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A new approach to physics teaching

ARTHUR V. FARMER

Physics teaching has not changed for a century. Yes, new material is included, but the teaching methods remain the same. We teach as we were taught, usually starting with kinematics and then to *But is that the way we learn?* How much does a student retain for later use?

Suppose you were attempting to learn to use new word processing software. The first thing you would do is read rather rapidly through the manual, avoiding details – an “Overview.” Then you might examine it in more detail. Finally, you would try using it to accomplish a task, referring back to the manual when necessary. The order in which you master the material is of no real consequence. This is the way most people would choose to learn in independent study and, therefore, is the way we should teach.

Such considerations have led me to develop a teaching method that I call the “Overview – Case Study Method.” I feel that this method is appropriate to the quantitative physics courses taught in high schools and in colleges.

At the same time, I am convinced that all students should have an exposure to the principles of physics, but in various ways including qualitative physics only. The multilevel approach that I developed and will describe in this article has most of the students in my high school taking physics as an elective. These three levels are not sequential; even the Advanced Placement course is a first course.

The overview used in the AP course

In my high school advanced-placement physics classes, I “overview” all of the physics course in four weeks. The students complete a 500-page qualitative college physics text¹ in this time. (I intend to replace that text with materials that I am now writing as explained later in this article.) Then for the next two weeks I review and introduce the equations of physics. So, in six weeks, the students have been exposed to all the principles twice and have at least seen the equations once.

At this point, I give a qualifying examination to see if any students should drop to a less difficult level.

Roughly 100 students, 30% of the student body at a grade level, are enrolled in this advanced placement level. Only one-fourth of these indicate a desire to pursue technical careers requiring calculus-based physics.

With these statistics, I cannot justify teaching only mechanics, electricity and magnetism as the calculus-based AP Physics C Exam expects. Besides, I believe in a total exposure to physics the first time through. Some of these students will never encounter physics again; they should know that there is more to physics than mechanics and E and M. So I only show calculus examples occasionally and the students take the AP Physics B Exam. Some do special study and take the C Exam as I will mention later.

This total exposure gives the student who encounters physics at the university level a foundation in the content of each of the courses in the physics series. It also duplicates the physics course for those students majoring in the life sciences.



Arthur Farmer was educated at Rensselaer Polytechnic Institute where he also taught while majoring in hypersonic aerodynamics in graduate school. Six years as a research scientist in industry convinced him that he did not want to work during summers. At his teacher wife's urging, he tried high school teaching and has continued for twenty years. In 1982 his program was selected as an exemplar program by the NSTA. In 1983, he was awarded the Presidential Award for Excellence in Science Teaching. (Gunn High School, Palo Alto, California 94306)

(A note on the Advanced Placement Physics Exams. The C Exam comes in two parts: Mechanics with calculus and E and M with calculus. The B Exam covers mechanics, E and M, heat and thermodynamics, waves, light and optics, sound, relativity, and modern physics but does not expect the student to use calculus. In 1984 the same free-response E and M question appeared on both exams indicating that, with the exception of using calculus, the level of difficulty is similar.)

The threat of the upcoming qualifying exam is needed to drive the students through the intense "Overview." As one girl said, "*Why not assign twenty more pages a night and then I can forget all my other courses?*"

Case Studies

Much of the rest of the year is devoted to "Case Studies," named after the problem-solving methods of law schools. These are problems designed to integrate as many principles from different fields as possible. While the students are working on those problems, usually for five to seven days per case, I lecture on the necessary material in more depth and assign supplementary problems. The principles covered by the problems are repeated frequently throughout the course. I feel that this *time-delayed repetition is the best way of learning for retention.*

As an example of a case study, the first one that the students encounter after only six weeks in the course concerns an alpha particle accelerated by an electric field and then passing into a magnetic field. I ask them to determine the energy and momentum of the particle at the end of the electric field. I ask them for the radius of the path in the magnetic field and what could be done to keep the particle moving in a straight path in the magnetic field.

From the overview, they know about alpha particles, momentum, energy, fields, and centripetal acceleration. However, they do not know the details of using these concepts. I hope that after a week they will. This type of problem is given much later in the year in a traditional course.

Another example of a case study is a dc circuit with pivoted parallel resistors in a magnetic field and also in a gravitational field. The current must be found which will provide a magnetic torque which will balance the gravitational torque.

After the qualifying exam, I issue a noncalculus mathematical text² used at Stanford and the University of California. Finally, a month before the Advanced Placement examinations, I issue a 70-page "Study/Review Guide" that I have written.

How well does the technique succeed? If the AAPT High School Physics Test given in May in California at a dozen university test centers is a judge, the answer is very well. The report of test results ranks the top ten percent of students taking the test, presumably the best in the state. Last year, of the top eight students in the state, seven were mine. Three of the last four years, the first student in the state was one of my students. And I have had as many as 26 of the 74 designated winners. Nationally, my students collect as many as eight percent of the fives awarded on the AP Physics B Exam. (I encourage all of my AP students to take the AP exam, about 60 to 70 actually do.)

Gunn High School has a high population of intelligent students, as does its sister high school. However, in a state of 22 million, Palo Alto does not have a monopoly on brains. Nor do we have magnet schools, just comprehensive

public high schools. My five classes range in size from 30 to 40 students.

Some students choose to try the AP Physics C Exam by doing additional work using a supplementary text.³ All six who did so last year received fives on both parts. (Five is a high honors grade.)

Textbooks

Although the noncalculus text we use is very good, most students tend not to read the text. Therein lies the problem with physics texts. They are too long and are designed to introduce the subject as well as present the heart of the material.

In high school teaching, the teacher should introduce the material and the teacher should go over the difficult material before the student uses the text. The text should be concise, emphasize intuitive development, and be designed for study rather than introduction. Physics teachers tend to forget that students have many other courses, all of which give homework and some of which are more interesting to them than physics.

I am writing a text, or program, to satisfy my needs. Fairchild Camera and Instrument Corporation is providing a grant for my half-time release to write this material and to make it available to teachers who would like to give it a try. If you are interested in trying this material, please contact me. I hope Fairchild's lead in supporting and attempting to upgrade education will encourage other industries to do likewise.

I alternate days of writing with days of teaching. My team teacher, Steve Kanim, is an electrical engineer disenchanted with industry. He is becoming an excellent teacher in his first year of teaching. He is as committed to my methods as I am and has contributed case studies. The overview at the beginning of the course helps to maintain continuity in this team-teaching effort.

My material will have an Overview, a User-Friendly Handbook of the principles (developed intuitively where possible) and their applications, case studies, and a Study/Review Guide. Eventually, a computer backup to each unit will provide immediate reinforcement, correct misconceptions, and provide evaluation of student achievement. The Handbook, case studies, and a Study/Review Guide should be finished during the summer of 1985.

I believe in efficiency of education and in teaching for retention. With increased science classroom efficiency, students anticipating science careers will still have time to experience the complete education that our comprehensive education system has to offer. We should not forget that the students have years of college in which to specialize.

The Overview - Case Study method is efficient. By mid-March we have finished the course. This includes relativity, thermodynamics and kinetic theory, heat transfer, fluids, ac circuits, polarized light, modern physics, simple harmonic motion, as well as mechanics, waves, sound, optics, and E and M.

If other teachers find this method as efficient as I think it is, *colleges should upgrade their physics programs* to build on this new high-school foundation. The overview method should be examined and tried in college as well, even in other disciplines. All science and engineering students should have a review of the principles of physics in their senior year to enhance retention of physics principles for future use.

The average student

So far I have been talking about students planning careers in science or at least capable of pursuing careers in science. What about the others? Should they be taught the principles of physics? I think so; let's examine my four reasons.

1. *Their physical survival.* What is more important than teaching students, as an application of Newton's laws, why they should use seat belts in a car? Incidentally, as a partner to the belts, a car should have a front end capable of collapsing two feet to provide sufficient time to survive a 40-mph head-on. Does your car? Or restated, do you apply the laws of physics to your life? I want my students to be able to apply physics to their lives.
They need to know what torques and forces cause a spinal disk to rupture. Or, as an application of heat transfer, how to survive overnight when they are lost while cross-country skiing.
2. *Their economic "on the job" survival.* They should understand the basis of this increasingly technological world even if they do not write the equations that describe it.
3. *Their survival as consumers.* The Jaguar automobile company used to advertise "Seems to defy the laws of physics!" Look in *Road and Track*; the times through the 700-ft slalom should convince you that there is little difference in handling between cars. Higher price tags really just buy better linear accelerations and monograms. Even the full-length mirror is overselling the consumer.
4. *Understanding and using physics principles.* Students should be able to use scaling to enhance cooking and defrosting times. They should know about lasers and holograms. They should have a knowledge about the nature of the universe.

Philosophically agreeing with the need to teach physics to all students presents another problem — How do you do it?

Multilevel physics offerings

High school physics teaching is quite different from college teaching once the physics enrollment exceeds the top few students in the school. The teacher must change hats. For the lower levels, a mathematical problem-solving curriculum is not appropriate. These students will not write physics equations in their lives. (Do you, except on the job?)

At the lower levels, if you attempt to plunge into mathematical physics you will hear the door slam thirty times and you will be without a class. Rightfully so. The same is true if you start the course with kinematics, a boring unit for this level. (To bring relevant applications of kinematics to these students, I discuss their possible defense on traffic tickets they acquire. This was an offshoot of two traffic cases that I won by using kinematics equations. Those were two of the few times that I wrote equations off the job.)

Students who are not technically oriented do not, in general, enjoy math. Many lower ability students hate it and fear it. Too bad, but that may be a result of not adapting math expectations to the abilities of the student. Perhaps less rigor and more real life applications in math class would result in more positive attitudes and produce students who are more willing to use the material in life. We

are in the same danger when we address physics to lower ability kids. If those same students leave physics saying that it was fun, we have succeeded.

At the lower levels, I only involve math when necessary. Those students are required to use math only in laboratory situations where I am constantly available to guide them in its use. Their use of math is usually limited to proportions, inverse-square relationships, definitions of curves such as parabolas, and simple algebra. Graphical vector addition is used with a laboratory on structures. As I gain their confidence, I may begin mentioning advance mathematical concepts such as integration when they are adding areas under curves in the solution to traffic problems. Of course, they do not integrate but they understand the meaning of calculus.

We have three levels of physics at my school: the AP level as described earlier, a middle level taught by a colleague in a traditional mode for students who have moderate math abilities, and a qualitative level for students wanting a knowledge of physics and its applications without the math. About equal numbers of students take each level.

All of these courses are one-year courses and are not sequential, a student takes only one. Students are not laned into the levels; the choice is theirs. However, AP Physics is recommended for students planning scientific or technical careers. *All are physics courses and all cover the same principles in different ways.* They are not physical science courses; chemistry and geology are not included.

Those of you who believe that a physics course must be mathematical, reflect thinking that is either elitist or does not perceive student needs. It is far more important that the students understand the qualitative uses of physics in their lives than that they be able to solve for the acceleration of a rocket. What percentage of your students will solve equations of physics in their careers? One hundred percent of your students should understand the reasons for the use of seatbelts.

I expanded physics enrollments in the high school that I was in from two classes to twelve classes years ago by the multilevel approach. The colleague who joined me now has similar enrollments in a different school. In my current school, *almost 90% of the students take physics as an elective.*

Teaching qualitative physics

Teaching qualitative physics is hard work. The easy way to teach physics, assigning homework problems and going over them the next day, is not available to the teacher of the qualitative level. My classes spend about half of their time in the laboratory. The other half of their time is spent in class discussion/inquiry sessions.

The technique that I have devised to keep this discussion lively and to provide the basis for grading I have named the "Arrow Method." The discussions frequently start with a question that I pose to the class. It will lead to a principle of physics or it will be an application of principles already learned. For instance, the seatbelt application of Newton's law starts with the question "Why wear seatbelts?" It follows a day of developing Newton's second law. If a student contributes in a positive sense to the discussion, that student will receive an "Up Arrow." It is not possible to evaluate their performance with letter grades and still keep the discussion lively. So if their contribution exhibits

thought, using principles of physics and if the applied logic is meaningful, I put an up arrow (a grease pencil slash) on a overlay on the seating chart. The student sees this motion and realizes that he (or she) was rewarded.

Positive performance is reinforced but there is no penalty for trying. If I sense that the contributor is on the right track, I frequently will stop that student and ask another one to continue the first student's train of thought. Thus students must think about their classmates' contributions. Oral questioning of this nature allows me to pursue a student's logic with a series of questions, forcing him to think. This is more meaningful than having him mark a letter on a multiple choice test. It's the same logic that justifies orals for a Ph.D.

Since the arrow system is the major source of their grade outside of the lab and outside of their assignments, they stay alert and try to contribute. Teachers observing this method comment on the almost 100% involvement of my students. Teachers have adopted the "Arrow System" in their classes and have taught it to other teachers. In fact, some use it to reward performance in the laboratory. One gives arrows to a student whose question initiates the discussion.

Shy students must be encouraged in the discussions or else they must be approached individually at the end of the class period. However, *encouraging a student to contribute verbally is good training for life outside of school*. Traditional written exams tend to penalize students who understand physics but cannot express themselves well in writing. That is especially true of students in the lower level — it is one of the reasons that they like oral questioning.

The arrows are transferred to the grade book by student assistants. The results are interpreted at grade time simply as a bar graph of performance based on the number of arrows. My team teacher and I both gave oral semester finals using this system. This was at the students' request. They said that they enjoyed the final. Enjoy a final?

The key to student interest — real-life applications

As you discuss any principle, you will eventually see students' eyes begin to glaze over. When that occurs, I immediately switch to a relevant application. Torque and levers lead to weight lifting, ruptured disks in a back, and sprained ankles. The concept of the inverse-square law is better reinforced by considering radiant heat from bonfires than with gravity. Newton's laws lead past seatbelts to rolling with punches, wearing football or motorcycle helmets, or spongy soles (rather than leather ones) on shoes. Better yet, introduce a principle in response to an application.

I am compiling a list of relevant applications and their brief explanations to include with my materials. However, that list should be available only to the teacher because having the students generate applications is excellent practice for their transferring physics to their outside lives.

As a homework assignment, I ask the students to report in writing on the application in their lives of the principle that we are studying. In particular, I want it to be something like sliding on wet pavement or an experience in the kitchen. *This begins the transfer process between the classroom and the outside world*. Part of this assignment is to draw a sketch of the event. Many students are reluctant to draw. I do not believe that the visualization skills of scientists and engineers are developed in most people. I try

to develop those skills in my students. I use these assignments as the basis of class discussions, usually on Fridays. The grade on this "Friday assignment" plays an important part in the final grade.

Books that can be used with the qualitative course are the one by Giancoli¹ mentioned previously, and the one I have been using by Paul Hewitt.⁴

Student-created laboratory experiments

Traditional class experiments do not embody the essence of experimentation — creating the experiment based on scientific knowledge and proving that the data generated is meaningful. They are very much like cookbook recipes. They are more of a training in the use of instrumentation, which is valid in college but not as valid in high schools where equipment is lacking.

For an excellent discussion of the questionable value of class-associated laboratories, see the article by W. S. Toothacker.⁵

I believe in having the students create some of their own experiments. Thus they experience the realities of experimentation including the lack of equipment, calibration problems, inadvertently changing more than one variable at a time, and frustration when things do not work. (The sometimes chaotic lab that follows has frustrations of its own for the teacher.)

Time constraints limit the number of student-generated experiments that the teacher can require. This is especially true for AP classes where the pressure of the test demands a rapid pace. (This year I am saving AP student-generated experiments for the May-June period after the AP exam.) However, other experiments can be designed to require some student imagination before they can succeed.

My heat transfer unit is an example of the way that qualitative-level students can explore a subject by experiments of their own design:

1. Before discussing heat transfer, I ask them to brainstorm in their lab groups ways to transfer thermal energy from a hot object to a cold one without touching them together.
2. The next day I ask them to examine, on an atomic or molecular basis, the mechanism that is responsible for each of the methods that they have proposed. They should now list their suggestions by categories of mechanisms.
3. Next they examine the variables within each group of mechanisms that would enhance heat transfer or restrict it. They have yet to experiment. Their time has been spent planning before they physically act. I believe in brains before brawn.
4. Selecting two categories, they must now design experiments to see if one or two of the variables act as they predict.
5. Time for physical action — they do it. And I run around like a "chicken with its head cut off" trying to get the equipment that they want. I try to channel "off the track" experiments into more meaningful ones, although I encourage serious efforts that promise to provide an educational experience, even though they may be doomed to failure.
6. The students write a report in a form similar to a scientific publication with an abstract and without a list of apparatus. I want an apparatus and procedure section written in past tense, not one that tells me what to do, as is their tendency.



Are cookbook labs enough?

The heat-transfer experiment requires two weeks to complete. It is an advantage to have sunny afternoons to experiment with radiation.

Shorter experiments

An example of a shorter, but not a cookbook, experiment that requires student imagination to complete is determining the density of objects without direct or displacement measurements of the objects' volumes. I only allow them to immerse the objects in a half-full (so it does not overflow) beaker of water that is on a triple-beam balance. Therefore, they can only make three weight measurements: beaker and water, beaker and water with the submerged object supported by a string, and beaker and water with the object resting on the bottom. The object cannot be weighed alone.

Since this laboratory problem is given after a unit on fluids, I hope that they will recall Archimedes' principle. Newton's third law implies that the buoyancy force upward results in an equal push downward on the scale and the weight of the displaced water is registered. The volume of the displaced water is then found from this. The displaced water's volume is the volume of the object.

Allowing the object to rest on the bottom determines its weight once the weight of the beaker with water is subtracted. Its density is then calculated from its weight and its volume. The measurement of floating objects requires forcible immersion with a device of negligible volume and some additional reasoning. Students must do the above reasoning for themselves. This experiment is given to all

levels. The AP groups manage in a day. With more time, the others also manage it.

As a conclusion to this experiment, I ask the students to explain *how does the scale actually know about the additional force due to buoyancy since it is ignorant of Archimedes' principle and of Newton's third law?* Many students correctly reason that the increase in water height when the object is immersed increases the pressure on the bottom.

One distinct advantage of the qualitative-level course is the freedom to have many laboratories of sufficient duration to develop scientific thought patterns in the students. One should not sell these students short; many exhibit remarkable logic and it is fun to observe their progress in the laboratory. Often they are more creative and more venturesome than the AP students. The most significant difference is the AP student's comfort with the use of mathematics.

Overcoming barriers to physics enrollments

All students need to be able to use the principles of physics — some as engineers, some as mechanics, and some as housewives (or househusbands). *It is our duty to foresee students' needs and to supply the necessary courses, taught in the appropriate ways.* Although college requirements do influence high school classes, those requirements should be delegated to a secondary position in relation to the understanding of physics as applied to life.

High school counselors tend to promote chemistry or advanced biology courses in preference to physics, probably because they do not understand physics and because phys-

ics teachers have kept it in a realm of "only for the best students." Regardless of the cause, counselors often cannot be relied upon to encourage physics enrollments.

To encourage enrollments, I address future students directly by giving brief presentations to other science classes. Chemistry and geology teachers do the same. All science enrollments benefit by this if it is done just prior to enrollment time for the following year's classes. This way students can choose classes based on knowledge of the courses offered.

My brief presentation covers their future needs as I perceive them and describes the differences in the levels. These needs are outlined in the above section entitled "The average student."

Summary

This paper is meant to encourage teachers to examine their teaching methods and purposes.

- The overview – case studies review method is a natural way and a powerful way to teach quantitative physics to students who enjoy mathematics.
- A course designed for the better student should cover all of physics. For this first exposure, the role of calculus should be limited to enrichment. (I intend to include calculus applications with my material eventually.) Forty-four of the eighty questions on the AAPT/NSTA High School Physics Exam are on mechanics and E and M, the remaining questions are devoted to other portions of physics.

- All students deserve to have an exposure to the principles of physics geared to the most probable way that they will use the material and geared to the methods by which they learn. This dictates teaching qualitative physics to many. All principles should be discussed, but laboratories and real-life applications should replace mathematical problem solving for the qualitative level.
- At all levels, especially the lower ones, everyday-life observations and applications of the principles of physics are the key to interesting physics classes.

Obviously there are other ways to teach physics than the ways that I have developed in my twenty years of teaching. A way that is successful for one teacher may not be the best for another teacher. However, we should agree that exposing all students to the principles of physics would increase scientific literacy in our technologically advancing society. This will enable them to deal with the constant changes in their lives due to scientific and technological innovations, make them more intelligent consumers, and make them more aware citizens.

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FRANK VERBRUGGE

Dr. Frank Verbrugge, Director of Computer Services and Professor of Physics at the University of Minnesota, died in Minneapolis on January 15, 1985, at the age of 71.

Professor Verbrugge was a graduate of Calvin College and received his Ph.D. from the University of Missouri in 1942. He served as professor and department chairman at Carleton College before starting his long association with the University of Minnesota in 1956. During the second World War, he worked on radar at MIT.

Frank Verbrugge joined AAPT in 1950 and served as President of the Association in 1962-63. He received a Distinguished Service Citation in 1965.