Millikan Lecture 2009: Physics for all: From special needs to Olympiads

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Can “all” students learn “real” physics? Physics First and Physics for All have become a success story for thousands of students in urban, suburban, and rural districts. At the same time, the International Physics Olympiad and other competitions have raised the expectation of what the most motivated students can achieve. Many physics educators are exploring ways to set higher goals for our most gifted students while also providing physics instruction to students previously excluded from our physics classes. Great novels and symphonies are accessible to people of different backgrounds and levels of expertise. We should develop teaching strategies that enable us to share an understanding of physics with all students because everyone deserves an opportunity to reflect on the wondrous workings of our universe.
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I. INTRODUCTION

Four hundred years after Galileo helped us find our place in the universe by pointing his telescope to the heavens, the physics community has lost its way. Galileo faced his trial for writing about the Copernican view that the Earth moved about the Sun. Was Galileo found guilty and placed under house arrest because he believed in a heliocentric view? Was it because he mocked the Church in his writings? Or was it because he tried to convince the Church that he was not trying to defend the heliocentric view? Although all of these actions probably contributed to his arrest, a passage from the transcripts of Galileo’s trials suggests that these transgressions were exacerbated because he wrote in Italian (the language of the people) rather than Latin (the language of the scholars). Evidence for this is found in transcripts from the trials: “But this is so far from Galileo’s preference that he tries to strengthen the Copernican opinion with new arguments of which foreigners would never think in this connection; and he writes in Italian, certainly not to extend the hand to foreigners or other learned men, but rather to entice to that view common people in whom errors very easily take root.”[1]

Galileo found himself in trouble in part because he wrote in Italian rather than limiting his audience to the educated elite. Today’s physics community insists on unnecessary math prerequisites and delivers instruction in such a way as to make physics accessible to the few. We have closed the classroom doors to too many students and kept our physics knowledge hidden from the public. While Galileo tried to broaden the audience of physics knowledge, our physics community has narrowed it. Let’s complete what Galileo started and bring physics to all.

II. PHYSICS FOR ALL

Physics for All is a new rallying cry in the United States. Although it usually implies physics for all in high schools, there is no reason why the message isn’t equally as important for earlier grades and for colleges and universities. The National Science Education Standards proclaimed that science instruction should provide access to all students.[2] As Executive Director of the American Association of Physics Teachers (AAPT), Bernard V. Khoury devoted a number of editorials to supporting Physics for All and AAPT’s Physics First position statement suggests that one of AAPT’s goals is to provide physics instruction to all students.[3]

As strong proponents of science education, most physicists would nod approvingly and support the general notion of “physics for all.” But, to many physicists “all” describes only those students who have the math background and reading and study skills to be successful in our traditional introductory physics classes. With that proviso, we have been successful. In the past the physics community has been pleased when the percentage of high school students enrolled in a physics class is greater than 20% and disappointed when the enrollment dips below. In the past few years we have every right to be pleased to see that the number enrolled has been approaching 30%. But 70% of students are still not exposed to the wondrous workings of our universe. We should not be content with 30% when 100% is within our reach.

The Physics for All banner that I march behind includes all students. It includes women and humanities majors. It includes those with poor math skills, those who have reading problems, and those who have learning disabilities. It includes those with ADHD and those for whom English is a second language. It includes those who have behavioral problems in school and those that have poor attendance. It includes those who do not plan on attending college as well as those high achieving students whom we usually include in physics instruction. Physics for All should include all of the disaggregated subgroups in the No Child Left Behind legislation[4]—minority students, ESL students, special needs students, and low income students. It includes every student who has been previously excluded from a physics classroom.

The people we target with Physics for All should be the same people we target with “freedom for all.” Just like the American definition of freedom for all has slowly evolved to include nonwhites, women, and the poor, the physics community’s definition of physics for all needs to include more than the limited group of white mathematically inclined men whom we have taught traditionally. Equal access to physics courses is one more step toward equal opportunities for all.

III. CAN ALL STUDENTS LEARN "REAL" PHYSICS?

One of the greater challenges associated with teaching Physics for All is that we have traditionally only taught physics to people with strong backgrounds in mathematics. Although mathematics is not included in the definition of physics, "the branch of natural science that treats those phenomena of material objects included in the subjects of mechanics, properties of matter, heat, sound, light, electricity and magnetism, and molecular and atomic processes,"[5] many physicists and physics teachers *a priori* decide that real physics requires extensive mathematics. We heard much about the importance of mathematics in introductory physics classes in the 1970s as some physics educators tried to thwart the introduction of Conceptual Physics and Physics for Poets.[6]

If we agree that real physics requires mathematics, we have to wonder which math is required to provide credibility? Is it vector cross products? Is it tensors? Or is it group theory? When the argument is made that real physics requires a certain minimum of mathematics, then what happens is that all courses can be shown to fall short. Some high school teachers will proudly declare that they teach real physics because they include the concept of torque and the use of vector cross products in their classroom. Other teachers may demand tensors or group theory, thereby excluding all high school courses from their definition. Few, if any, introductory college courses meet this requirement. As we move to higher level courses, an extension of this argument will eliminate most physics offerings from the definition of real physics.

The purpose of using a math requirement to define physics and to denigrate any course that does not meet the math requirement is to insist on a certain rigor, but it limits the population of students who can learn some physics. The analogous use of criteria to define what is and what is not real baseball or real cello playing and to deny individuals access to sports or music instruction would appear foolish at best. Can anyone seriously consider a movement by major league baseball players to outlaw Little League because real baseball players throw 90 mph pitches while Little League players can only throw 50 mph? What would be the reaction if we forbade 12 year olds the opportunity to practice the cello because they do not sound like Yo-Yo Ma? We recognize that all people can gain an appreciation of sports and music and enjoy participating even though only a small percentage will become professionals. We should offer physics instruction to these same individuals.

IV. USING INQUIRY TO TEACH PHYSICS FOR ALL

Once we agree to teach physics for all, we have to create classroom lessons that can both interest and challenge all students, including students with poor math skills as well as high math achievers. We should not be satisfied with inviting all students into a traditional physics classroom but should try to help all students with exemplary inquiry-based lessons that apply the knowledge we have acquired from research on how people learn.[7]

Consider, for example, the pendulum that is a mainstay of many physics laboratories. In many of these courses the laboratory is performed as a verification exercise of conclusions stated in the text and/or by the teacher. In the text, the students learn that a simple pendulum's period depends on its length and is independent of its mass and angle (for small angles). The students are provided with a data chart and told to record values for the length and period and to draw a graph to verify that the period is proportional to the square root of the length. In some laboratories the students are told which lengths to use (for example, 10, 20, and 30 cm). The teacher, in trying to help the students capture a range of lengths, implies that only these lengths will work well and few students will try 27 cm or any other intermediate value. Occasionally, a follow-up laboratory is performed to show that the period of a simple pendulum is independent of the mass. The student technicians have followed instruction, produced good results, and improved their graphing skills in what is often referred to as a "cookbook lab."

To the student in a traditional pendulum laboratory, a physics experiment is reduced to a succession of steps to be followed. Without the hint of inquiry, many of the goals we have for laboratories are not met.[8] In addition, the instruction has avoided any of the wide range of pendulum applications that could capture their imaginations.

There are a number of alternatives for the introductory pendulum laboratory that support inquiry and help students understand both the process and content of physics. In the Ref. 9 Bruce Alberts describes a pendulum investigation that begins with the teacher giving each student a pendulum. As the teacher counts 20 s out loud, the students measure the total number of swings of their individual pendula. One student reports out that her pendulum swung 15 times, while another reports 12 times and another reports 17 times. The teacher wonders aloud why everybody did not get the same results. The students (even in the elementary grades) will respond that the pendula are not identical. They quickly recognize that some have different lengths, some have different masses, some were pulled back to different angles and some had different colors. The teacher can inform the class that at the end of the laboratory session, the class will be presented with a pendulum of a specific mass, a specific length, and specific color string. The students are told that they will have to predict the number of swings of this pendulum in 20 s. The students can go to work and investigate a pendulum to help them make this prediction. This laboratory work is exciting to do. The advantages of this approach include crucial elements of inquiry,[9] as well as more of the defined goals of laboratory investigations.[8] Also, this approach supports the laboratory as part of an instructional model where the exploration precedes the explanation. It is no longer a verification laboratory but rather a puzzle to be solved.

One of the advantages associated with an inquiry-based approach is that it promotes differentiated instructions, one of the key elements of successful teaching.[10] An inquiry-based approach allows for the same lesson to challenge students of all interests, motivations, and backgrounds. In the pendulum laboratory, the math requirement can be limited to recording the data and making a graph of period versus length. Some students can increase the math load and plot the square of the period versus the length, while others will use a curve-fitting program. These students can then calculate the acceleration due to gravity from the slope of their line.

The differentiated instruction can also include extensions of the physics and math. Imagine a pendulum that is filled

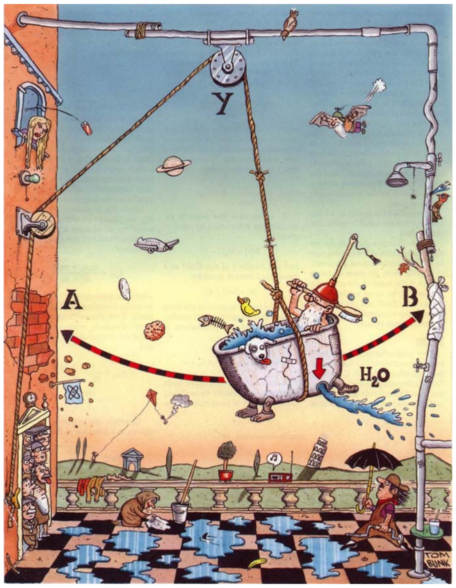

Fig. 1. A leaky pendulum. How does the period of a pendulum change as the water leaks out?

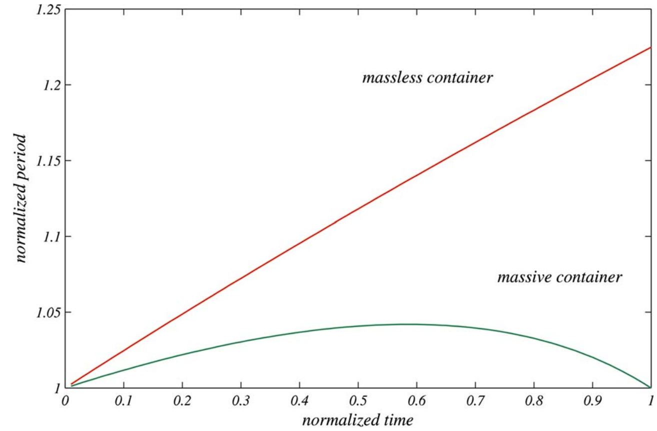

Fig. 2. Solution to the leaky pendulum. As water leaks out from a massless container, the effective length of the pendulum increases and the period increases. (The period change in the massless container is not linear.) If the mass of the container is taken into account, the effective length of the pendulum will first increase and subsequently decrease with corresponding changes in the period.

with water. As the pendulum swings, the water leaks out through a hole at the bottom as is artistically illustrated in Fig. 1. What happens to the pendulum's period as the water flows? We may ignore any momentum effects and just focus on the period of the pendulum with a decreasing volume of water. Most physics students incorrectly conclude that the decrease in water does not change the period of the pendulum because the period is independent of the mass. Others incorrectly conclude that the period of the pendulum increases as the water leaks out—not because of the mass change but because of the change in the effective length of the pendulum. As the water leaks out, the center of mass of the pendulum bob moves down, and the effective length of the pendulum increases. Others correctly conclude that the period first increases until so much water has left the massive container that the center of mass begins to rise and the effective length shortens and the period subsequently decreases. This result is quite surprising in that nobody seems to be bothered when hearing that a pendulum slows down, but everybody is bothered when a pendulum speeds up. The derivation of this result can be found in *Quantoons*.[11,12] The assumptions in Refs. 11 and 12 are that the fluid flows through a small hole at a constant rate from the bottom of a pendulum bob that is a cubical container. It is also assumed that the mass of the container is equal to the initial mass of the liquid. A plot of the period versus time is shown in Fig. 2.

V. THE ROLE OF MATHEMATICS IN PHYSICS FOR ALL

As we conceive problems for the differentiated classroom, we have to ask if the added difficulty arises because of complexities in math or physics. Physics does use math, but sometimes the math is added without any new insights into physical principles. The additional math is often added inadvertently by the physics instructor who has always found math straightforward, easy, and enjoyable. What is the math requirement for students to understand the physics? How should this math requirement be altered when the course is for biology majors? For example, the addition of vectors is crucial physics because forces add as vectors. Breaking a force into its components is similarly important physics. If you restrict the addition of vectors and the resolution of vectors into components to 30°, 60°, 90° triangles and three, four, five triangles, there is enough variation so that you can test for understanding of both vector addition and vector resolution into components. Requiring students to use the cos 17°, sin 39°, or tan 10° adds no new physics but increases the math load. We must constantly ask ourselves, "How much of what we teach is physics and how much is math?" and "When do we have to combine the physics and math and with what level of math?" Let's not add the math if it intimidates students and adds nothing to the physics understanding.

I emphasize that I love math and that I've always enjoyed it. Eugene Wigner's statement about the "unreasonable effectiveness of mathematics in the natural sciences" sends shivers through me.[13] It's probably one reason that I found the study of physics so appealing. That being said, I also believe that physics class should not be the second math class of the day.

Math, for many students, becomes a barrier to physics knowledge. Most members of the physics community have no difficulty in seeing the equivalence of $d=1/2at^2$ and $t=\mathrm{sqrt}(2d/a)$. People who are less conversant in the language of mathematics see these two equations as totally different. What should we do with these students? We can inform them that they don't belong in physics class—a strategy I reject. Alternatively, we can try our best to help the students learn how to use algebra to move effortlessly from one equation to the other. The problem with this approach is that we mistakenly think that it shouldn't take more than a few minutes of class time to do this. What we forget is that there is a talented and dedicated math teacher down the hall who has been trying to help this student for the past 2 months with transposing an equation like this and has not had much success. What hubris to think that we can teach math more effectively than the math instructors.

There is another alternative that provides access to physics for low achieving math students and does not require us to teach algebra. Recognizing that all students do not have the algebraic skills to move from $d=1/2at^2$ to $t=\text{sqrt}(2d/a)$, we might think that providing the students with both equations would help. Actually, providing two equations (which do not look alike) implies that there may be two different equations that describe the relation of distance to time of a falling object. What we can do is introduce just the equation $d=1/2at^2$. Students can become adept at finding the distance that an object on Earth will fall in 1 s, 2 s, 3 s, and any other time by using their calculators. Students can then be given problems of falling objects on the Moon where the value of the acceleration due to gravity is $1.6\ \text{m/s}^2$ rather than $9.8\ \text{m/s}^2$. When the students are very comfortable with calculating the distance fallen, you can ask them, "How much time will it take for an object on Earth to fall 50 m?" You don't do this the first day. You should wait until the students are comfortable with calculating distance fallen when given the time of fall. A student's first response will be to correct you, "This isn't how it works. You give us the time and we give you the distance." You can then respond by asking the students if the answer is 2 s? They can quickly use their calculators and their equation $d=1/2at^2$ and reply that the object only falls 19.6 m in 2 s. They can then be asked if the time for a fall of 50 m is more or less than 2 s. Students quickly determine that the time is between 3 and 4 s. They can try 3.1 and 3.2 s and reach the correct answer by trying different values and using only $d=1/2at^2$. They solve for the time numerically. They do this in as little time as it would take them to transpose $d=1/2at^2$ to $t=\text{sqrt}(2d/a)$. They don't have to use the square root button on their calculator and will make fewer errors. More importantly, they come to recognize that there is one equation that relates the distance and time of a falling object and can appreciate the elegance and simplicity of physics.

Would our mathematical prerequisites allow a great physicist such as Michael Faraday into our introductory physics class? Michael Faraday grew up as a poor boy in London and left school at age 14 to apprentice to a bookbinder. His math skills were particularly poor, and yet, he arguably became the best experimentalist of the 19th century. Faraday's weakness in math pushed him to create the field concept. Late in his life, after numerous successes in chemistry and physics, some scientists continued to question Faraday's status as a physicist because of his deficiencies in math.[14]

Michael Faraday in America today would be a poor student in an urban community. He would either find himself in a school that offers no physics, one in which there was a physics class but no laboratory equipment or one in which there is a physics class with laboratory equipment along with a parallel physics course for those students with poorer skills who do not have access to the laboratory.[8] Regardless of the school, there is a good chance that Faraday's talents would go undiscovered. Although I would like to believe that I would recognize this prospective student's interest, motivation, and desire, I suspect that the easier path would be to deny him admission. Are there any Faradays in America today whom we are ignoring? What policy or instructional changes would help them?

When we require math prerequisites and insist on more math even when no additional physics is learned, we close the doors to many students. When we begin the semester with a math exam and then use scores on that exam, not to find ways to support students but to convince them that they should drop the course, we are effectively telling a Michael Faraday that he does not belong in the physics class. Students can learn physics and learn to appreciate physics when we offer introductions spanning a range of mathematical complexity and find creative ways around some of the math.

VI. THE ROLE OF LABORATORIES IN PHYSICS FOR ALL

Some introductory physics classes insist on mathematical complexity but fail to expose students to laboratory experiments. Laboratories are expensive, require preparation, and pose safety issues. They can also be an effective tool for learning physics.[8] We believe in physics principles because models and theories are consistent with experimental data. When physics is presented without a laboratory, students are provided with "faith-based" physics. When students don't engage in laboratories, the experimental side of physics is a mystery to them.

Laboratory activities must be part of an integrated instructional unit to be effective in meeting the goals of laboratory activities.[8] A crucial element of the integrated instructional unit is that student engagement in a laboratory activity precedes the introduction of the concept.[15]

An optics lesson can be used to illustrate the important role laboratories can play in supporting inquiry-based lessons.[16] The introduction to lenses and image formation begins with students exploring lenses to create images. The students are not told how to hold the lens or where to place the light source or the screen. Their instructions are to form an image of the light source that is larger than the light source, one that is smaller, and one that is the same size. Student teams try all sorts of orientations. The students "mess around." As the teacher moves about the class, he or she can insist that the image must be in focus and insist that the students make finer adjustments in the positions of the lens and screen. If the teacher mentions that the image should be erect rather than inverted, the students will try to rotate the lens or turn it over. As they fail in their attempts to make the image erect, they are learning about lenses and image formation.

After this initial activity, the student investigation can then become more quantitative where the students record the object distance and image distance and create a data chart and graph their results. All students are able to complete this part of the optics lesson and are ready for the introduction of a ray model of light. Once again, all students can learn how to make ray diagrams. And all students can then compare the results of their laboratory investigation to the results from the ray model. All models have limitations. Students should recognize that rays of light leave the tip of the arrow and all of those rays that travel through the lens converge at the tip of the image for a real image. The ray model includes all of these rays, while the ray diagram only uses two or three of these rays as shown in Fig. 3. All students will be able to understand the ray model and surmise that if half the lens is obstructed, the entire image will appear, but it will be dimmer.[17]

During this laboratory exercise, differentiated instruction provides the opportunity to challenge all students and to provide support and interventions for those that need it.[10] While some students may still be working on collecting data or completing ray diagrams, others can be deriving the lens equation $1/f=1/d_o+1/d_i$. Some students can derive this

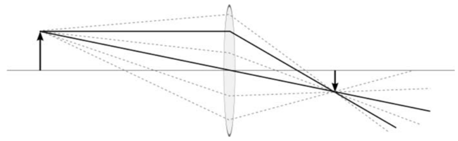

Fig. 3. Light rays and a converging lens. Light diverges from the tip of the arrow. Light is modeled as many rays, which travel through the lens and converge at the image. Only two of these rays of light (shown in bold) are used to locate the image in traditional ray diagrams. The use of only two rays can produce misconceptions in understanding.

equation geometrically from similar triangles in the ray diagrams, while others can follow along as the derivation is presented. Other students can use the graph of their experimental results and can derive the equation by recognizing that the graph is a hyperbola translated off the axes by a distance equal to the focal length of the lens.

A small number of the most mathematically sophisticated students can be invited to solve a complex lens problem that would challenge anybody in physics: A lens of focal length f is cut into two parts perpendicular to its plane. The half-lenses are moved apart by a small distance δ as shown in Fig. 4. (The gap is exaggerated for clarity.) How many interference fringes appear on a screen at a distance L from the lens if a monochromatic light source (wavelength λ) is placed at a distance d ($d > f$) on the other side?

This problem was solved by high school students at the 1972 International Physics Olympiad in Bucharest, Romania. The International Physics Olympiad problems given in competition form to individual students have increased in complexity since 1972 when only Eastern Bloc countries participated. United States involvement in this competition began through efforts by Jack M. Wilson, Kenneth Ford, Ron Edge, and myself in 1984.[18–21] In 1993 the United States hosted the Olympiad for 41 countries.[22] This Millikan Award is given in recognition of the part these individuals and I and so many others (including A. P. French, Hans von Baeyer, Delores Mason, Leon Lederman, Roy Champion, Patty Rourke, Yvette van Hise, and Larry D. Kirkpatrick) played in the early Olympiad effort, which has encouraged and brought recognition to the highest achieving physics students in the United States.

Returning to the problem, when a lens is split in half, some students are able to see that each half of the lens will produce its own focal point and that the distance between these focal points will be related to the space between the two halves of the lens. By creating two sources of coherent light, the most able students will recognize that there is an interference pattern and can then quantitatively describe the distribution of maxima and minima. The number of interference fringes is given by

$$N = \frac{\delta^2}{\lambda} \frac{(L+d)}{L(d-f)-(df)}. \tag{1}$$

In this series of lens lessons, we ask, "Which part of the lesson is the real physics?" Is the real physics only the difficult mathematical component where students extend the concept to a split lens, or is the real physics limited to the derivation of the lens equation through the geometry of similar triangles in ray diagrams or from the graphical analysis of the data? Or can we agree that all of these activities are real physics, including the investigation and inquiry with the lenses and the creation of images and the graphing of the image distance versus the object distance? Some of this physics lesson are accessible to all students. And all students should have an opportunity to be exposed to it. In addition, some of this physics lesson are intended to challenge even the most highly motivated and highest achieving students.

It is informative to discuss the illustration that appeared in *Quantoons*[12] for the split lens problem shown in Fig. 5. Tomas Bunk, an artist, has never studied physics but has taken on the challenge of creating illustrations for physics concepts in *Quantoons* and *Active Physics*.[30] He learns the physics necessary to produce his illustration. As you can see, he learned how a lens focuses light, how a mirror reflects light, and how the image through a lens can be upside down. Bunk has provided an insight into his creative mind by writing about the process behind his art.

Fig. 5. Split image quantoon. A "quantoon" illustration for the split image problem. Tomas Bunk, an artist with no physics background, learns physics as he creates images for physics problems.

Fig. 4. Split image. A point source of monochromatic light placed at a distance greater than the focal length of a converging lens produces an image point on the far side of the lens. When the lens is split into two halves as shown, two image points are produced. These coherent image points can create interference fringes on a distant screen.

> "After reading the title of this article, I decided immediately to use it for my illustration. Split is where I was born and where I grew up, a beautiful city on the Mediterranean coast of Croatia. Looking back on my childhood, Split meant always the most perfect place—the temperate climate, the

azure blue sea, the town rich in history, founded by the Romans. But in 1995, when I drew this illustration, bloody war was raging, which shattered my image of a perfect paradise. The illustration shows the sunny past, but under the fractured lens we see the sinister side, the destruction and death. Today, ten years later, the fragments of the broken lens have grown together in to one piece and the light that passes through is pure and perfect again."

Through this quotation, we can see how physics can be a metaphor for life and can interest people who might not become physicists but who can still learn and interpret physics content. In my teaching, I have strived to find other opportunities to prod students into using the physics principles they learn in class as metaphors for their own writing. To assist them, I present examples of how writers and poets do this in their creative endeavors.

VII. BRIDGING RESEARCH AND PRACTICE—ACTIVE PHYSICS

The goals of quality physics instruction include higher student achievement, student engagement with physics content, enhanced appreciation of physics in the world, and improvements in the ability to use critical thinking to solve problems that students will encounter. To meet these goals, generations of physics educators have tried all sorts of interventions and conducted all sorts of research that has helped illuminate how people learn.[7,23–25] This research literature on learning as well as research on student motivation[26] must be combined with other research about instructional models[15,27] to produce materials that will help us reach our goals. We must also remember to develop materials and professional development that will support and assist teachers so that they can use these materials in the way that they are intended to be used.[28,29]

Active Physics[30] is a curriculum that attempts to bridge research and practice. It is described here not as the unique solution to bridging research on how people learn with instructional models with physics for all but as a proof of concept. The journey of *Active Physics* began with an initial National Science Foundation (NSF) grant awarded to AAPT and AIP. Physicists, physics teachers, and science educators developed the concept, created the curriculum, and tested the curriculum on a small scale. Hundreds of physics teachers then field tested *Active Physics* with their students and provided research data on its effectiveness in their classrooms, leading to rewrites and improvements in the materials. The third edition has just been published and incorporates the changes requested by users across the country from large urban areas to small rural schools. We continue to listen and modify the material based on new research results and data from teachers and teacher leaders implementing the curriculum. This Millikan Award recognizes all of their contributions, and it is my sincere hope that readers peruse this list of exceptional educators as provided in the introductory pages of *Active Physics*.

Active Physics is different from a traditional physics program. It contains all the physics content teachers are expected to teach in a first year high school course, but it is held together with challenging projects. It has forces, energy, waves, electricity, and magnetism, as well as optics and modern physics, but the content is always placed in a larger context that emphasizes student learning through inquiry as well as motivating students through a problem-based learning approach. Students learn about waves, sound, and light as part of their requirement to create a brief show that will entertain their friends (Chapter 5: *Let Us Entertain You*). Students apply what they have learned about energy, momentum, and Newton's laws to build an improved safety device for a car (Chapter 3: *Safety*). Students take ownership of their understanding of atomic and nuclear physics as they develop a museum exhibit on the atom as well as suggesting something that can be sold in the museum store (Chapter 8: *Atoms on Display*).

The format of each chapter can be seen by focusing on a single chapter—*Physics in Action*. On the first day, students are introduced to the Chapter Challenge, which will be the focus of their work. The challenge for this chapter is to create a series of voice-over dubs for sporting events. These can be considered tryouts for a job as a "physics sports commentator." The physics sports commentator will be handed the microphone during a broadcast and will have to explain some of the sports action as examples of physics principles. To actually secure this kind of job, physics content knowledge is necessary but not sufficient. The commentator will also have to be entertaining, articulate, and enthusiastic.

How can the students get started? How can they complete such a challenge without the necessary physics knowledge? That's what makes *Active Physics* unique. Students are introduced to the physics they need to complete the challenge on a need-to-know basis.

On day 1, before the chapter sections begin, the class discusses the Criteria for Success. The students decide what is expected in an excellent physics broadcast and how each of these components will be graded. For instance, they may decide that the rubric for grading will include the following factors: (a) The use of physics terms and principles in the narration, including the number of physics principles used and the use of equations when appropriate; (2) the quality of the oral narration including the entertainment value; and (3) the quality of the written script of the narration. Note that entertainment value is not a "physics content" criterion, but it is required for someone to be a successful sports commentator and is therefore is included in grading.

The class will also need to decide whether each factor carries equal weight or if one should have a greater impact on the grade. In this way students will have a sense of what is required for an excellent presentation before they begin and also develop a sense of ownership. Later they will revisit the criteria before work on the challenge is finalized. They conclude this first day by reflecting on the Engineering Design Cycle, a strategy that gives them some sense of how to accomplish this challenge.

The second day begins with the first of nine sections. As one section is completed, the next one begins. Each section includes all parts of the 7E instructional model,[15] including an opportunity to *elicit* students' prior understanding while *engaging* them, to *explore* a physical phenomenon prior to *explaining* that concept and then elaborating on related physics. The students then *extend* that knowledge as they transfer their learning to the chapter challenge. Students and the teacher *evaluate* throughout the section. *Active Physics* is an inquiry-based curriculum—students always explore before they explain (for example, ABC=Activity Before Concept).

For example, Sec. 1 is entitled *Newton's 1st Law: A Run-*

Fig. 6. Newton's first law. An illustration can help engage students and elicit their prior understandings of Newton's first law. By using a cartoon, we have found that all students including English language learners and special needs students can fully participate and contribute to this introduction to the lesson.

ning Start. Each section begins with a cartoon, which the teacher can use to introduce some of the aspects of the next activity. More importantly, the cartoon is used to begin to engage the interests of the student with a simple What Do You See? question as shown in Fig. 6. Student answers to this question need not be correct or even relevant to physics, but it is important that they provide some response to the question. We have found that all students, including those with special needs or English language learners, can respond to "What do you see?" They get engaged and the teacher gets an opportunity to elicit the students' prior understandings.

This cartoon is followed by the What Do You Think? question. "Why does a soccer ball continue to roll across the field after it has been kicked?" This question is intended to further elicit prior understandings of the students. If the teacher listens intently and asks follow-up questions, a student's prior understandings come to the surface. This question is not intended as an opportunity to correct students; rather it is an opportunity to find out "what the student thinks." At the end of the section, after the students become engaged in an exploration activity and use evidence from that investigation to answer questions, you will return to this query with a What Do You Think Now? question. At this point, it is appropriate for teachers to help students with confusions or inconsistencies in their responses. The What Do You Think? question is directly related to Newton's first law, the physics principle in this section. Formally, you can say that these questions elicit the students' prior understanding and are part of a constructivist approach.[31] Typically, students write a response for 1 min, followed by 2 min of discussion. But the teacher should not try to reach closure here. The question opens the conversation.

The students then begin to investigate by recording what happens when a ball rolls down a u-shaped ramp and rises on the other side. They measure how high the ball goes on the far side and use the evidence from their observations and, following a reasoning similar to that of Galileo's, come to the conclusion that a ball rolling on a flat surface will continue to roll forever if friction were somehow eliminated.[32]

The Physics Talk summarizes the physics principles and provides historical background to enhance understanding. It also presents students with text, illustrations, and photographs, which provide greater insight into the physics concepts. This section is most similar to the traditional textbook explanation of physics. What makes it unique is that the explanations refer back to activities and experiences that we are confident that the students have had. A typical text expects that the student has observed a ball rolling across a table, while *Active Physics* insures that all students have had the common experience of rolling a ball across a table with which to build conceptual and mathematical understanding. Similarly, a typical text declares that when you are riding on a bus and the bus stops short, you keep moving forward. The text does not take into account that some students might never have been on a bus or that some students might have been on a bus and remember that they went backward (a false memory). By having the laboratory investigations precede the "physics talk," *Active Physics* can describe what happens on a bus by referring to what happened to a clay figure on a cart when the cart hit the wall. The concept development is always based on observations that the *Active Physics* student has experienced. These observations provide the evidence required for students to understand the new concepts.

Physics classes have always had students with a range of interests, mathematical abilities, and motivations. As we provide access for all high school students, there will be a wider range of students along these dimensions. For this reason we have introduced *Active Physics Plus* to each section. This section provides additional explorations, deeper analysis, more mathematics, or additional content for some students. The teacher can assign it to students who finish earlier than others or suggest that students complete this for extra credit. The section allows all students to stay engaged when some students need more support on the earlier concepts. Active Physics Plus provides more mathematics and/or more concept development and/or more inquiry.

What Do You Think Now? revisits the original What Do You Think? question and provides an opportunity for students to reflect on any changes in understanding. You can use this exercise in a similar manner with a written response in the student notebook followed by a short classroom discussion.

One of the inherent difficulties in learning physics is connecting new content to larger concepts that form the skeletal structure of physics and that distinguish science from other disciplines. *Active Physics* helps students to see both the trees and the forest by focusing on four essential questions. These are similar, though not identical, to those introduced by others.[33–35] In the section on Newton's second law, students are first asked What Does It Mean*?* about one of the concepts introduced in the section. This question is similar to those that are typically asked of students (see Table I). Students are then asked How Do You Know? In response to this question, students refer back to some observational or experimental evidence that they have observed in the section. The usual answer to "How do you know" is "We did an experiment." Students are then asked Why Do We Believe*?* This question takes one of three forms, which help students better understand how physicists view their discipline. Students are shown how the concept introduced in this section connects with other physics content, fits with the "big ideas in science," and meets physics requirements such as consistency between experimental evidence and models or theories. The "Why Do You Believe" is our attempt to communicate the tacit knowledge that physicists develop, which helps them determine if a new question belongs within the domain of physics.[34,36,37] Finally, students are asked "Why Should I Care?" Research has shown that student success is strongly correlated with student engagement.[26,38] By asking

Table I. Four essential questions. Four essential questions are returned to after every physics section or 3 days of instruction. These questions help the students summarize the new content (in this example, Newton's second law) as well as guide students to understand the physics of each section in relation to the larger principles of all physics knowledge. In the left hand column are the four essential questions. In the right hand column, students are asked a specific question, shown in italics, about the new physics content. The text guides students in the "Why Do You Believe" question by describing how the new physics content "connects with other physics content; fits with big ideas in science; and meets physics requirements" prior to asking a specific question.

Section 3: Newton's second law: Push or pull			
What does it mean?	*What does it mean when Newton's second law states that acceleration and mass are inversely proportional?*		
How do you know?	*What part of your investigation convinced you that larger forces produce larger accelerations?*		
Why do you believe?	**Connects with other physics content**	**Fits with big ideas in science**	**Meets physics requirements**
	Force and motion	***Change and constancy**	**Good, clear explanation, no more complex than necessary**
	**Newton's second law is used to describe and explain motion of large objects and small objects. It helps you better understand the motion of people in sports, cells in the body, colliding atoms, and planets in the solar system. Why do you believe that if you push on a truck, the truck may have a tiny acceleration?*		
Why should you care?	*All sports involve motion. All accelerated motion involves unbalanced forces. If you identify an acceleration of a person or an object in your sports video, you can discuss the forces that cause that acceleration. What in one way that this idea will come up in your voice-over challenge?*		

students why they should care, they are asked to see the relevance of this section's physics concepts to the chapter challenge.

Why are students learning about Newton's laws? In *Active Physics* they have a project to complete, and understanding Newton's laws is a required component of that project. The section Reflecting on the Activity and the Challenge provides a brief summary of the activity and again relates the activity to the larger challenge of creating a voice-over dub for a sporting event.

The section concludes with a Physics to Go homework assignment. Here, students are asked about the specifics of the activity and required to apply their knowledge of physics principles to new situations. Often, the homework will include an additional activity, Preparing for the Chapter Challenge, which provides students with the chance to do some background work toward their final challenge.

Following the Physics to Go homework, many activities have Inquiring Further exercises. These exercises often require the student to design and do an experiment. Typically, the Inquiring Further option will be more challenging and can be used for extra credit. Once again, this option is an example of how physics for all can challenge all students.

The chapter continues through additional sections where students are introduced to other physics concepts such as projectile motion and energy. In the middle of each chapter, students find a Chapter Mini-Challenge, which provides students an opportunity to try out one or two of the physics principles that they are considering for use with their challenge, the voice-over dub of a sporting event. Students get a first opportunity to gauge the difficulty of the challenge. They also get to see how other teams are approaching the chapter challenge. They receive and provide feedback on their mini-challenge. Having this chance to see what works and what doesn't work makes the final challenge that much more successful. Such feedback is important for the engineering design process.

The Chapter Challenges that the students complete at the end of the chapter are often a part of an actual job by real people. Physics at Work introduces students to these people who use the physics in the chapter as part of their career. Reading about their lives and jobs brings another facet of the importance of physics to students and might get them thinking about their own future career regardless of whether they plan to enter the workforce after high school, college, or with a Ph.D. In addition, Connections with Other Disciplines provides examples of how each physics principle has applications in biology, chemistry, and earth science. In a Physics First course, this section previews how physics will apply to their future studies. For those who have studied these other sciences, the examples provide a fresh perspective on some of the science they learned.

The Chapter Assessment section is framed around the Engineering Design Process (goal, input, process, output, and feedback) and begins with a review of the activities and key concepts. It then outlines the steps that the students may follow in completing the challenge. The chapter concludes as the students present one of their voice-over dubs to the class. Before the students present their voice-over dubs to the class for the Chapter Challenge, the criteria are reviewed by the class and finalized. Presenting the Chapter Challenge has important learning outcomes.

(1) Students review and increase their understanding of the physics concepts in preparation for completing the challenge.
(2) Students get to review each concept in different ways as they observe other teams present.
(3) Students are motivated because they are engaged in the creative aspects of the chapter challenge.
(4) Students demonstrate their expertise about ways to relate physics to their personal challenge execution.
(5) Students from different backgrounds and cultures can offer insights into their backgrounds through the chapter challenge.

In addition to the Chapter Challenge Assessment, traditional assessment questions and problems are also provided in addition to the hundreds of traditional questions and problems in each chapter, which are introduced during and after each section. Students are reminded of these when the chapter assessment is presented.

Teachers can begin the year with any chapter. Chapter 1, *Driving the Roads*, asks students to convince their parents that they can drive safely. It includes the physics of position, velocity, and acceleration. It is a logical although not a mandatory choice to begin the school year because it also contains "launcher" materials that introduce the learning components to both the teacher and students and help provide students with a reason why this research-based approach to physics will help them succeed. Traditionally, such background information is limited to the teacher's edition of the text. We recognize that the rationale for our instructional model is not a "teacher secret" and include these educational materials[28] for the students. Providing a rationale for the structure of the book helps students learn about their learning and supports and encourages metacognition. For example, the launcher explanation for the What Do You Think Now? states:

> "At the beginning of each section, you are asked to think about one or two questions. At that point, you are not expected to not necessarily come up with a correct physics answer, but you are expected to think about what you know. Now that you have completed the investigation, you have learned the physics you need to know to answer the questions. Think about the questions again.
>
> Compare your answers now to the answers you gave initially. Comparing what you think now with what you thought before is a way of "observing your thinking." Remember, research shows that stopping to think about your learning makes you a better learner."

VIII. EXPECTATIONS FOR ALL

Bringing physics instruction to all students not only requires a close look at content and the ability to differentiate instruction so that all students are challenged. Inviting all students to the physics classroom provides some teachers with their first interaction with students who have experienced much less success in high school. Some of these students have poor attendance and require a different set of class management strategies. Some of these students simply don't buy into the story that if you do well in school, you can get a better job and life will be good. Some of these students have not seen enough evidence of this American dream in their neighborhoods.

The crucial attitude that physics instructors must adopt when all students enter the physics classroom is that all physics students can succeed. The Pygmalion studies of the 1960s showed that teacher attitudes toward students become self-fulfilling prophecies. If a teacher is told that a random group of students will outshine a second group of students, then the students do.[39] The expectation effect has been seen in symphony orchestra interviews. When the judges could see that the performer was a female, she was rarely hired. When the symphonies placed musicians behind a curtain for the audition, women were selected.[40,41] Our goal is to find a way to build relationships with our students and yet keep a curtain in position so that our subtle prejudices do not come into play. And if we catch ourselves thinking that "this student will not succeed," we must work hard to rid ourselves of such judgments because they will affect student performance. We don't know how our body language, our eye contact, or how our verbal messages communicate our expectations, but we know from the Pygmalion studies and the orchestra auditions that they do.

We cannot trust ourselves to be impartial when we have formed judgments in our minds. That is what the research indicates, and so we are left with no alternative but to convince ourselves that all of our students will be successful and to act accordingly as we conduct our classes. One way in which to remain impartial is to randomly call on students to respond to questions. By using a deck of cards or popsicle sticks with student names, we would not call on some students because they are good in physics and can answer the tough questions and call on other students for only the easier questions. Randomly calling on students provides an opportunity for struggling students to get a difficult question correct and, if incorrect, for us to probe the depth of their understanding.

The three key expectation messages we must consistently deliver to all of our students are "This is important;" "You can do it;" and "I won't give up on you."[42] Our students have all learned language, and they have all learned to read. Certainly, they can all learn physics.[43]

IX. CONCLUSIONS

Physics for all can be achieved. We can accept all students into our classes and differentiate instruction so that all students can succeed and all students can be challenged. In altering our courses to accomplish this mission of physics for all, we have the opportunity to adjust teaching strategies, develop curriculum, and adopt instructional models that can bridge research and practice. We can look toward the International Physics Olympiad to define the high bar of theoretical and experimental work that high school students and first year college students can attain. We can look toward *Active Physics* as a model for bridging research and practice in a comprehensive curriculum that includes laboratories and theory and the nature of science.

We do have choices. We can offer courses that preclude students with poor math backgrounds and thereby deny enrollment in our introductory classes to today's Michael Faradays. We can continue to offer physics to the select few and maintain the premise that physics is "for the elite." Or we can march along the path first traveled by Galileo to present physics to all.

Two passions drive my professional life—my passion for science and my passion for teaching.[44] I find beauty in the world and in representations of the world through science. I find delight in discovering new ways of seeing familiar phenomena. My love of science grows stronger when I explore ways to communicate this vision of the world through teaching, curricula work, and related activities.

In the pursuit of my passions, I am confronted too often with inequities in our schools, inequities that prevent many of our students from getting access to a quality science course, a quality science teacher, or an opportunity to discover and experience the joy of science. This unfairness requires me to spend time and energy fighting for these children so that they too can become student scientists. Addressing equity issues has become my third passion because justice for children demands it.

Great novels and symphonies are accessible to people of different backgrounds and levels of expertise. People of all knowledge levels can enjoy Steinbeck's *Grapes of Wrath* and Beethoven's Ninth Symphony. We should develop teaching strategies that enable us to share an understanding of physics with all students. Everyone deserves a peek at the wondrous workings of our universe.

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