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A physics lecture for the 21st century

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Abstract

In order to take advantage of new technologies and the results of physics education research, the physics lecture in the new century must evolve from what it has been in the past. A suitable pedagogy must be chosen that focuses on the goals of student learning in physics, namely the active construction of a conceptual framework and the development of accompanying mathematical and problem-solving skills. An example of one attempt to do this is presented, focusing on the topic of oscillatory motion.

With the debate finally over as to the proper starting date of the new millennium, we have now, unquestionably, entered the 21st century. The moment of this occasion has given me pause to think about physics teachers and lecturers, like myself, who were meeting their classes at the turn of the previous century. What do we, today, have in common with them? How have things changed?

I suspect that some of our goals and many of the challenges we face have changed little in the course of a hundred years. Physics is still a very difficult subject, requiring a high degree of mathematical literacy. Students at university find it very challenging, and we get only small numbers of them to choose physics as a major or career. Certainly the 20th century saw discoveries in relativity and quantum theory that challenged the very fabric of physics, requiring new interpretations of old concepts and, eventually, radically different ideas in both physics and philosophy in order to keep pace. The mathematics needed to do today's physics is greatly expanded from what it was 100 years ago. And yet the physics teacher's job, in its essence, has remained the same. In teaching physics, I would propose that the goals are: (1) that the students learn to understand certain concepts about the physical world; (2) that they learn the mathematical skills needed to do quantitative reasoning using these concepts; and (3) that they be able to combine the concepts with the mathematics in the successful solution of problems presented to them. This, I suspect, has changed little since the year 1901.

A hundred years ago, our colleagues delivered their lectures, assigned their students to read the relevant literature, and posed to them questions and problems just as we do today. In those lectures, they probably showed their students how to solve some difficult problems. The lecturers undoubtedly complained to each other from time to time about their students' appalling lack of dedication, lamenting the fact that they clearly had not read the material assigned nor had they understood the lecture, as demonstrated by their poor performance on the exam, which simply required them to apply their knowledge to the solution of a few elementary problems.

Today we have beautifully written and illustrated textbooks on almost every topic in physics, tailored to suit students at different levels of preparation. They come complete with student study guides and computer-based ancillary materials. We have the World Wide Web and fast computers. We have sophisticated laboratory and demonstration equipment, with computerized data

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acquisition and analysis. And yet, the professor's lament to his/her colleagues today would probably echo that of the professor at the turn of the last century. Why so? Do all of these advances in education and the associated technology make no difference to student learning?

They can, and they should. But, alas, they do not always do so. I am convinced that the root of the problem lies in the need to bring the new technologies to bear on the problem of teaching and learning in ways that require us to reinvent the 'lecture' for the new century. In short, we cannot simply put chalk to blackboard and 'tell the story' of physics as our colleagues did a hundred (or even ten) years ago (and, indeed, as some of them still do). Because the most important thing that we have at our disposal today is a body of literature from decades of educational research and more than a decade or so of actual 'physics education research'. And what this research tells us is at least three fundamental things. First, not all students learn at the same rate. Second, not all students learn in the same way [1]. Finally, to really learn, students must actively construct the knowledge themselves [2]. The studies bring these points home very clearly, with sufficiently broad and persuasive statistical evidence to validate my own anecdotal experiences.

Clear articulation of the student-learning goals mentioned previously (i.e. conceptual understanding, mathematical literacy and problem-solving skills), along with the realization that they represent separate acts of learning within a framework of knowledge that must be constructed individually by each student, leads to the conclusion that the traditional physics lecture (even one that includes working example problems) may not be the best way to foster student learning. For these reasons I have done my best to incorporate a variety of teaching and learning strategies into my classes in the hope of more effectively teaching a larger number of students. This has not been done capriciously, or with a disregard for the fundamental objectives of the courses being taught. Rather, I have been very careful not to 'throw the baby out with the bath water.' Nevertheless, in a matter of less than a decade, my own teaching has evolved from a very traditional lecture format (not unlike that of a professor 100 years ago) to one that incorporates 'just-in-time-teaching' via the World Wide Web and active learning techniques including peer instruction and group problem solving. I trust that my teaching of physics will continue to evolve, and that the evolution will continue to be driven by the three student-learning goals mentioned above.

To make all of this concrete, let me present the outline of a few class days from my first-year introductory physics course. The textbook chapter this week is entitled 'Oscillatory Motion', with all of the usual topics including the kinematics and dynamics of a mass on a spring, simple and physical pendulums, and both simple-harmonic and damped motions. The book itself [3] is quite wonderful, with well-written explanations for each topic, presented in a logical and orderly fashion. But, just like the lecturer a hundred years ago, I fear that my students may not have read the relevant section of the book before attending my lecture today on damped and driven oscillations. The solution? I give them each an individualized reading quiz via the World Wide Web, which they can take at any time in the 24 hours preceding my lecture. I use the WebAssign program [4], which allows me to pose multiple-choice, numerical or short essay questions, which come directly out of the reading material for that day. In order to discourage 'collaboration' on the reading quiz, each student sees the questions in a different order, and each gets unique numbers for all numerical questions. Students can access the quiz from any computer connected to the World Wide Web. Today's quiz has five multiple-choice questions. An example is shown in figure 1.

The quiz is due 15 minutes before the lecture, at which time I access WebAssign via my own computer and view the statistics on student responses. All 24 of my students have successfully completed the quiz. On most of the questions,

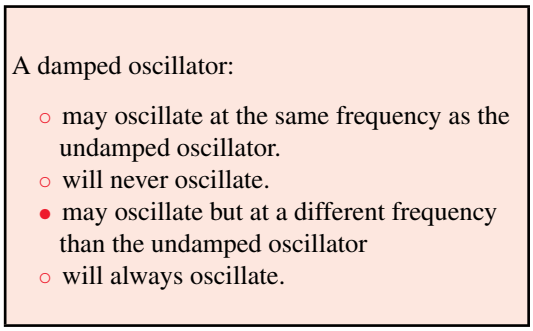

Figure 1. WebAssign Reading Quiz Question.

more than 90% of the class chose the correct answer. But a third of them incorrectly answered the question in figure 1, and they all chose the same incorrect response: 'may oscillate at the same frequency as the undamped oscillator'.

The idea here, of course, is not just to make the students read the textbook before coming to the lecture. It is to allow me to do 'just-in-time teaching' or JITT [5]. That is, by checking student responses and scores on the daily reading quiz before going to class, I can deliver a much more effective lecture, emphasizing those points that caused difficulties on the reading quiz and perhaps leaving out points that were already clear to the students after their reading. JITT makes my lectures much more focused and effective. Today, I will be careful to explain (and to demonstrate, by bringing in an oscillating car on an air track where I can adjust the damping) the fact that the damped oscillator does not have the same frequency as the undamped one!

Another great promise of web technology (and WebAssign in particular) is in the 'Physlets' being developed primarily by Wolfgang Christian at Davidson College [6]. These are scriptable, Java applets that can be attached to any web page, which are as close to 'hands-on' physics (or should I say 'mouse-on') as one can imagine. One creates an interactive simulation of a physical phenomenon with which the students play and interact over the web. They can then be questioned about it, and led to interpret and learn from their experiences. I have been incorporating Physlets into my WebAssign problems, both as prelab exercises and in reading quizzes, for the past two years. Before this week's lab on oscillations, for example, the students encountered the WebAssign question shown in figure 2. The animation (not, alas, visible in the static figure shown here) allowed them to see how a position versus time graph was built up from the actual motion of the oscillator. When, in the actual lab experiment later in the day, they made a damped oscillator from a large pie plate attached to a mass on a spring, and used an ultrasonic motion detector to follow its motion, the computer-generated graph of position versus time was something they understood, conceptually. The lab manual, which all of them were supposed to have read before taking the quiz, told them explicitly how to examine the graph to get the times and amplitudes of successive peak points, and then to fit these data to a decaying exponential function in order to obtain the oscillator decay constant. To my chagrin, reading the short essay responses of the students just prior to the lab class indicated that only about half of them understood this process. As a benefit of JITT, I made sure in my brief lecture at the start of the lab period that they knew how to analyse the data in terms of the theory of damped motion.

So, I have done my best to ensure that students have done the reading preparation for both lecture and lab class and that I understand to some extent what points they did and did not understand from the reading. But I still need to teach! After all, the students eventually need to be able to solve the problems on my test. Of course, before any problems can be solved, the associated concepts must be understood and organized. Again, the traditional physics lecture is often deficient in that the student who simply listens while a lecturer explains concepts and takes notes about what he/she hears may not actively engage the concepts in his/her own mind. The alternative is a classroom practice that requires each student to engage the concepts during the lecture. I have found one such practice in the technique of peer instruction using 'Conceptests'. Dr Eric Mazur of Harvard University has explained these in detail [7].

My implementation of this technique usually involves breaking the material from my daily lecture into three or four blocks, each focused on a particular concept. After my brief explanation or discussion of the concept, I pose a question to the entire class using the overhead projector. The question is of the multiple-choice variety, and both the question and the possible answers are chosen to illustrate the particular concept in focus. The students are asked to think about the question individually for about 1–2 minutes, and to arrive at their own answer. Then, for the next 2–3 minutes, they are asked to discuss (or argue about) their answer with their neighbours in order to arrive at a consensus answer. At the end of this time, the class is polled for their answers, and one or more of them is asked to explain their reasoning in choosing that answer.

Figure 3 shows a Conceptest from yesterday's lecture on oscillations, taken from Mazur's book.

During the peer discussions, the noise level in the room goes up and a lot of teaching and

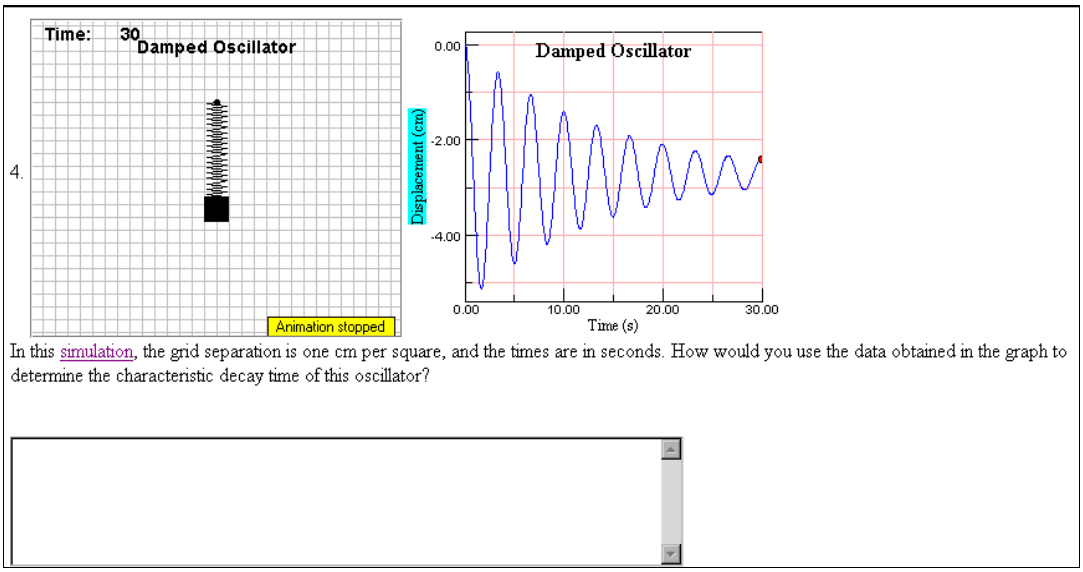

Figure 2. Physlet illustration of damped motion.

learning goes on. No one is allowed to abstain, and the questions are carefully chosen so that (a) they illustrate specific concepts and (b) they are neither too easy nor too difficult. The goal of a good Conceptest is that fewer than half of the students will be sure of the right answer before the peer discussion, but all of them will know and understand it afterwards. By active engagement and by teaching and learning concepts in their own language, conceptual understanding improves dramatically. (Of course, in the event of a failed Conceptest, the instructor must be prepared with a follow-up.) In yesterday's lecture on pendulum oscillations, the Conceptest shown in figure 3 was successful, although perhaps a bit too easy.

A person swings on a swing. When the person sits still, the swing oscillates back and forth at its natural frequency. If, instead, the person stands on the swing, the natural frequency of the swing is

1. greater.
2. the same.
3. smaller.

Figure 3. Conceptest on Pendulum Oscillation [7].

Having made sure that my students have some level of conceptual understanding, I still need to work on their ability to solve problems involving these concepts. I used to work out a few of these in my lecture each day, to show them how I approached the task of problem solving. But students seeing problem solutions presented by an expert problem solver do not, themselves, automatically become expert problem solvers. It may be because they missed any one of the three goals mentioned above that are the foci of learning. Even if they do homework problems involving the same set of concepts, they tend to mimic what they've seen, and often show that they have not understood the concepts well enough to bring them to bear on the solution of the problem. A common difficulty familiar to any physics teacher is the student who believes that problem solving is a 'plug and chug' activity where, once the appropriate equation has been determined, all that is necessary is to plug in the correct values of the known quantities to extract the desired unknown.

What is really needed is an approach to physics teaching and learning that stresses conceptual understanding, teaches the needed mathematical skills, and then requires the student to actually learn how to solve problems as an expert does. An expert begins with concepts (some of which do have associated mathematical equations that express quantitative relationships)

that are organized into a particular framework, and then reasons through to a correct solution. Over the past decade, Kenneth and Patricia Heller at the University of Minnesota have developed a cooperative learning technique in which small groups of physics students (3–4, grouped heterogeneously by ability) learn to become expert problem solvers [8]. The technique involves role-playing and a very methodical approach to a solution using a standard rubric. At the same time, it encourages different groups to come up with unique solutions to the same problem. The problems posed are context-rich, and the level of difficulty is such that even the best student in class would have a difficult time solving one in the 50-minute class period. However, by learning effective techniques of cooperative problem solving (which also illuminate the expert's method) all groups are able to solve the problem in the time allotted. Students find it unnatural at first, but by mid-semester when I hand out a group problem, the noise level in the room rises and stays at quite a pitch for the whole hour. Walking around the room I observe a lot of very effective teaching and learning going on in ways and in words that I could never have imagined. This technique has proven effective for students at all achievement levels, both in the Hellers' research studies and in my own classes.

So, in my final 'lecture' on oscillations tomorrow, I intend to get the students to work on a group problem. I have carefully placed the students into groups of three, placed heterogeneously by ability. That is, I have one high-achieving student teamed with one low-achiever and one from the 'middle of the pack'. I change the groupings every three weeks. Each student plays one of three roles in the solution process: Manager, Recorder or Sceptic. Each is assigned specific duties, and they must produce a solution to the problem in 45 minutes following a five-step method. Roughly, the steps are: (1) focus on the problem; (2) describe the physics; (3) plan the solution; (4) execute the solution; and (5) evaluate the solution. But the five-step method is, in fact, a detailed approach to problem solving in which the minutest details are stated explicitly. My students have studied the method, and know that their grade depends not so much on 'getting the right answer', but on adhering to the steps in the method.

007 to the rescue

James Bond (Agent 007) and his beautiful partner have been captured and rendered unconscious by their evil enemy, Dr Maybe. They awaken and find themselves inside a completely enclosed room, with a highly polished floor 20 feet square, in the centre of which is a wooden platform attached by heavy springs to all four walls. On top of the platform, at its centre, rests a large metallic box. Suddenly, from inside the box, the recorded voice of the evil Dr Maybe begins to speak:

'Good morning, Commander Bond. Welcome to the last chapter of your miserable life! Underneath this box, embedded in a hole in this platform, is a bomb. The detonator is set to trigger in exactly two minutes. However, this metal box weighs two tons, so that neither you nor your pretty friend will be able to push it away to uncover the hole. Have a nice day.'

Jumping up quickly, Bond gets on the wooden platform, and attempts to push the metal box off of the hole. His worst fears are confirmed, however, when he's unable to budge it.

'Curse that static friction,' he mutters, 'it must have a coefficient of at least 0.1.'

Suddenly, he gets an idea. Jumping off the platform, he tries to push the whole platform to the side, but, pushing with all his weight against the heavy springs, he can only move it about 50 cm.

'Oh, James,' says his partner, 'it's no use. We're going to die.'

'Don't be too quick to give in,' he replies. 'If I can drive this platform into oscillation, perhaps I can shake the box loose.'

How big would the oscillation need to be?

Figure 4. Context-rich group problem.

Tomorrow's problem is given in figure 4. This illustrates a number of the features of a good group problem. The 'question' must be gathered from a context-rich situation in which the students must understand the concepts involved.

Not every number needed in the problem solution is given, and there may in fact be numbers given in the problem statement that are irrelevant to its solution. (Problems in real life are often like this!)

In a well-planned solution, a group might first find the spring constant by estimating how much force Bond applies to the platform (how much does 007 weigh?) and applying Hooke's law. Then, assuming the two-ton box to make up the bulk of the system's mass, and converting units correctly, they could find the platform's natural frequency of oscillation. Finally, combining in Newton's second law the force of static friction, the platform's mass and the maximum acceleration of an oscillating system, they could find the amplitude of oscillation needed to dislodge the box. (Of course, Bond always survives. How else could he reappear in another group problem later in the semester?)

After each group attempts to solve the problem, I will analyse their solutions and try to discover if and how they went wrong. I will subsequently have them analyse their own solution for the same reason. Eventually, the goal is that they will all learn to solve problems like experts, never omitting any of the essential steps in the solution method.

So, I suppose my week of lectures about oscillations doesn't look much like a week of lectures on that subject from a century or even a decade ago. And yet, my students learn more effectively than they used to, they are more engaged in the class, and they never fall asleep! They read and utilize the textbook more fully. More of them can answer both conceptual and problem-solving questions correctly on my tests. Come to think of it, I guess I don't have as many complaints about them as I used to. They must be sending me better students. Or, perhaps, I've just come up with a physics lecture better adapted to the 21st century.

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Web resources

- Just-In-Time-Teaching: http://webphysics.iupui.edu/jitt/jitt.html
- WebAssign: http://webassign.net/info
- Physlets: http://webphysics.davidson.edu/Applets/Applets.html
- Peer Instruction and Conceptests: http://galileo.harvard.edu/
- Group Problem Solving: http://www.physics.umn.edu/groups/physed/Research/CGPS/CGPSintro.htm

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