]	2
505	Simply TV	EMG0550	$439	2
	Graphics Solutions for Microsoft Windows			
601	Thunder/24 Family for Windows			2
	Thunder/24 for Windows (EISA)	PCG-0116	$1,499	
	Thunder/24 for Windows (ISA)	PCG-0126	$1,499	
	Thunder/24 for Windows (VL)	PCG-0136	$1,499	
	SuperMatch Display Calibrator Pro	PCG-0320	$799	

SUPERMAC

215 Moffett Park Drive
Sunnyvale, CA 94089-1374
(408) 541-6100

Appendix VI. Price Quotes

POLARIS INDUSTRIES

141 West Wieuca Road, Suite 300-B, Atlanta, Georgia 30342-3219 Local *404-252-3340* Toll-Free *800-752-3571* Fax *404-252-8929*

CCD Camera Module Pricing

Quantity/Price

Model	1-9	10-24	25-100	100+
MB-812A (Compact Remote Head)	$219.95	$189.95	$169.95	CALL
MB-810B (Micro-Size CCD)	$185.95	$159.95	$149.95	CALL
	1	2-4	5-24	25+
MB-912C (Color Remote Head CCD)	$349.95	$324.95	$295.95	CALL

*Prices subject to change without notice.

Evaluation kits are available for an additional $19.95

Evaluation kits include.....

- Camera Connector
- Power Supply
- Video Cables
- Video Manual
- Application Notes
- Mounting Hardware

Payment Method

VISA ——— *MasterCard* ——— DISCOVER ——— C.O.D.

Shipping Options...

Polaris Industries delivers through United Parcel Service (UPS) or the U.S. Postal Service. Shipping charges are based on item size, package weight, delivery location and shipping method.

- For C.O.D. deliveries add $5.00 handling charge
- Shipping rates available upon request
- All Air and Pr[illegible] shipments must be prepaid or charged to a Credit Card

Delivery Methods...

UPS offers three methods of delivery

- **Next Day Air** - Packages arrive next business day
- **2nd Day Air** - Packages arrive second business day
- **Standard Ground** - Allow two to seven business days for delivery

1-800-752-3571

Date: Fri, 21 Oct 1994 14:32:23 -0400 (EDT)
From: David Houghton <findfh@sonic.urich.edu>
Subject: price quote
To: gilfoyle@urvax.urich.edu
Cc: suddarth@urvax.urich.edu
Message-id: <Pine.3.07.9410211423.A20531-a100000@sonic.urich.edu>
MIME-version: 1.0
Content-type: TEXT/PLAIN; charset=US-ASCII
Content-transfer-encoding: 7BIT

Microsoft Excel v 5.0 for the Mac $72.00 each
source: Egghed Software FIN: 91-1233491

Microsoft Excel for the Powermac $77.00 each
source: ASAP Software FIN: 36-3328437


```
**************************************************************************
*                                                                        *
*   David Houghton                      e-mail: houghton@urvax.urich.edu *
*   Senior Buyer                                findfh@sonic.urich.edu   *
*   100 Special Programs Building        voice: 804-289-8161             *
*   University of Richmond, VA 23173       fax: 804-289-8809             *
*                                                                        *
**************************************************************************
```