

**Millikan Award Lecture, 2006:
Physics For All**

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Abstract: We physics teachers must broaden our focus from physics for physicists and other scientists to physics for all. The reason, as the American Association for the Advancement of Science puts it, is that “[w]ithout a scientifically literate population, the outlook for a better world is not promising.” Physics for all (including the first course for scientists) should be conceptual, not technical. It should describe the universe as we understand it today, including special and general relativity, quantum physics, modern cosmology, nuclear physics, the standard model of particles and interactions, and quantum fields. Many science writers have shown that this description is possible. It should emphasize the scientific process and include such societal topics as global warming, nuclear weapons, and pseudoscience, because citizens need to vote intelligently on such issues.

I. INTRODUCTION

I’m surprised, delighted, and a little overwhelmed by this award. Many thanks to the American Association of Physics Teachers. In my opinion, the AAPT is our nation’s most important physics organization – and I’m not just saying that because they gave me this award! Another fine organization, the American Physical Society, is bigger and better known. But in this era of widespread uses and misuses of science and technology, science education is more important than additional research. Research is important, but our biggest science-related problem today is not so much a deficit of research as it is a deficit of public understanding and rational control of where science and technology are taking us. For that, we need education. So, more power to the AAPT!

I also thank my wife Marie Riley for her love, for being a source of much-needed stability, and for her years of encouraging words.

In the meeting program, I gave this talk the bloated title, “Thoughts on Physics Education for the 21st Century.” I’d like to re-name it “Physics For All,” because that’s the one thought that I want to talk about, and because our Executive Officer Bernie Khoury has used this phrase in his excellent editorials on this topic.¹

Because I’ve been involved for many years in efforts to expand education about physics-related societal issues, I interpret this award as recognition of the importance of societal topics as part of a complete physics education. In this effort, I’ve had many collaborators, especially the many people connected with the APS Forum on Physics and Society, and more especially, many people involved in the AAPT’s informal Physics and Society Education group. The key people who helped launch (at the summer 1994 AAPT meeting) and maintain that group are Al Bartlett, Jane Flood, Jane Jackson, Harvey Leff, Peter Lindenfeld, Gordon McIntosh, John Roeder, and John White.

The Physics and Society Education group helps organize meeting sessions, and has an email discussion list.²

“Physics for all” means physics literacy for all students, certainly all non-scientists but also all scientists. I’ve have four points about physics for all. (Have you ever noticed that

speakers always have about four points? I mean, have you ever heard a talk with just two points?)

First and foremost, we educators must broaden our focus from physics for scientists to physics for all. Second, physics for all should be conceptual, not technical. Third, physics for all should be about physics as we understand it *today* rather than as we did in the 19th century. Fourth, physics for all must be connected to its social implications.

II. BROADENING THE FOCUS

Project 2061, launched in the 1980s by the American Association for the Advancement of Science, aims to improve the nation's scientific literacy. The project's handbook, *Science for All Americans*,³ concludes its section about "the need for scientific literacy" with these words:

"The life-enhancing potential of science and technology cannot be realized unless the public in general comes to understand science, mathematics, and technology and to acquire scientific habits of mind; *without a scientifically literate population, the outlook for a better world is not promising.*"⁴ [Italics added.]

Strong words from one of the world's largest scientific organizations. That statement is even more obviously and painfully true today than when it was written in 1989. It implies that every student – *every* student – needs a culturally and socially relevant physics or astronomy course.

Why is science literacy so important? The answer is simple: *industrialized democracies cannot survive unless their citizens are scientifically literate*. Think about it: science and technology drive every industrialized nation. And in democracies, it's the people – the taxi drivers, lawyers, teachers, journalists, politicians, housewives, and so forth – who decide about energy policy, global warming, science in the classroom, and much more. If they don't understand science, if they have negative attitudes toward science, if they are wrapped up in pseudoscientific baloney, then the outlook for the nation is not good.

The AAAS is saying that science literacy is about survival. But, even in industrialized nations, few people are science literate. They don't know what a molecule is, or what causes the seasons. They can't or won't read a science-related article in the newspaper. About 50% of Americans believe that humans were created separately from the other animals and by a non-natural miracle. Physicist and educator David Goodstein observes that "our [American] educational system is bad enough to constitute a threat to the ideal of Jeffersonian democracy ... Approximately 95 percent of the American public is illiterate in science by any rational definition of science literacy."⁵ Despite all the scientific research going on in the United States, and despite our many first class universities, America is quite capable of falling into a dismal third-world status brought on by a scientifically ignorant electorate.

We physicists are not taking this responsibility seriously. Physics education isn't just about physicists, and it's not just about scientists. It's about all people, it's about everybody's quality of life, and in fact it's about the survival of civilization. But look at practically any Ph.D.-granting physics department and ask yourself, "What are this department's priorities?" Highest on the list will be faculty research, faculty grants, and faculty publications, followed by Ph.D. students, and then graduate-level courses.

Undergraduate physics students will be next. Many departments hold undergraduate programs in such low esteem that even their own undergraduates receive little attention, and their stream of graduating seniors narrows to just one or two per year. My own department was, for a time, an example. From the 1980s through 1994 we granted an average of only 2 bachelor's

degrees per year. Then, in 1994, we tried something new: we hired Gay Stewart, our first faculty member hired for physics education and physics education research. Because of her focus on undergraduate students and on physics by inquiry, our number of majors immediately picked up until we had about 12 graduates per year during the late 1990s, and over 20 per year for each of the past three years.

Below undergraduate physics majors in priority is the undergraduate courses for engineers, biologists, pre-med students, and other scientists.

The lowest, and sometimes non-existent, priority is undergraduate education for non-scientists, that is, for that 90 percent of the students who will graduate to become our K-8 teachers, attorneys, journalists, mothers, business people, politicians, and presidents. These are the people who will determine science's and the planet's future, but you couldn't tell it from the short shrift they get in most Ph.D.-granting physics departments.

These mistaken priorities are built into the hiring, promotion, pay, and tenure policies of nearly every Ph.D.-granting physics department. In my department and most others, research is practically the only criterion for hiring and tenure. Untenured faculty members teach general introductory courses at their peril, because time devoted to these courses is time not spent on research, and such distractions can cost them their job. Consequently, my department and most others are always short of people who are capable of teaching introductory courses, and such courses are often relegated to graduate assistants and other temporary help.

Non-Ph.D.-granting colleges do better on the average. But I fear that many of them take their cues from the Ph.D.-granting institutions – poor models indeed!

In looking over Robert Millikan's biography – you'll recall that this talk is the Millikan Award Lecture – I noticed that he was very involved in undergraduate education at the University of Chicago. He authored two introductory college physics textbooks, three other undergraduate physics textbooks, and a textbook for a high school laboratory course in physics. Unfortunately, most researchers today are not following Millikan's example.

Far from being the lowest priority, physics courses for non-scientists are the most important courses we teach. Physics departments don't see it that way, and universities don't see it that way, but that's the way it is, nevertheless. All the physics research in the world will do little good if the state of the nation and the state of the planet continue to deteriorate. *Every physics department worth its salt needs to teach physics courses and astronomy courses for non-scientists*; these courses can be taught in a few large classes or many smaller classes, but the bottom line is that *these courses need to be taken by the majority of the non-science undergrads on the campus*. I'm proud to report that my own department achieves this goal: Slightly over 50 percent of the non-science undergrads on our campus take either our liberal-arts physics course or our introductory astronomy course at some point before they graduate. I'd prefer that the figure were 90 percent, but 50 percent isn't bad.

As for students of physics or other sciences, they too need a wide-ranging, conceptual, liberal-arts physics course at some point in their career, presumably in high school. Like most other people, most scientists are scientifically illiterate. Most scientists finish college with little knowledge of such societal topics as global warming, the scientific process, or energy resources. They know very little about modern physics topics such as the standard model of particles and interactions, the concepts of quantum physics, or the recent revolution in cosmology. And we know from physics education research that they often lack qualitative understanding of the underlying concepts of physics. It's a real mistake to push future scientists directly into a math-oriented "Advanced Placement" physics course in high school, where they will spend two

semesters learning 18th-century mechanics and 19th-century electromagnetism, when they have not first learned the broad concepts of classical and modern physics and their relevance for their own lives and for the planet. All science students, especially physics students, need their first high school course in physics to be broad, conceptual, include lots of modern and contemporary physics, and to be connected to its social context. Then they'll be ready for that AP course.

III. CONCEPTUAL PHYSICS

My friend, fellow textbook author, and fellow Millikan Award winner, Paul Hewitt, titled his 1982 Millikan lecture “The missing essential—a conceptual understanding of physics.” I regard Hewitt as the pioneer of the conceptual approach to physics teaching. In his lecture⁶ he writes that “[a] physics student who lacks a conceptual understanding of physics and who is working physics problems is akin to a deaf person writing music or a blind person painting. Too many physics students are cranking away on analytical problems they have no feeling for.” Hewitt’s main recommendation is that teachers should “provide students a first course in physics that is entirely conceptual,” and that such a course is appropriate for both non-science and science students. I couldn’t agree more.

The great physicist Victor Weisskopf studied in Gottingen from 1927-29, exactly where and when quantum mechanics was invented. He had a difficult time with some of the new mathematics. He relates that

“I was very lucky in one respect. The main theoretical physicist, Max Born, fell sick and had to be replaced for a year by a physicist from Holland, Paul Ehrenfest. He took an interest in me. He had a tremendous influence on me, because he said: “Forget these complications. All these Gottingen people talk much too highfalutin mathematics. That’s not the essential thing. Physics is simple, but subtle.” That is what Ehrenfest said. And it *is* simple, but subtle. From him I learned this tradition: that if you could not say it in a simple way, you didn’t understand it.”⁷

Physics education research by Arnold Arons, Lillian McDermott, Edward Redish, Alan Van Heuvelen, David Hestenes, and many others confirms that students in courses that place primary emphasis on problem solving rather than on underlying concepts come away with little conceptual understanding of physics.⁸ They can work formula-based problems, but ask them a simple conceptual question about the forces involved when a truck rams a Volkswagon, and you soon discover that they don’t understand Newton’s third law.

Avoid algebra entirely in courses for non-scientists. Why do they need to be able to calculate how long it takes a block to slide down an inclined plane? Proportionalities can be helpful, but please dispense with solving equations for x . On the other hand, do not dispense with numbers. Powers of ten, numerical estimation, interpretation of graphs, proportionalities, probabilities, and exponential growth are all part of the “numeracy” that every citizen needs.

If you think that “conceptual physics” means “physics for dummies,” or that conceptual physics is for people who don’t like physics, then please do not try to teach non-scientists. In fact, many non-scientists are extremely bright, quick to pick up on subtle concepts, and especially good at interdisciplinary connections. Widely read books such as Brian Greene’s *The Elegant Universe*, which teaches general relativity, quantum field theory, and string theory using correct physics and without math, testify that conceptual physics can be considerably *more* sophisticated, in its own way, than math-based physics. And the wide-ranging audience for this and similar books shows that at least a segment of the general public loves physics, provided only that it’s presented in language they can understand.

IV. “MODERN” PHYSICS

When I write of modern physics, I often put “modern” in quotes. It’s an ironic title for physics since the beginning of the preceding century. Perhaps it’s still a useful title, but 20th and 21st century physics are referred to by working physicists not as “modern physics” but as simply “physics.”

What’s surprising is that most introductory physics courses still nearly exclude modern physics, although relativity and quantum physics have been our basis for understanding the universe for over a century. Thus, not only most non-science students, but also most science students never learn the contemporary view of time, space, matter, radiation, particles, fields, energy, causality, locality, the ultimate constituents of the universe, or the origin, structure and evolution of the universe.

Certainly the enduring classical principles, such as Newton’s first law, conservation laws, and the laws of thermodynamics, should be included in general physics courses. Other broad classical principles, such as Newton’s second and third laws, that are good approximations in everyday situations, also belong in many general physics courses, especially those geared toward practical applications. But why the excessive focus on all things classical, to the near exclusion of modern and contemporary physics, especially in broad introductory courses? Physics is supposed to be the study of the real physical universe. Isn’t this what we should be teaching, as revealed by our best current knowledge?

It’s especially ironic that we don’t teach modern physics — often called “the good stuff” — when it’s so inspiring for students. The popularity of such books as *The Elegant Universe*, *The Accelerating Universe*, *A Brief History of Time*, and Lisa Randall’s recent book *Warped Passages* testifies to the fascination modern physics holds for many non-scientists.

Even if you’re sleeping through this lecture, I hope you’ll listen closely to the next one by Lisa Randall, and that you’ll take some of her ideas about the universe’s hidden dimensions home to your own science and non-science students.

I’m sometimes asked how I find time to cover significant amounts of both classical and modern physics in the one-semester course for non-scientists that I developed and taught (until retiring from teaching in 1999) at the University of Arkansas. The answer was stated well in the title of an AAPT session around 1990: “Trim the bloated elephant.” Trim the introductory course and the introductory textbook by cutting the superfluous classical fat. Do introductory students really need to understand the fine details of geometrical optics, acoustics, and DC and AC circuits, at the expense of general relativity, quantum entanglement, and contemporary cosmology? Focus on the great principles rather than the smaller details. Dispense with excess math and dispense with excess problems. I devote at least 50 percent of my one-semester general introductory course to modern and contemporary physics, and nobody complains that the course moves too fast, or that the course is “a kilometer wide and only a millimeter deep.”

Students need to hear about special relativity. They should not miss such wonders as the relativity of time, which implies that one-way time travel to the future is possible, or the equivalence of mass and energy, which Einstein considered the most important consequence of his special theory. I’ll come back to this topic in a moment.

Students need some general relativity as the basis for understanding the crowning glory of contemporary physics and astronomy: the new cosmology. We are living in the golden age of cosmology. It started in 1992 with the Cosmic Background Explorer, “COBE.” For millenia, humans have asked: Where did the universe come from? Where did Earth come from? What is

the universe made of? What is the architecture of the universe? Where do humans fit in? For the first time, we are finding evidence-based answers to such questions. And those answers are at least as much about physics as they are about astronomy. How can we ignore the teaching opportunities presented by this moment of discovery? Students deserve to share in the excitement. As an introduction to the new cosmology and its significance, I recommend Joel Primack and Nancy Abrams book *The View from the Center of the Universe*.⁹

Students need to know the fundamentals of quantum physics, which is at the heart of the philosophical divide between Newton's mechanical universe and the post-Newtonian non-mechanical universe. In these days when science so influences our culture, everybody needs to understand this difference. All students need to understand the revolutionary consequences of quantum physics, quantum uncertainty, and quantum non-locality. And students need to learn at least the basic ideas of quantum field theory, our most fundamental and well-verified physical theory, along with the standard model of particles and interactions. And in this time of nuclear power and nuclear weapons, we must not ignore nuclear physics (a topic that's already covered in most introductory courses).

General relativity, quantum physics, quantum field theory, and the standard model sound difficult to us because we usually think of them in abstract, mathematical terms. But if you understand these ideas yourself, you can present them in ordinary English. They're not easy ideas, but neither is Newton's second law an easy idea.

Here's an example of one of the great modern physics principles, the equivalence of mass and energy. Let's do it in the "Peer Instruction" manner that physics educator Eric Mazur recommends to promote active learning even in large classroom settings.¹⁰ Here are a couple of magnets. They're lying on the table, stuck together. Now I'm going to (with some effort) pull them apart and put them, separated, back on the table. Question: In which situation does the system of magnets (which includes their fields) have more energy: before, or after, or is there no change? Talk with your neighbors, and then we'll vote.

OK. How many say the system has more energy before separation? How many say after separation? How many say there's no change?

...Too many of you are sitting on your hands. I'll need to see 90 percent of you voting before we can dismiss the class. So talk with your neighbors and let's try again: How many say "more energy before"? How many say "after"? How many say "no change"?

Very good, class. It's "after," because I had to do work on the magnets in order to separate them, and the second law of thermodynamics tells us that work transfers energy.

Next question: In which situation does the magnet system have more *mass*: before, or after, or is there no change? Talk with your neighbors, and we'll vote.

That's right. It's "after," because energy always has mass, says Einstein. And mass always has energy. That's the idea of $E = mc^2$. Like all the equations of physics, $E = mc^2$ is first and foremost an idea, expressible in words.¹¹

Now ponder this question: Where is the excess mass that the system has after separation? Where is it located?

It's in the so-called "empty" space between the magnets. It's in the electromagnetic field. "Empty" space *weighs*!

$E = mc^2$ is simple but amazing—like all great physics.

There's more: many physicists have always believed that "field mass," such as exists between these two magnets, accounts for all mass. If so, then *everything* is just "empty" space. John Wheeler calls this "mass without mass."

Let's see what Wheeler and others are talking about. Have you ever checked out the masses of quarks, as found in any chart of the standard model of particles and interactions? You'll find that the up and down quark's masses are, respectively, 0.3 percent and 0.6 percent of a proton's mass. But a proton is made of only two ups and one down. So, the stuff a proton is made of has a total mass of only about 1% the mass of the proton!¹² A similar situation holds for neutrons. Where's the other 99%? The answer is in the strong and electromagnetic force fields acting between the quarks! But nearly all the mass of ordinary matter comes from protons and neutrons. So most of the mass of ordinary matter is field mass, just like the mass of the magnetic field between these magnets!

There's still more: it seems odd that most of the mass of normal matter comes from fields, while the mass of the quarks and electrons and so forth is "real mass" (officially called "bare mass") that doesn't come from fields. Why should there be two such different sources of mass? The answer is that the elementary particle masses probably come from fields too, through an idea that Peter Higgs invented in 1964. According to this hypothesis (there is still no experimental evidence for it), the entire universe is uniformly filled with a "Higgs field." Massive elementary particles, such as quarks and electrons, interact with this field, and massless elementary particles, such as photons and gluons, do not. The energy resulting from this interaction, divided by c^2 , is the mass of the particle. So, quarks and so forth get their mass (their inertia) by interacting with the Higgs field.¹³

If so, then all mass comes from fields. In a sense, matter is entirely "empty," like the "empty" space between these magnets. As poet Gertrude Stein said in a different context, there is no there there. And THAT is the ultimate meaning of $E = mc^2$.

The signature of the Higgs field is the quantum of that field, the "Higgs boson." There's still a chance that it will be discovered at Fermilab near Chicago.¹⁴ If not, and if a Higgs field actually exists, then it will probably be discovered at the even more energetic "large hadron collider" under construction at the CERN research center in Switzerland. Stay tuned!

Most of us find this stuff fascinating. So do most students. And it's good physics. We've been talking here about Einstein's mass-energy relation, fields, field mass, bare mass, quarks, the Higgs field, and the Higgs boson. It's really not that difficult. It is possible, and useful, to talk to non-scientists about contemporary physics.

As you can see from this example, fields are central to all of modern physics. Although there are still some physicists who seem to believe that fields are simply useful mathematical fictions, all the major theorists since Maxwell have recognized that fields are physically real. If you believe energy is conserved, you've got to believe fields are real. Here's why: when an electron on Earth sends a signal to the moon, it takes about a second for the signal to get there. But the signal transfers energy to the moon. Where was that energy during that second? It was between Earth and the moon – it was in the electromagnetic field! So if you believe that things possessing energy are real, that is, if you believe that things possessing mass are real (because energy and mass are equivalent), you've got to believe that fields are real.

Steven Weinberg says "quantum fields are the basic ingredients of the universe, and the particles are just bundles of energy and momentum of the fields."¹⁵ In other words (as we also just saw in discussing $E = mc^2$), *the universe is made entirely of fields*. You can teach modern physics without math, but you can't teach it without fields. The lesson for physics teachers is that we need to be sure students really understand the field concept.

I can't resist mentioning one of my favorite ideas: we could simplify the teaching of ordinary quantum physics in introductory general physics courses for scientists and non-

scientists by using concepts from quantum field theory. This simplification doesn't change the mathematics in the least, but simply recognizes that electrons, photons, and other particles are field quanta.

Once you understand the classical electromagnetic field concept, the idea of a quantized field is simple. For instance, when we say that the field of a monochromatic light beam is quantized, we simply mean that the field's total energy must be either 0, or hf , or $2hf$, etc., and *never* any other value. A quantized field is like a bowl that can *only* contain 0 cm, 1 cm, 2 cm, etc. of water. So when that field interacts with matter, an entire hf joules of energy — a quantum — must instantaneously disappear from the entire spread-out field and show up in the atom with which the field happened to interact.

We see in this simple interaction between light and matter the two great surprises of quantum physics, namely uncertainty (because nature doesn't know which atom will interact), and non-locality (because the energy is gathered instantaneously from the entire spread-out field and deposited in one atom). According to relativity, energy has momentum, so the hf joules of energy hit the atom with a jolt, as though the field were a particle. This "particle" is called a photon. But the energy is still distributed at all times in a space-filling field that satisfies the uncertainty relation, that is, one that has a non-zero spatial extension Δx .

These thoughts stem from Dirac's work around 1927. He realized then that quantum field theory resolves such issues as wave-particle duality. Briefly, the resolution for the electron double-slit experiment is that each electron (that is, each electron field) comes through both slits, but collapses to the size of an atom when it interacts with a single atom in the screen. But this resolution hasn't filtered through yet to most physicists — probably because physicists tend to communicate too much in mathematics and too little in words. For more about teaching quantum physics, and about wave-particle duality, see Ref. 16.

V. CONNECTIONS TO SOCIETY

To lift a couple of paragraphs from my textbook:¹⁷

"[Humankind is not adjusting well to the scientific age.] Our most vigorous technological efforts have gone into weaponry to continue the organized killing of our own species. But today the threat of war pales beside the more insidious technology-related environmental threats. Driving all the other problems is the exponential growth of our species. Our 6.5 billion population is already beyond the estimated carrying capacity of the planet, yet we will probably number 9 billion by 2050.

The population explosion and technology have magnified humankind's environmental effect enormously. Humans alone now appropriate some 40% of Earth's total plant growth; we have transformed or degraded 45% of the land surface; we have nearly dried up major rivers by using over half of the accessible fresh runoff water; we have unbalanced the chemistry of our air and water by doubling the natural contribution to Earth's annual production of "fixed" nitrogen; human over-exploitation has made 66% of marine fisheries extinct or nearly extinct; we have raised species extinction rates to between 100 and 1000 times their rates before human domination; we have driven 25% of the bird species to extinction; and we have raised atmospheric carbon dioxide levels to 34% above any level in the past 450,000 years. The combined long-term effect of all this is unpredictable. Although there is probably still time to solve the problems that we have caused, one must ask: Will we?"¹⁸

The survival of civilization is not guaranteed. Stephen Hawking was recently asked by

Yahoo's "Ask the Planet" website to pose a question for internet users to answer. His question was: "In a world that is in chaos politically, socially, and environmentally, how can the human race sustain another 100 years?" Within a few days, 17,000 had responded. Many were doubtful that we will survive.

And yet business continues as usual, and most of us teach our physics courses as usual, with little or no social content. I find this amazing. It's as though we were sitting in a sinking lifeboat, discussing Newton's laws. Somebody had better think about rescuing the lifeboat! Newton's laws are terrific, but today we must also find room in every physics course to consider the health of this rare jewel of a planet. There will be no physics education on a devastated Earth.

Every introductory science course should include societal topics. Such topics should not be tacked on to the end of the course, but should instead be integrated into the science so that students experience science and society as really connected. Insert societal topics at appropriate points throughout the course, somewhat in the manner that traditional problems are inserted into math-based courses. Such inserts can range from a few minutes to an entire lecture. There are plenty of physics-related topics: ozone depletion, global warming, all sorts of transportation issues, the precautionary principle (scientific uncertainty should not be a reason to postpone measures to prevent harm, that is, it's better to be safe than sorry), risk assessment, biological effects of radioactivity, the steam-electric power plant, fossil fuels, nuclear power and related issues, all sorts of renewable energy resources, exponential growth and the population explosion, energy efficiency, the search for extraterrestrial intelligence, pseudoscience, nuclear weapons and related issues, the energy future, and the bottom line in every introductory course: the scientific process.

There's plenty of good physics in these topics, and students are fascinated by their social relevance. Although societal topics occupy only some 15% of the time in my course, it's the part that students remember best, and the part that seems to attract them into the course. The reason: This stuff is directly relevant to their lives. It's been quite noticeable, in my course and elsewhere in my physics experience, that more women than men are interested in the social side of physics. My guess is that greater emphasis on the human relevance of physics would attract more women into physics.

Although few instructors will want to include all these topics, every instructor should include a few. My top choices are overpopulation and global warming. As Al Bartlett has taught us, overpopulation is a driver of all the other human excesses that are destroying the habitability of this beautiful planet. The "population bomb" is all too real. In fact, it exploded decades ago and is devastating the planet, as is evident in Rwanda and the rest of sub-Saharan Africa, Bangladesh, Pakistan, India, China, and especially the United States, where energy shortages, water shortages, congestion, overuse of oil and other resources, enormous carbon dioxide emissions, and uncontrolled overdevelopment are rampant.

Physicist and AAAS President John Holdren tells us that "Over the next several decades, [global warming] will come to be understood as the most dangerous and the most intractable of the environmental impacts of human activity."¹⁹ Without serious action, global warming could advance beyond a point of no return within just a few decades.²⁰ Your grandchildren could find themselves facing global disaster. For a fascinating scientific read about global warming and related issues, see James Lovelock's *The Revenge of Gaia*.²¹ For a general overview of global warming science, see John Houghton's *Global Warming*.²²

But let's end on a happier note. Let me describe some socially relevant physics concerning transportation efficiency. Although we often measure automobile efficiencies in

kilometers per liter of gasoline, “passenger-moving efficiency” is a more general and useful measure because it can compare different modes of travel and because we really want to move passengers rather than the two-ton car. We can measure it in passenger-kilometers (the number of passengers times the number of kilometers) per megajoule of energy. Measured this way, what do you suppose is the most efficient way to transport humans? Talk with each other about it. For the answer, see Table I. For bicycling and walking the energy comes, of course, from the extra food calories (above those consumed while resting) consumed during those activities.

Now let’s broaden our efficiency comparisons to the entire animal and technological kingdoms. How do bikes and buses compare with birds and bees? We shouldn’t use passenger-moving efficiency for this comparison, because tiny creatures like bees would come out far ahead since they use so little energy to transport one passenger. Instead, we need to give the animal credit for its mass, including the mass of any vehicle. So the natural measure for this comparison is “mass-moving efficiency,” measured in kilogram-kilometers (the mass of the animal plus any vehicle that might be involved, times the distance) per megajoule. So whales and airplanes get credit, in the numerator, for the large mass that they must transport. Now, in terms of mass-moving efficiency, how do birds, bees, bikes, and buses compare?Table II shows typical values.²³

Again, the human on a bicycle comes out far ahead! I regard the bicycle as one of the world’s most elegant pieces of technology. I ride mine to campus every day, and have always made a point of living within an easy bike ride of work. Getting to work in a couple of tons of carbon-belching steel is not the way I want to begin my day.

What’s the secret of the bicycle’s efficiency? The answer lies in the most basic physics: Newton’s first law and the second law of thermodynamics. Bicycles have wheels. Rolling vehicles are able to take advantage of Newton’s first law by maintaining their motion. Walkers such as horses and humans must start and stop their legs with every step, which involves accelerations, forces, work, and energy. That’s why Carl Sagan used to say that if animals were to evolve on a planet that was “paved” by lava outflows, they would evolve wheels. On Earth, there are salamanders that form hoops to roll down hills.

Trains and automobiles employ wheels too, but they also employ heat engines. The second law of thermodynamics declares that engines running at practical temperatures are horribly inefficient. But animals convert chemical energy directly into work so they are not heat engines and don’t have to contend with the second law.

The bottom line is that we need to teach “relevant physics”—physics based on our present knowledge of the universe, and physics with a social component—to all students.

¹ Bernard V. Khoury “Education ... Priority or Problem,” AAPT Announcer **31** (1), 4-5 (2001); Bernard V. Khoury “Physics for All,” AAPT Announcer **30** (4), 6 (2000).

² If you want to join the list, email me at ahobson@uark.edu.

³ F. James Rutherford, *Project 2061: Science for All Americans* (American Association for the Advancement of Science, Washington, DC, 1989).

⁴ *ibid.* p. 13.

⁵ David Goodstein, “The science literacy gap: A Karplus Lecture,” J. Sci. Educ. Tech. **1** (3), 149-155 (1992).

⁶ Paul G. Hewitt, “The missing essential—a conceptual understanding of physics,” *Am. J. Phys.* **51** (4), 305-311 (1983).

⁷ “Weisskopf and Ehrenfest,” *Am. J. Phys.* **59** (8), 754 (1991).

⁸ See for example Lillian C. McDermott, “How we teach and how students learn—A mismatch?” *Am. J. Phys.* **61** (4), 295-298 (1993); Lillian C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry* (John Wiley & Sons, New York, 1996); Alan Van Heuvelen, “Learning to think like a physicist,” *Am. J. Phys.* **59** (10), 891-897 (1991); Alan Van Heuvelen, “Overview, Case Study Physics,” *Am. J. Phys.* **59** (10), 898-907 (1991); David Hestenes, Malcolm Wells, and Gregg Swackhamer, “Force concept inventory,” *Phys. Teach.* **30** (3), 141-158 (1992); David Hestenes and Malcolm Wells, “A mechanics baseline test,” *Phys. Teach.* **30** (3), 159-166 (1992); Arnold B. Arons, *A Guide to Introductory Physics Teaching* (John Wiley & Sons, New York, 1990).

⁹ Joel Primack and Nancy Ellen Abrams, *The View from the Center of the Universe: Discovering Our Extraordinary Place in the Cosmos* (Riverhead Books, New York, 2006).

¹⁰ Eric Mazur, *Peer Instruction* (Prentice Hall, Upper Saddle River, NJ, 1997).

¹¹ See Art Hobson, “Teaching $E = mc^2$: Mass without mass,” *Phys. Teach.* **43** (2), 80-82 (2005).

¹² More accurately, in a quantum chromodynamic model of the proton in which the up and down quark masses are set equal to zero and the other 4 kinds of quarks are omitted, the computed mass of the proton is found to be accurate to within 10%. See Frank Wilczek, “Mass without mass I: Most of matter,” *Phys. Today* **52** (11), 11-13 (1999).

¹³ It’s perhaps misleading to call this process an “interaction,” because the Higgs field is not a force field in the usual sense. A more appropriate phrasing might state that, due to the Higgs field, the Higgs mechanism” causes particles to have a rest mass m and hence mc^2 joules of rest energy. See Gordon Kane, *Supersymmetry: Unveiling the Ultimate Laws of Nature* (Perseus Publishing, Cambridge, MA, 2000), pp. 149-152.

¹⁴ Adrian Cho, “Aging atom smasher runs all out in race for most coveted particle,” *Science* **312**, 1302-1303 (2006).

¹⁵ Steven Weinberg, in *Conceptual Foundations of Quantum Field Theory*, edited by Tian Yu Cao (Cambridge University Press, Cambridge, UK, 1999), p. 242.

¹⁶ Art Hobson, “Electrons as field quanta: A better way to teach quantum physics,” *Am. J. Phys.* **73** (7), 630-634 (2005); also Art Hobson, “Teaching quantum physics without paradoxes,” accepted for publication in *The Physics Teacher*, preprint available at <physics.uark.edu/hobson/>.

¹⁷ Art Hobson, *Physics: Concepts & Connections* (Prentice Hall, Upper Saddle River, NJ, 2006), 4th ed., p. 288.

¹⁸ The figures in this paragraph are based on Peter Vitousek, Harold Mooney, Jane Lubchenco, and Jerry Melillo, “Human domination of Earth’s ecosystems,” *Science* **277**, 494-499 (1997).

¹⁹ John Holdren, “The energy-climate challenge,” *Environment* **43** (5), 8-21 (2001), p. 10.

²⁰ See for example, Richard Kerr, “Looking way back for the world’s climate future,” *Science* **312**, 1456-1457 (2006); also James Lovelock, *The Revenge of Gaia* (Perseus/Basic Books, New York, 2006), pp. 46 and 51.

²¹ James Lovelock, *The Revenge of Gaia* (Perseus/Basic Books, New York, 2006).

²² John Houghton, *Global Warming: The Complete Briefing* (Cambridge University Press, Cambridge, UK, 3rd edition 2004).

²³ Table II is based on the data in S. Wilson, "Bicycle technology," *Sci. Am.* **228** (3), 81-91 (1973).

TABLE I. Passenger-moving efficiencies of different human transportation modes

Human on bicycle	18. pass-km/MJ
Human walking	5.
Intercity railroad train	1.7
Urban bus	0.9
Carpool auto (occupancy = 4)	0.7
Commercial airplane	0.4
<u>Commuting auto (av occupancy 1.15)</u>	<u>0.2</u>

TABLE II. Mass-moving efficiencies of animals and machines

Human on bicycle	1100 kg-km/MJ
Typical fish	600
Horse	500
Human walking	300
Typical bird	200
Intercity railroad train	100
Urban bus	55
Hummingbird	50
Carpool auto	40
Commercial airplane	40
Fly, bee	20
Commuting auto	12
<u>Mouse</u>	<u>5</u>