Millikan Lecture 1995: Do they just sit there? Reflections on helping students learn physics[a)]

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I. INTRODUCTION

This occasion has motivated me to reflect on the events and people who have helped make it possible. My real interest in physics began with a summer workshop. Shortly after Sputnik, The National Science Foundation provided grants to bring high school kids to universities for summer programs. I am an alumnus of one of the first of these programs. Later, my undergraduate institution received a grant from the Ford Foundation to encourage careers in college teaching. I was part of that program. So, by the time I was 21, I had become addicted to grant money.

During graduate school I was fortunate to have two thesis advisers—Manoj Banerjee and Carl Levinson—who always insisted that I explain the physics behind all of the wonderful equations that I was deriving. They would never use the phrase "conceptual understanding" but they taught me much about what it meant.

In 1972 the Physics Department at Kansas State University decided to hire someone who specialized in physics education. At that time no Ph.D. programs existed, so they hired someone with no formal qualifications for the position. Since then, the Department and particularly the Department heads—Chuck Hathaway, Chander Bhalla, and Jim Legg—have provided an environment in which I could grow. Even before I officially started the job at KSU, I attended another NSF-supported summer workshop where I met Bob Fuller. Life has never been the same. If I were to continue to list everyone who has been an influence on my career, we would still be here on Friday. Actually, only I would still be here.

However, I wish to mention one person of whom most of you have not heard—John Giese. Early in my career John entered Kansas State as an undergraduate physics major and served as a lab instructor under my direction. After completing a Ph.D. and a couple of post-docs, John returned to KSU as an Assistant Professor and a year ago was promoted to Associate Professor. Because he had been both a student and a faculty member in our Department, John provided us with a unique perspective on our teaching. He also taught us much about facing adversity because he daily dealt with a very big adversary—cystic fibrosis. As John's career progressed, his interest in teaching and learning grew. If John's health had not failed, this meeting would probably have been his first AAPT meeting. Unfortunately, on 23 July, John lost his lifelong struggle with cystic fibrosis.

I mention John here today because I believe that many other young faculty members similar to him exist. They have active research programs, are working toward tenure or have recently received it, and are very concerned about the education of physics students. They know something is wrong, but they may not know what and may be unaware of the research and development concerning physics learning. John found some support for his educational activities in our department; many others do not. A reasonable goal for this Association is to find ways to provide that support. Such an effort is a tough job, but if we are truly serious about changing the way physics is taught, we need to begin now.

Finally, my family has provided endless support and inspiration. As a child, my daughter, Kim, was always asking questions and never rested until she had an answer which she understood. My son, Kevin, attended his first AAPT meeting at the age of 6 months and presented his first paper when he was 15. He now represents our group in a variety of ways from building interactive World Wide Web pages to appearing on the cover of *Physics Today*.[1] My wife, Jackie Spears, has had such a profound influence on both my personal and professional life that I cannot imagine where I would be today without her. Almost certainly, I would not be standing here.

To begin, what I would like to do is tell you about the origin of the title for this talk. It comes from long ago when my daughter, Kim, was about 8 years old. At that time Kim liked to visit the University, walk around, and see what was happening. One day we were walking down a hallway, and Kim was looking in the rooms as a young, rather inquisitive girl does. She saw a scene which for her was very unusual—over a hundred students sitting in a room and watching one person talk (Fig. 1). A short conversation occurred at that time. She asked me the rather obvious question, "What are all those people doing?" I came up with what I thought was an excellent answer: "They're learning physics." Her response was: "Do they just sit there?" Thinking about how people might learn physics was rather new to me, but I realized immediately that this question was profound. At the age of 8 or 9 she knew that just sitting there was not the way that people learned—it certainly was not the way that she learned. That question has stuck in my mind; it is one that I think about frequently.

II. HAVE WE CHANGED?

Kim posed her question about 20 years ago. So, I thought that the occasion of this presentation is an opportunity to ask, "Do they *still* just sit there?" I asked this question in a somewhat altered version via Internet and of people attending the 1995 Summer AAPT Meeting. Basically, the question asked respondents to comment about how their teaching of physics has changed over the years. I asked:

> What has been the most significant change in your teaching?
> Did technology play any role in that?
> What changes might occur in the future?

The responses to these queries contained some surprises—at least they were surprises to me. The biggest surprise was that a large fraction of people talked about changing from the teacher-centered environment to a student-centered environment. Over two-thirds of those who answered the first question mentioned this type of change. Many people actually used words like "teacher-centered" and "student-centered." Others did not, but the implication

Fig. 1. A scene similar to the one which inspired the title of this paper.

was there. From these results I would conclude that listening to students and trying to understand them and their points of view has become a much greater part of physics teaching than it was 15 years ago.

Two of the anonymous respondents to my survey summarized the responses well

> "Originally I knew what was correct and told the students so that they would change their ideas."
>
> "It has taken me a long time to understand that most students are not like me and that they all have something to contribute."

III. MODELS OF INSTRUCTION

To consider and understand the change from teacher-centered to student-centered activities, I find models of instruction useful. The most common model in physics teaching seems to incorporate the lecture, laboratory, and recitation although frequently lab and recitation components are minimal. Models in physics and models of instruction should have some sort of theoretical base. I have always had difficulty finding a theoretical base for the lecture. However, recently I was reading a new book by Diana Laurilard,[2] and she finally gave me the theoretical base for the lecture: "[Imparting knowledge] is done through lecture and all college faculty can talk."

The lecture model does not lend itself to student-centered activities, but most others do. The Learning Cycle,[3] developed originally as part of the Science Curriculum Improvement Study (SCIS),[4] has been used at all levels of science teaching—from elementary school to university. Recently, Hestenes and his group[5] have modified the Learning Cycle to create the Modeling Cycle which I find quite intriguing. Van Heuvelen's *Overview, Case Study Physics*,[6] is based on physics education research and adapts well to large introductory classes. Many other similar models exist.[7] *Workshop Physics*[8] and *Studio Physics*,[9] for example, are based on other similar models. All of the models provide a framework for understanding how students think and learn.

Except for the standard lecture/lab/recitation model, all of these models have some common goals. The development of conceptual understanding is an important component. A goal is to have students describe and explain physics in words, not just solve numerical problems. Another goal which is found in most models is to assist the students' general intellectual development, as well as improve their knowledge of physics. These goals are generally reached through student-centered activities. That is, the student rather than the teacher becomes the center of the learning process.

The models establish a teaching/learning format which is frequently based on concepts related to intellectual development. A common component is exploration activities in which the students perform activities such as laboratory experiments before a new concept is introduced. Explorations as part of physics learning are not new. In preparing for this talk I consulted a book closely related to the Millikan Medal—Millikan and Gale's *Practical Physics*.[10] I have the second edition printed originally in 1920. Every chapter of this book begins with an experiment. The chapter opening is not just a description of an experiment but instructions that indicate the student is expected to do it. For example, the chapter on induced currents starts with "Let 400 or 500 turns of #22 copper wire... ." Clearly, Millikan and Gale expected the student to do the experiment. They present all the details. In 1920 an experiment preceded "the lecture." Today, most models of instruction encourage what Millikan and Gale did before such models existed—introduce a new idea with a student activity.

Another critical (and common) component is an application activity. Students immediately apply a newly learned concept in a laboratory setting. They do not just work problems at the end of the chapter, they use experiments to help them learn.

With these ideas about learning in mind, I will present to you a problem that I faced several years ago. I had a large class, over 100 students. I did have some assistance ranging from undergraduates, who sometimes did not know any physics and did only clerical work, to first year graduate students who knew some physics but only knew the lecture way of learning because that was the only one they had seen. The assistants were available about 12 h a week. It was not enough help to break the class into several smaller classes. (I was working with elementary education majors but the same situation could hold for any introductory physics class.) I wanted the course to be student-centered, so the question was: How could I create a student-centered environment with these limitations?

IV. LEARNING CYCLES IN LARGE ENROLLMENT CLASSES

Many possibilities have been tried: Homework on the Internet, interactive demonstrations and videos, discussions among students, using more technology, and desktop experiments[11] are just a few possibilities.

All of these ideas are very useful, but I began from a different approach. Instead of beginning with teaching strategies I began with a model of instruction—the Learning Cycle. The idea was to provide some way for the students to perform Learning Cycles within a large class setting.

My students start each cycle with a "self-paced" exploration. Self-paced is in quotes because they schedule their own time to complete the exploration, but, if they do not turn it in before class starts, they do not receive credit for it. They go into a room which has a number of experiments—very similar to desktop experiments except in a laboratory environment. We work on a Monday/Wednesday/Friday schedule so the explorations are available after class on Monday and must be completed before class on Wednesday. Then, the whole group meets in the class on Wednesday. We introduce a new concept, but we always start with "Well, tell me what you learned?" What did you observe from the exploration?"

Because they have all had the same experiences before class, they discuss the activities even though we are meeting in a room that holds 100 people. After the discussion and the introduction of new concepts, we move on to a self-paced application which is due by class on Friday. This application is graded more carefully than the exploration in that we look at how they apply the concepts introduced on Wednesday. The grade provides feedback on how well they are applying the concept that they just learned. On Friday, we come back together as a large class. This class always starts with questions about the application. The standard "Do you have any questions?" almost never stimulates a question. So I prepare more specific questions by watching the students complete the application. By seeing what is causing them difficulty, I compose questions that I can ask if nobody else has one. When we have completed the discussion of the application, we summarize the week and start the next cycle.[12,13]

This scheme is not as good as a real Learning Cycle with 30 or fewer students, but it is much better than standing and talking to the students. I have used this approach for 17 or 18 years. My colleagues say "How can you teach the same class that many times?" Well, when you listen to the students and respond to their needs, it is not the same class; it is never the same as the previous year. Somebody always comes up with a different idea or approach that teaches me something new and takes the class in a direction that it has not gone before.

V. HOW TECHNOLOGY HELPS

Technology has been mentioned above. I did gather information about technology from the surveys. Some items that were specifically mentioned in the responses included:

> "Computers are used in the lab, particularly MBL."
> "Videos in both demos and lab."
> "Increasing the communications with students through Internet."

An interesting feature of my nonscientific survey is that many people who are using technology also mentioned changing to student-centered activities. That comment led me to question if the application of technology is leading to a more student-centered classroom or does the desire for a student-centered environment lead us to use more technology?

A good response to this question was given by Paul Walker.[14] Having technology in and of itself is so ridiculous that it has to lead to student-centered classes. You have to do something valuable with the technology.

Clearly, student-centered classes can exist without technology, and technology can be used in a teacher-centered environment. However, technology can be most valuable when it helps us move toward student-centered learning. First, many concrete examples that could not be investigated otherwise can be completed with various types of technology. Technology does not eliminate the need for desktop experiments or experiments with marbles and all the other wonderful inexpensive (and sometimes expensive) equipment. However, the technology expands our possibilities by eliminating some of the drudgery. With spreadsheets and other tools, we can concentrate on physics instead of number crunching. Technology can help create classes which are more student-centered by enabling us to introduce more complex situations. We can introduce friction because we can deal with it using microcomputer-based labs or measurements from video. These realistic events are closer to the students' experiences than those frictionless planes that *we* all know and love so well. Thus we can focus on students' views of the world, not the physicists' idealization of those views.

In addition, information technologies can provide learning paths which can be different for each individual student. When a large quantity of learning material is available, the selections which one student uses for learning physics could be quite different from all of his/her colleagues. Each can find in the collection of information a match with his/her own needs, styles, and background. For this individualized learning to become a reality, we need a technology which provides the ability for searching and organizing large amounts of information. Here, we expect the *Physics InfoMall*[15] to be a real help. With megabytes of information including 19 textbooks and thousands of articles from which to select, students can find something that matches their needs. They can create their own paths for learning concepts from each exploration through each application.

This approach, however, has a trap in it. The hard question is: Can we expect students who clearly are not very aware of their own learning styles to develop, from a vast amount of information and resources, their own learning paths? At present the answer is probably "No." However, with the vast amounts of information available on CD-ROM and the World Wide Web, our students' future success will be coupled to learning how to sort through information and create such paths. Part of our job as teachers will become teaching students how to work with vast amounts of information, just as our job now includes helping students' intellectual development.

VI. VIDEO IN STUDENT-CENTERED TEACHING

Prior to the 1980s video was a very passive medium. The viewer could only control the channel selector and on–off switch. The videodisc, which gave the student control over video, provided interactivity and a means to create student-centered learning materials. Videodiscs enable us to provide students with experiments that cannot be done in the lab and experiments that require specialized equipment. However, videodisc production requires a professional video studio. Thus the students cannot create their own videodiscs. One problem with professionally produced videodiscs is that anything can be done with video. When students watch a physical phenomenon, they do not know if it is real or a special effect. They do not know that physicists do not have the same budget that George Lucas has to make the films. Thus videodiscs or videotapes can leave a credibility gap.

This situation changes with student-captured digital video. With the multimedia computer students may capture video to a disk. This video can be analyzed and provide numerical data. By collecting data from their own scenes, students can gain insight into the physics related to a wide variety of events.[16]

A part of the process of physics that can be taught with digital video is modeling. Much of physics research is about modeling nature. Yet, in most physics courses we never use that word explicitly. When we do, we are teaching only the quantitative aspects. Yet, physicists develop intuition and qualitative models. Using video, we can give students this qualitative experience and help them see how physicists use modeling.[17]

Fig. 2. A high jumper in motion (photograph provided by the KSU Department of Intercollegiate Athletics).

As an example, consider a video scene of a high jump which is taken from the *Physics of Sports* videodisc[18] (Fig. 2). The question that we pose to students is: Why does she jump in the way that she does? She is given a bar to jump over; why doesn't she just hop over it? If the students treat her as a point mass at her hip, they will never understand it. Instead, they must build a qualitative model of the high jumper and treat her as an extended object, as in Fig. 3 Then, they learn that her center of mass does not quite go over the bar. By drawing the stick figure model on top of the video image, students develop an understanding of what a model is, the value of such models, and their limitations. This procedure can be a step in the process of moving from concrete video images to abstract and idealized models.

Several groups have now developed and published similar programs for analysis of video.[19–23] Each of these programs has similar capabilities, but each also has some unique features. They are particularly valuable if the students use them to analyze video that they have recorded themselves.

One can complete this analysis without a multimedia computer. The low-cost approach requires a blank transparency, a videodisc or videotape player with single-frame display, and a marking pen. Then, the students may write on the transparency which is attached to the video screen. In this way, they can collect data or build models using low technology. (This approach was inspired by a TV program called *Winky Dink and You* that I watched on Saturday mornings when I was a young kid. Winky Dink asked kids to write on a transparency on the screen and help him/her out of various jams. So, when your kids are watching the Mutant Ninja Power Morph Simpsons on Saturday morning, they may be getting inspirations for teaching future physics classes.)

Fig. 3. Using stick figures students can build a simplified, qualitative model of the high jumper and collect quantitative data. The number represents the fraction of body mass in each segment.

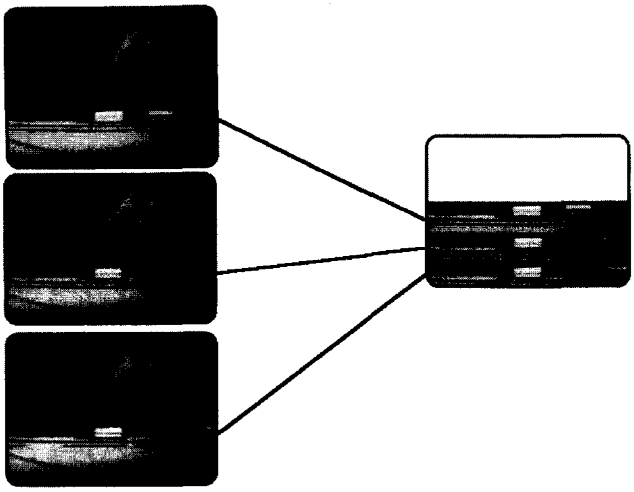

Fig. 4. A visual space-time diagram is built by combining parts of consecutive frames in a video.

Synthetic Video Processing is a weird phrase that recognizes that digital video is just bits and bytes. Thus any computer can modify it in ways that cannot be done with the analog formats. One change is to play a scene from a reference frame which is different from the original. Another is to combine parts of different video frames into one picture. Again, these approaches can help students start visualizing some of the complex concepts of physics. The video helps the transition from concrete objects to abstract concepts.

For example, we developed a digital video technique called Visual Space-Time diagrams. It came about because I was teaching special relativity from a graphical point of view.[24] Students were having trouble with the concept of a space-time diagram. So we developed a method of constructing space-time diagrams from a video scene.[25]

These diagrams are created as the students are viewing the scene. The basic concept is shown in Fig. 4 In a simple event, such as a one-dimensional collision, most of the video image is uninteresting. Only the center strip has useful information. So, our program takes this strip from every video frame and puts it near the bottom of the screen. Each frame is stacked on top of the previous one. Figure 5 shows the result of this "stacking." The resulting space-time diagram is composed of parts of real images.

Once we have created this diagram, we can play back the video in different reference frames. This approach focuses on student understanding and student manipulation of video images to help them understand abstract ideas. We can concretely answer the question, "How would the event look if I were in the reference frame of one of these carts?"

We combine the Visual Space-Time analysis with the other analyses of video images and a miniature video camera.[26] The students actually put cameras in the other reference

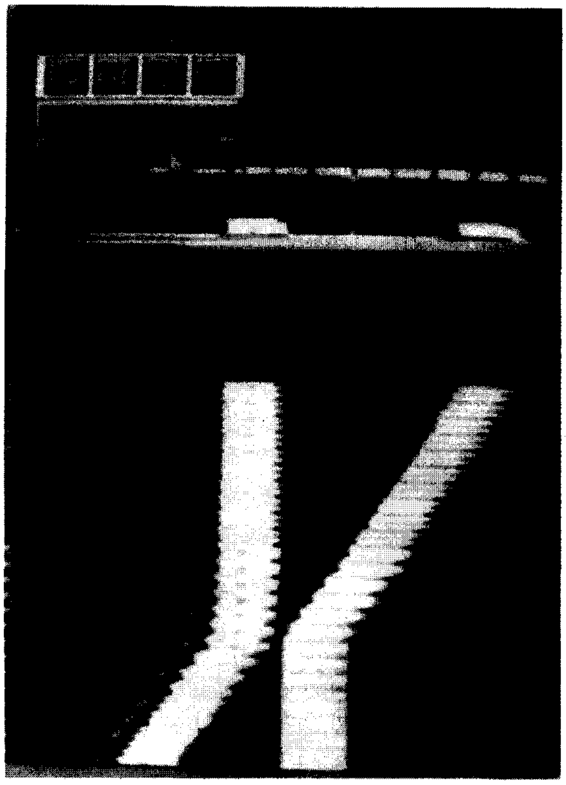

Fig. 5. A visual space-time diagram of an elastic collision as seen in the lab reference frame.

frames. By analyzing the video from the different reference frames they can see which quantities change and which do not. Then they synthetically go into reference frames, such as the center of mass, which are difficult to visualize or to put a camera in. This combination of several different approaches using video enables students to relate concrete experiences to physics. Perhaps, most importantly, we find that students, even those with no previous computer experience, can complete this analysis easily and enjoy it.[27]

VII. FUTURE DIRECTIONS

I also asked about the future. Student-centered learning was mentioned many times. "I would like to be totally in the background—never lecture again," expressed a point of view which was repeated many times. Greater use of technology was another theme. (I think that included the person who wanted to replace his dean with a computer.) Attracting physics students with diverse backgrounds was also mentioned. Finally, a few people believed that teaching more 20th Century physics, particularly in introductory courses, was in the near future.

These last items represent a direction in which I am moving. We understand students' learning somewhat, and we would like to increase the understanding about quantum mechanics, particularly among groups of students who have traditionally not found physics interesting. To reach this goal, we have started Visual Quantum Mechanics. We will bring to this project conceptual learning, hands-on activities, visualization with computers, and connections between classical wave motion and quantum physics.

We also want to bring in some nontraditional sources where some of the quantum physics has appeared. Kenneth Snelson, well-known sculptor, has developed a series of art works on the atom. A booklet which accompanied the exhibit describes his model of the atom.[28] His model is not quite the physicist's model of the atom, but it is an interesting one. We would like to look at his model using some of Minstrell's facets[29] and see how it compares to student models. *Hapgood*[30] by Tom Stoppard is about spies and how spies are like wave-particle duality. These types of materials might interest some groups of students, particularly those groups who are underrepresented in physics classes.

We have just started this effort. We have been told by some of our colleagues that it can not be done, and we really should not be trying. Arnold Arons has discussed whether we ought to be trying at all.[31] While we cannot state now exactly how the final Visual Quantum Mechanics materials will look, we do know that when students use our materials, *they will not just sit there.*

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PUPIL AND TEACHER

We meet this morning for the first time in the interesting relation of Pupil and teacher.

> We are as it were about to start on a long tour of exploration of the wonders of Physical external nature and I am to be the guide.

We have both duties to perform. On my part I would prove negligent to my trust were I not to exert all my faculties in endeavoring to arouse you to a sense of the importance of knowledge and to a diligent use of all the means put at your disposal for attaining it.

> I shall endeavour to impart my instruction in the simplest manner possible without any regard to myself.
> I shall endeavour to avoid startling you with paradoxes or attempting to recommend my subject by well turned periods. I shall endeavour to present to you truth in its *simplicity* which like beauty needs not the foregn aid of ornament.
> I shall endeavour to teach you what I conceive to be the proper method of your future study.

To *indeavour* to give you a clear idea of the difference between knowledge and wisdom.

> A man may be able to speak 50 languages and at the same time be unable to utter a wise remark of his own in any of these languages.

Or he may be a walking encyclopedia of facts and the knowledge which he possesses might almost as well for any good it does him or anybody else have remain on the shelves of his book case instead of being transfered to his head.

Joseph Henry, "Introductory Remarks for Natural Philosophy Course," (1846) in *The Papers of Joseph Henry*, edited by Marc Rothenberg (Smithsonian Institution Press, Washington, 1992), Vol. 6, pp. 426–427.

THE FIRST HOUR OF DAY ONE

All that we have learned about the quantum principle suggests that *it* is the primary principle. God created it, if one speaks jokingly, on day one, and geometry and everything else came out on day two. But in the first hour of day one, how did even the quantum principle come to be created, and does that go back in some strange sense to logic?

John Archibald Wheeler, in *A Question of Physics: Conversations in Physics and Biology*, conducted by Paul Buckley and F. David Peat (Routledge and Kegan Paul, London, 1979), p. 60.