COMPUTER-BASED INSTRUCTION BRINGS ADVANCED-PLACEMENT PHYSICS TO GIFTED STUDENTS

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In this article, we describe two college-level introductory courses in physics, with calculus prerequisites, that are entirely computer-based. These courses have been developed by the Education Program for Gifted Youth (EPGY) at Stanford,[1] a research project that provides year-round, accelerated instruction in mathematics and physics to gifted or advanced middle- and high-school students via computer-based courseware.

Students in EPGY run multimedia courseware at home or in school on personal computers using the MS-Windows operating system. Our software, unlike traditional applications of computers in education, is intended to be the primary means of instruction and not merely a supplement to a regular class. It is precisely in those settings in which a regular class cannot be offered, either because of an insufficient number of students or the absence of a qualified instructor, that our software is intended to be used. Because we are concerned with college-level physics courses, which presuppose calculus, the issue of teacher qualification is a significant one.

We have used our course model over the last four years to teach advanced-placement (AP) calculus and physics courses to gifted middle- and advanced high-school students. The remainder of this article focuses on the EPGY course software in the context of the AP physics courses.

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Background to EPGY

The EPGY program started in 1985 as a proof-of-concept project funded by the National Science Foundation to create a first-year course in calculus that would be entirely computer-based.[1] Our motivation was the fact that fewer than 25% of U.S. high schools offer AP calculus. If a computer program were the primary means of instruction, calculus could be made available to more qualified students.

Because our purpose was to provide access to advanced courses in situations in which on-site qualified teachers were unavailable, we have had to concentrate on developing software that can play the role of both instructor and demonstrator. We have assumed that our software will be used by students, and not by instructors, and have therefore endeavored to make it as instructionally self-contained as possible.

The calculus course was complete in 1990 and was used to teach the AB curriculum of AP calculus (the first two quarters of college calculus) to 13 students in the 1991 year. Of these 13 students, six scored 5, six scored 4, and one scored 3 (where 5 is the top score and 3 is passing). Because of this success, we expanded the course during 1991 to cover the BC curriculum (the third quarter of college calculus). In 1991-92, we offered the course to four students, all of whom scored 5.

Following these results, we decided to tackle the problem of using the same technology to teach college physics. Because our students had already taken calculus, we decided to develop courses to cover the AP Physics C curriculum in mechanics as well as electricity and magnetism, courses corresponding to the first two quarters of college physics with a calculus prerequisite. The problem of availability is even

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more extreme for these courses: they are offered by fewer than 10% of U.S. secondary schools.

Courses offered

Since December 1992, we have offered three sections of our AP mechanics course and one section of our AP electricity and magnetism course. We will classify students who have taken these courses into three groups, based on which exam they took and when they took it.

The first group consists of those who took Physics C: mechanics in the 1992-93 school year. This course was offered to all students who had taken calculus with us in 1991 or 1992. All those from the 1992 class chose to participate, and six (three boys and three girls) of the 13 students from the 1991 class accepted the invitation. We will refer to this group of ten students who took the AP exam in 1993 as Mech93.

During the 1993-94 academic year, we offered two sections of mechanics. The first section consisted of students who began the course in September 1993 hoping to complete both the mechanics and the electricity and magnetism courses during the year. The second section began in January 1994 and consisted of students who planned to take only the mechanics AP exam. These students were all required either to have completed a calculus course during the previous year or to be enrolled in a calculus course concurrently with the physics. Because these eight students all took the AP exam together, for the purposes of this article we treat these two sections as one group, which we will call Mech94.

The electricity and magnetism course was offered for the first time in December 1993. The group of students that took this course, which we will call EM94, comprised nine of the ten students who had been in Mech93, together with four students from Mech94. All 13 of these students took the Physics C: electricity and magnetism exam in May 1994.

EPGY Lessons in Mechanics

Lesson Number	Textbook Chapter	Subject or Title
9010	2.1-2	Motion in one dimension. Velocity.
9020	2.3-4	Motion in one dimension. Acceleration.
9030	3.1-5	Motion in two or three dimensions. Vectors.
9040	3.6-7	Relative Velocity and Projectile Motion.
9050	3.7	Projectile Motion. Examples.
9060	3.8	Circular Motion.
9070	4.1-2	Newton's Law I.
9080	4.3-4	Newton's Law II.
9090	4.1-4	Newton's Law. Examples.
9100	4.5	Forces. So What are They?
9110	4.6	How to solve physics problems.
9120	4.6	How to solve physics problems.
9130	5.1	Friction.
9140	5.1	Analysis of Car's Motion.
9150	5.2	Drag Forces.
9160	5.3	Problems with more than one object.
9170	5.4	Pseudoforces.
9180	6.1	Work and Energy.
9190	6.1	Work and Energy. Example.
9200	6.2	Work Done by a Variable Force.
9210	6.3	Work and Energy in Three Dimensions.
9220	6.3	The Dot Product.
9230	6.4	Work and Potential Energy for Systems of Objects.
9240	6.4	Potential Energy and Work Done by a Conservative Force.
9250	6.5	Work, Energy and Equilibrium.
9260	6.6	Conservation of Mechanical Energy.
9270	6.6	Conservation of Mechanical Energy—Examples.
9280	6.7-9	Work-Energy Theorem with Non-conservative Forces.
9290	7.1	Conservation of Momentum.
9300	7.2	Subject or Title Motion of the Center of Mass.
9310	7.3	Conservation of Momentum.
9320	7.4-5	The Center of Mass Reference Frame.
9330	7.6	Collisions in One Dimension.
9340	7.6	Completely Inelastic Collisions.
9350	7.7	Collisions in Three Dimensions.
9360	7.8-9	Impulse and Average Force.
9370	8.1	Rotational Motion.
9380	8.2	Torque.
9390	8.2	A Rotating Pulley—Example.
9400	8.3-4	Rotational Kinetic Energy.
9410	8.5	Angular Momentum.
9420	8.5,8.7	Conservation of Angular Momentum.
9430	8.6	Rolling Objects.
9440	8.8	Precession of A Gyroscope.
9450	8.9, 9.1-5	Static Equilibrium.
9460	10.1	Gravitation.
9470	10.2-3	Newton's Law of Gravity.
9480	10.5	Moon Falling Towards the Earth.
9490	10.6	Gravitational Potential Energy.
9500	10.7,10.4	Gravitational Field of a Spherical Shell.
9510	12.1	Oscillations.
9520	12.2-8	Examples for Simple Harmonic Motion.

The main prerequisite for taking the physics courses with EPGY was having the appropriate mathematical background for the course taken. We did not require that students first complete a conceptual-physics course such as AP Physics B, and in fact only two from Mech93 and five from Mech94 had taken any physics before.

All these students ran the physics course at home on personal computers. They were in contact with Stanford instructors primarily by phone and electronic mail, though monthly review sessions at Stanford were open to them as well.

System requirements

The EPGY courseware consists of a course driver common to all courses, together with course-specific files containing lesson and lecture material. The course driver is necessarily dependent on a particular architecture and operating system. However, the lessons and lectures are machine-independent, and in principle can be used on any machine to which the course-driving system has been ported.

The EPGY course-driving system was developed on IBM RS6000s using the ACPA sound card and the X-Windows display system. During 1991 such a system cost well over $10,000. The course driver was ported to personal computers using MS-Windows in the summer of 1992. At that point personal multimedia computers were available for less than $3000. While we were running on RS6000s, the number of students was limited to the number of computers we could put in schools. After we ported the program to personal computers, we required students to supply their own machines to run the course. However, students participating in EPGY who qualify for financial aid are exempt from this requirement; we supply them with computers belonging to EPGY.

Under the MS-Windows operating system, the following is the minimal configuration necessary to run the course software: a 386-compatible computer with 4 Mbytes of RAM and MS-Windows 3.1; a hard drive with 20 Mbytes of free space and a 1.44-Mbytes floppy drive; a VGA monitor; a 2400-baud modem; and an 8-bit sound card with a compatible CD-ROM drive.

Because we make extensive use of symbolic algebra in processing student input, a computer faster than a 386 is desirable. For some of the problems in the physics course, even a fast 386 can take over 1 min to process a student answer. Certain optional features built into our lecture-delivery system require considerable digital signal processing and do not operate correctly on slower machines. For these reasons we recommend that students who do not have a computer buy at least a 486DX33.

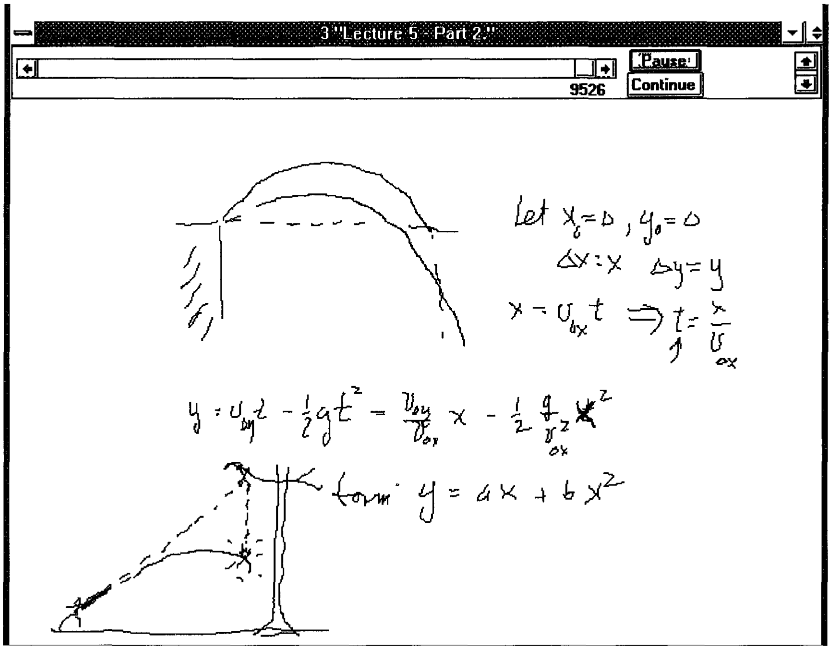

Figure 1. Handwritten blackboard from mechanics lesson 9050 preserves the informality of the classroom.

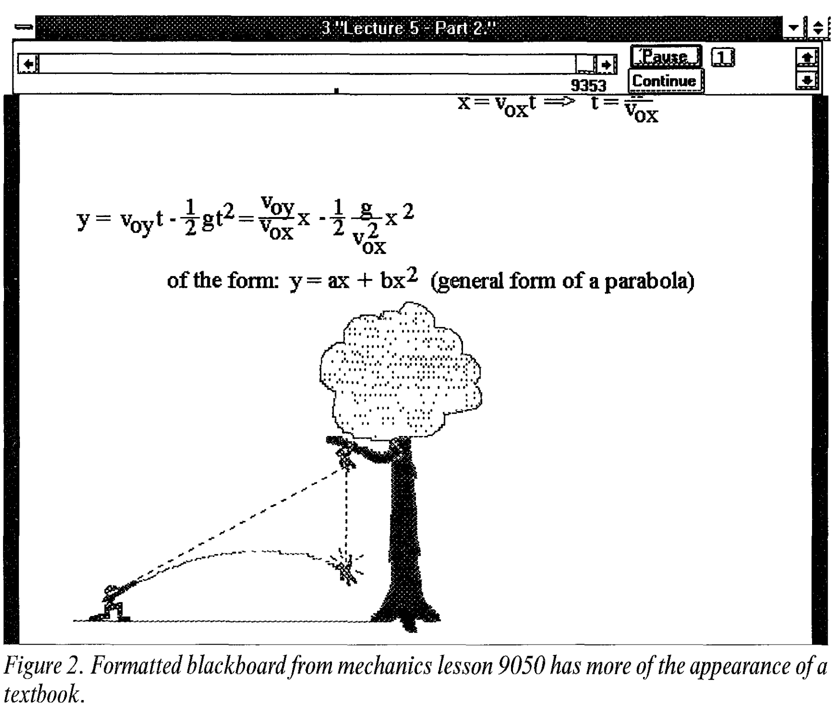

Figure 2. Formatted blackboard from mechanics lesson 9050 has more of the appearance of a textbook.

Course design: lessons and lectures

The EPGY courses are completely computer-based, with the computer delivering the vast majority of the instructional material. Online course components include a complete, interactive, multimedia exposition of the curriculum material involving digitized sound and graphics, an interactive problem-solving environment, mastery quizzes, problem sets, and databases of off-line problems. Additionally, a derivation system using the Maple symbolic computation system is available to students for doing computations. The fundamentals of this derivation system are also used in processing student answers so that a wide variety of equivalent mathematical expressions can all be counted as correct.

Similar to their classroom counterparts, our courses are divided into several lessons, each of which corresponds to a topic in the course being taught. These lessons have been designed to mirror the form of the standard university presentation of the material (see "EPGY lessons in Mechanics," p. 381; a list of the EPGY lessons in electricity and magnetism is available from the authors on request.)

A computer lesson usually begins with a lecture, in which a student listens to digitized sound recordings while graphics tablet-writing (or formatted text and graphics) appears on the computer screen in real time, synchronized to the voice, so that the net effect closely resembles that of a teacher writing on a chalkboard while lecturing. The lectures in our courses have been given by Mason Yearian, a professor in the Stanford University Department of Physics and director of the Hanson Experimental Physics Laboratory. Screen dumps of the two types of lecture are shown in Figs. 1 and 2.

The lectures have been designed to preserve the informal nature of spoken physics as contrasted with the more formal prose style of textbooks. This design is important because—as has been observed by many people, though not rigorously proven—oral lectures are an important part of learning the mathematical and physical sciences. Spoken physics can be more intuitive and flexible than textbook physics, and lecturers can waver in their degree of rigor to suit the point being made. Such lectures give students an opportunity to learn how to talk informally and how to draw diagrams and write physical equations.

We agree with Hestenes and Wells concerning the importance of keeping lectures short.[2] The lectures in the courses described here are broken into segments of not more than 10 min each, after which students are required to do some exercises or to investigate a computer simulation.

We use lectures based on graphics tablet and digitized sound, rather than full-motion video, to reduce the requirement for digital storage space and cut down on production expense. Moreover, the graphic images of handwritten equations and the like are much sharper visually than what can be obtained by ordinary video procedures that include shots of the lecturer and the chalkboard.

The lectures are followed by a set of simple questions that review the students' understanding of the material just presented. After these review questions students work a set of interactive exercises (see Fig. 3). The interactive exercises consist of a quiz on the material covered in the lecture; interactive, step-by-step exposition of a detailed argument; or a derivation in which the student is asked to obtain the answer to an exercise.

The exercises become more difficult as the student progresses into a lesson. Depending on the complexity of the exercises, the student may have to make several intermediary computations. These computations can be done with either paper and pencil or a calculator. Eventually, we hope to offer the use of our Derivation System, a symbolic computation system built on top of Maple.[3,4]

It is important to emphasize that students are not constrained to giving numerical answers. In fact any answer may be accepted that is mathematically equivalent to the one intended by the author. The computer is able to achieve such flexibility by processing the answers symbolically, taking into consideration their mathematical meaning, and thinking of possible correct answers in terms of equivalence classes.

A simple example from algebra shows the natural variety that a student's answer can take. Suppose a student is asked to solve the equation $x^2 + x + 1$ in the complex plane. One may want to accept as correct all the following variants:

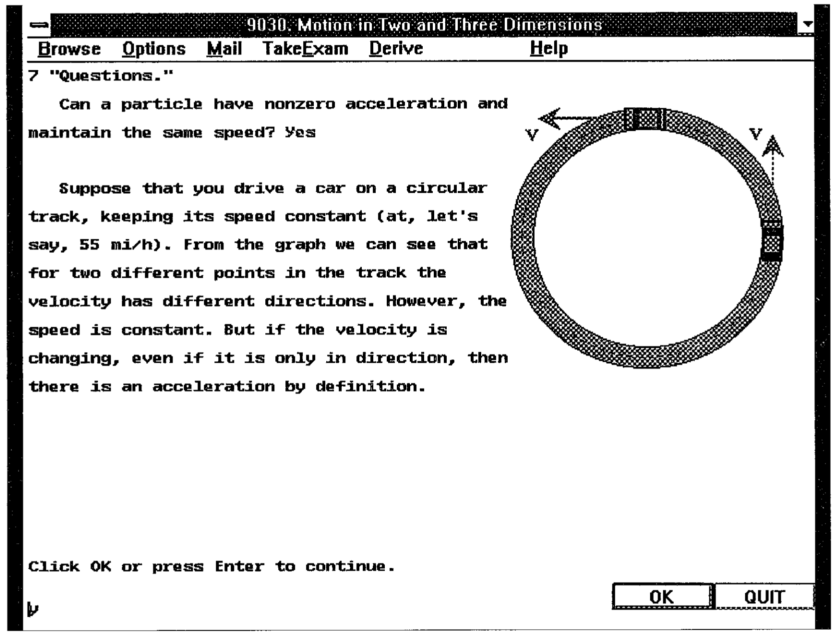

Figure 3. Exercises such as this one from mechanics helps to develop understanding of the lecture material.

$$\frac{-1+i\sqrt{3}}{2} \text{ and } \frac{-1-i\sqrt{3}}{2};\ -\frac{1+i\sqrt{3}}{2} \text{ and } -\frac{1+i\sqrt{3}}{2};$$

$$\frac{-1}{2}+\frac{i\sqrt{3}}{2} \text{ and } \frac{-1}{2}-\frac{i\sqrt{3}}{2};\ \frac{-1}{2}+i\frac{\sqrt{3}}{2} \text{ and } \frac{-1}{2}-i\frac{\sqrt{3}}{2}$$

in addition to several others with essentially the same form, not including variations in spacing. To code each of these pairs of answers for the purposes of simple string comparison would be tiresome and fail to exploit the semantic content of the mathematical expressions. By taking advantage of the fact that the answers are mathematical expressions and by using the symbolic computation program Maple for evaluation and comparison, a great increase in flexibility for both student input and author coding is obtained. Furthermore, by processing the answers with Maple, the computer treats as correct and equivalent expressions such as (3,4), in which a vector is expressed with parentheses, and $3\hat{i} + 4\hat{j}$, in which a vector is expressed in terms of the unit bases.

When students get the correct answer, they receive another exercise or lecture. If the answer is incorrect, they see a short explanation of how to solve the problem, either in the form of a lecture or as text. In some cases, rather than explain the answer to students, the course may reformulate the problem into several simpler intermediate problems and lead students through the solution step by step.

Independently of the above, all answers given, correct or incorrect, are stored on the student's computer for further evaluation by the instructor at a later time.

One lesson generally comprises two to four lecture-exercise units. After students have completed a lesson, they are expected to read their textbooks and do standard problem sets. Students spend on average as much as 75 min doing additional off-line homework—reading and solving exercises in the

Sample EPGY student report

```
Wed Oct 6 16:21:32 PDT 1993
---START 750008964 ---
Thu Oct  7 08:49:24 1993
!REMARKS

from    student-epgy-id        at 9010 / 1 / 1
        ------------------

last typed:
Hello, 9010 is fun.
---START 750283415 ---
Sun Oct 10 13:03:35 1993
!REMARKS

from    student-epgy-id        at 9010 / 1 / 1
        ------------------

last typed:
    Are we allowed to fax homework?

---START 750291196 ---
Sun Oct 10 15:13:16 1993

!HISTORY
 Oct 16 01:33:05, START 9070 0
 Oct 19 08:19:45, PB_TYPED
 Oct 19 08:19:46, CONNECT 4
 Oct 19 08:19:48, CONNECT 1
 Oct 19 08:25:14, CONNECT 8
Oct 19 08:25:14, END
 Oct 19 08:25:14, START 9070 2
 _r 5
 _r 3
 _r 8
 Oct 19 08:25:34, CONNECT 20
Oct 19 08:25:34, END
 Oct 19 08:37:29, START 9070 4
 _r 10
 _r 19
200
 _w 89
```

textbook[5]—for every lesson they complete online. Laboratory work is also required of students. Homework and labs will be discussed in more detail below.

The report facility

Electronic communication between the students and the human instructors plays an important role in the EPGY courses. Every time a student is asked a question, his or her computer records the length of time to answer the question, whether the answer was correct or not, and the correct answer—if the student's response was incorrect. The computer responds with a similar sequence for subsequent askings of the same question. This information is stored in a report file, which students are required to send electronically to Stanford once a week. To send such a report the student simply chooses `Report` from a pull-down menu in the MS-Windows menu bar. Depending on how the student's machine is configured, it will either dial the Stanford computer immediately and transfer this report or it will write it to a file for the student to send as simple electronic mail. Once the report is received by the Stanford computer, the reporting facility processes it. This processing consists of filing the student's responses in the student database and in sending any comments or questions by the student to the Stanford instructor as e-mail.

When the student's computer has dialed into the Stanford computer directly, the reporting process ends by transferring any messages that the student has in his or her mail box to a file on the student's computer. Students can then review their mail after the reporting session has terminated. In this way, the actual phone connect time is kept to a minimum.

The reports supply the course instructors with detailed information about individual student progress (see "Sample EPGY student report," this page). Such information is useful both for purposes of tutorial support and also for detecting problems in the course material.

The first line of the report has the date that the student enrolled in the course. Next come blocks of text that have the header `-----START xxxxxxx-----`. Each of these blocks represents a complete report sent by the student. The number following the word `START` is the date on which the previous report was sent. Following this are two option fields, identified by `!REMARKS` or `!HISTORY`.

Remarks are messages to be sent to the instructor as electronic mail by the reporting facility. One such message starts immediately after the third line and contains the text, `Hello, 9010 is fun.` Note that the message header has the information `at 9010/1/1` indicating that when the student sent this message he or she was at lesson 9010, exercise 1, page 1.

The history field contains information about student usage and performance. Whenever the student gives a correct answer, the computer registers it as `_r`. Every time the student gets a question wrong, the computer registers `_w`. The numbers beside the `_r`'s and `_w`'s are the lengths of time in seconds used by the student to answer the questions. It is pointless to register correct solutions, because the instructor knows what they are. It is very useful to register incorrect solutions. In the sample student report, an incorrect solution of 200 is noted for the third question of exercise 4 in lesson 9070.

The amount of individualized information in the student reports is substantially larger than that usually obtained from a teacher in a conventional classroom. Having these data available enables an EPGY instructor not only to compare the performance of different students but also to pinpoint subjects in which a student is stronger or weaker, so as to take remedial actions if necessary. Another significant use of the data is in making modifications to the course from year to year. By finding questions that most students get wrong, we are able to identify weaknesses in our lectures, which we attempt to remedy when revising the course.

Other asynchronous communication

In addition to being able to ask questions as part of a report, students can ask a question at any point in the course merely by selecting `Comment` from a pull-down menu in the MS-Windows menu bar. Unless the question is urgent, it is not sent immediately, but merely added to the remark field of the report to be sent at a later time. Students can also send standard electronic mail at any time to each other and their instructors. This electronic dialogue brings to computer coursework an analog of traditional class interaction.

Off-line work

Students are required do homework and laboratory experiments in addition to online work. The homework exercises have been taken from the textbook *Physics for Scientists and Engineers* by Paul Tipler.[5] Students are required to write their solutions on paper, the way they would for a standard class, but can evaluate their own performance by viewing instructor-provided solutions online. These solutions are stored in a coded form, and students have access to them only after they have submitted their work. The solutions are often accompanied by lectures that work through the steps of the problem in detail, just as a course assistant would at a review section.

Student experiments have consisted, in the mechanics class, of simulations done using the *Interactive Physics* program and, in the electricity and magnetism class, of hands-on experiments using the text *ZAP! A Hands-on Introduction to Electricity and Magnetism* by Morrison, Morrison, and King,[6] developed by the ZAP! project, a joint effort involving physicists at MIT and CalTech.[7] These experiments and the difficulties we encountered with them will be discussed elsewhere.

Classroom environment

We try to create a classroom environment among the students. We encourage them to work together on problem sets and facilitate this cooperation by making available a DOS BBS, which they use as a forum for discussion. In the laboratory component of the course, we encourage students to work together on weekends in groups of two. We have also configured the reporting system to send automatically, once a week, a progress report on all the other students to every student. These reports promote a sense of friendly competition and help students to find others at knowledge levels similar to their own. The final component is the review section. We will discuss below these review sections and the ways in which we envision replacing them by electronic means.

Results

Results so far have been quite promising. The first group of students, Mech93, scored well and in a pattern similar to that of the first group of calculus students (see table). Of these students, 88% received scores of 4 or 5, as compared with 47% of students nationally. Moreover, the national numbers are for all students, whereas the majority of EPGY students were in 11th grade or below when they took the exams. Of the eight students in the country in grades 9 or below who took the 1993 Physics C: mechanics AP exam, five were from our program.[8]

During the 1993-94 academic year, eight of our students took the Physics C: mechanics exam, and 13 took the electricity and magnetism exam. All these students passed, and over 80% scored 4 or 5. Although the College Board has not yet released its statistics for the 1993-94 academic year, we expect to account for about 15% of the students under grade 11 who took Physics C exams. Given the small number of students in our program, this figure is impressive. In the next five years we expect to account for over half the students taking these examinations while in their first two years of high school.

Table. 1992–93 Physics C: mechanics exam results.

Student	Grade	Sex	Prior Calculus Exam & Score	Physics C Mechanics Score
1	8	M	BC-5	5
2	9	M	BC-5	4
3	9	F	BC-5	5
4	9	M	BC-5	3
5	9	F	AB-5	5
6	10	M	AB-5	5
7	10	M	AB-4	4
8	11	M	AB-4	4
9	11	F	AB-4	4
10	12	F	AB-4	N/A

Towards the future

The main problem we face as our student population increases in size and geographical diversity is that of supplying tutorial support in situations in which the asynchronous, text-only aspect of e-mail inhibits effective communication. For the last two years we have addressed this problem by offering optional discussion sections at Stanford. These sections are given about once every three weeks during the course, increasing to once a week for the three weeks before the AP exam. Attendance at these sections has run at about 50%, with some students attending more frequently than others. Attendance in the final three weeks has run at about 80%, with almost all students showing up at least twice.

Our experience with these discussion sections has demonstrated that software development is an iterative process. One must not think of the first version of the course software as the final product but, rather, must design a working version and see how it does. As weaknesses are isolated, they are addressed in the present at the review sections and in the future by revising or expanding the course software.

This is not to say that we envision the software running without any kind of review sections. However, the review sessions we have in mind for the future will use an important new feature which we have dubbed, in accordance with the trends of the day, "the virtual classroom." We are currently adding this feature to our classes.

Our virtual-classroom software will combine shared-whiteboard capability with voice conferencing. Students and their instructors will use graphics tablets and digitized sound to communicate with each other. Students will hear the voices of their instructor and classmates and see the shared chalkboard. The result will be more dynamic and interactive. This fall we will begin our first experiments with this new feature, using IBM's Person to Person conferencing software.

The virtual classroom will let us transform the review sections into remote interactions. These courses will become truly computer-based and useful to students who live far away from Stanford.

It should be evident that the tutorial role of the computer in EPGY courses is considerably more central than the role technology frequently plays in mathematics or science education. The computer in our program is no mere computational aid, electronic textbook, or drill assistant. Rather, we have sought to exploit the technology as fully as possible to produce stand-alone courses that capture and maintain students' interest while efficiently teaching college-level subject matter. With the addition of the virtual classroom, we hope to make university-level courses in physics widely available to advanced students in secondary school. Finally, because we have put the entirety of the course online, our program makes it possible to offer college-level physics instruction to students in situations in which they usually would be unable to obtain it.

Although the students described in this article all scored in the top 5% on the mathematics portion of the Scholastic Aptitude Test, we believe that our courses are probably suitable for students scoring in the top 20%. This group probably encompasses all students who are ready to take the Physics C courses while still in high school.

We also feel that our instructional model can be adapted to other groups of students. With some success, we have used the same model to teach courses in beginning algebra, intermediate algebra, and precalculus to adult students at community colleges.[9] We have discovered that such students have different needs and require different pedagogical approaches. Ideally one should be able to design a course that has several paths for students of different ability. In such a course the performance of the student would determine the level of the lectures received. In this way the course could adapt itself to fit the needs of the student. The result would be a course that actively engaged students regardless of their ability level. As we revise and improve our existing software, we hope to make progress in this direction.

About the software

Although we do not at present plan to market our software as a stand-alone commercial product, we are happy to make arrangements with individuals or schools to use these materials either as complete instructional packages or as supplements to existing physics courses. For more information, contact the author by e-mail at `ravaglia@epgy.stanford.edu` or by post at the address given below.

A demonstration version of the program is available from the author. For a copy, send $10.00 to Demonstration Program, EPGY Ventura Hall, Stanford CA 94305-4115. The demo is also available via anonymous ftp from `epgy.stanford.edu`, as is additional information about EPGY. The URL for the EPGY Web page is `http://kanpai.stanford.edu/epgy/pamphs/pamph.html`.

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