Reprinted from *Proceedings of the '99 International Conference of Physics Teachers,* Guilin, China, August 1999.

RELEVANT PHYSICS FOR EVERYONE: TEACHING SOCIETAL TOPICS IN INTRODUCTORY PHYSICS

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Abstract: Industrialized societies can succeed only if their citizens are scientifically literate. Thus, every citizen's education should include "relevant science." A relevant science course should be conceptual rather than technical, and should include the connections between science and its cultural and social impacts. I have developed and taught a course of this type since 1976. This "active learning" workshop will discuss societal topics that can be included in such courses. Examples include global warming, transportation, exponential growth, pseudoscience, risk assessment, nuclear weapons, nuclear power, technology assessment, and the energy future. A textbook is available: "Physics: Concepts and Connections," by Art Hobson (Prentice Hall Publishing Company, 2nd Edition 1999, planned for translation and publication in China).

Introduction: The Need for Science Literacy for All Citizens

Readers are probably aware of widespread scientific illiteracy, and of the grave significance of this fact. For example, physicist and educator David Goodstein observes that "approximately 95% of the American public is illiterate in science by any rational definition of what we mean by science literacy."

Many educators believe that *all* citizens--including non-scientists--need to be scientifically literate. *Science for All Americans*, a study sponsored by the American Association for the Advancement of Science (AAAS), presents a compelling reason for universal science literacy:

> What the future holds in store for individual human beings, the nation, and the world depends largely on the wisdom with which humans use science and technology. ...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.*

The Union of Concerned Scientists, a U.S. non-governmental organization of scientists working to solve the environmental and security threats facing humanity, recently published a powerful statement affirming the societal importance of science. The statement was signed by thousands of prominent world scientists, *including a majority of the world's living Nobel Prize winners in science.* This "World Scientists' Warning to Humanity" states in part:

> Human beings and the natural world are on a collision course. ...If not checked, many of our current practices...may so alter the living world that it will be unable to sustain life in the manner that we know. Fundamental changes are urgent if we are to avoid the collision our present course will bring about.
>
> We the undersigned, senior members of the world's scientific community, hereby warn all humanity of what lies ahead. A great change in our stewardship of the earth and the life on it is required, if vast human misery is to be avoided and our global home on this planet is not to be irretrievably mutilated.

It is surprisingly easy, fun, and rewarding to change a socially and culturally irrelevant science course into a relevant one. This paper presents recommended teaching principles for introductory college-level physics courses for non-scientists and then presents, as a specific example, one of the many societal topics that can be taught in such a course: transportation and energy use.

Some General Principles for Introductory Courses

One important principle for *every* introductory physics course, for scientists as well as non-scientists, is *concepts first*, before calculations. Many studies have shown that students in traditional physics courses learn only how to solve certain standard types of problems, without actually learning the physics concepts that are the main point of the course. Conceptual understanding should be the focus, rather than the mere ability to memorize formulas and carry out routine calculations. A careful instructor can express even the most sophisticated modern scientific topics in nontechnical, conceptual, but accurate language that nonscientists can understand.

There are, however, a few quantitative skills that are relevant for nonscience students: interpreting graphs, probabilistic reasoning, making estimates, powers of ten, and proportionalities, for example. In my experience, all students can develop these abilities and incorporate them into the flow of a science course without detracting from the central concepts.

Interactive engagement is now recognized as an important technique in introductory courses. Educational research has shown that traditional lecturing, in which students listen passively, results in surprisingly little real learning. Instead, teaching styles in which students actively engage in discussing questions with each other, actively work out answers for themselves, and interact with the instructor, are measurably more effective in imparting real understanding.

Most introductory science courses are crammed with far too much material. Thus it is important to *restrain the amount of subject matter*. What to leave out? The key here is to begin from the opposite question, "What to include?" and include *only* what is relevant to your specific course goals, perhaps omitting many "standard" topics.

Modern and Philosophical Topics

Although most introductory courses are primarily devoted to classical theories, especially Newtonian mechanics, citizens need to understand *current* scientific views. Although quantum and relativistic physics have been our basis for understanding the universe for nearly a century, many introductory courses still nearly exclude them. Thus many nonscientists and scientists alike finish college without discovering that there are a few loopholes in $F = ma$, not to mention misconceptions in the classical views on time, space, mass, radiation, matter, energy, continuity, observation, causality, locality, and physical reality itself. Students seldom get a real feeling for what is arguably the central scientific theory of our time, quantum theory.

Physics courses and textbooks are so full of pre-twentieth-century physics that it is difficult to get to modern physics. The solution is to simply omit many classical topics. For example, my course omits linear momentum, impulse, angular momentum, torque, rigid body rotations, center of mass, stress and strain, liquids, the gas laws, specific heat, sound, electric potential, electric resistance, Ohm's law, circuits, Faraday's law, alternating current, geometric optics, reflection, refraction, mirrors, lenses, color.

For centuries, the philosophical assumptions of science have strongly influenced our culture. For example, the Newtonian concept that we are ultimately ruled by universal natural laws, rather than by Kings or other individuals, formed the intellectual background for the American Revolution. Thus there are strong reasons, especially in science literacy courses, for stressing the philosophical aspects.

Open up, for class discussion, such questions as the nature of scientific knowledge, materialism, the origin of life, the relation of technology and ethics, the origin of the universe, science and religion, and the meaning of quantum theory. Scientific methodology is the most significant science-related philosophical topic. Many science educators urge that this be the focus of science literacy, because today's citizens must base their public-policy decisions on observed evidence and rational thought--the methods of science--rather than on tradition, authority or superstitious beliefs.

Social Topics

Citizens must be able to form intelligent opinions about science-related social issues, or industrial democracy cannot succeed. To accomplish this social goal, it is sufficient to simply include a representative sampling of societal topics within a standard physics course. This is easy to do, without using too much class time, by using a few societal topics as examples that illustrate the basic physics. Thus social topics can largely replace the standard problems that occupy so much time in more technical courses. An occasional class period devoted to global warming, ten minutes devoted to transportation, or an article from a recent newspaper, can accomplish wonders in awakening students to the full range of social topics.

Social topics are highly motivating teaching tools, imparting an unforgettable relevance that affects students long after the final exam. These topics contain plenty of good science--science that students are likely to want to learn because they see the connection to their own lives.

Table 1 lists several physics-related social topics that could be included in an introductory physics course, together with a description of where each topic might naturally fit within the course, and how much time I actually devote to this topic in my own course. Do not feel that, in order to present a socially relevant physics course, you must present very many of the topics in Table 1! Instead, try introducing one or two of these topics into your course the next time you teach it, and then consider adding additional topics later. These topics can be inserted, or deleted, in any introductory course, depending on the time available and the interests of students and instructors.

Some of these topics are controversial. For example, many religious fundamentalists object to the theory of biological evolution. They would like me to present "creationism" (the belief that the species, and especially humans, were separately created, and that Earth itself was created only a few thousand years ago) as an acceptable alternative to evolution. My method of dealing with controversial topics is to always teach the scientific consensus, and to teach the evidence supporting that consensus--such as the radioactive evidence for Earth's 4.6-billion-year age.

As an example, the following section discuses one of the topics listed in Table 1.

TABLE 1. Social Topics That Could Be Included In An Introductory Physics Course

Topic	**Where It Would Fit**	**How Much Time In My Course**
Energy consumption in U.S.	Energy, thermodynamics	10 minutes
Transportation and energy use	Energy, thermodynamics	20 minutes
Fossil fuels	Energy, thermodynamics	10 minutes
Steam-electric power plant	Energy, thermodynamics	20 minutes
Global ozone depletion	Electromagnetic spectrum (ultraviolet)	50 minutes
Global warming	Electromagnetic spectrum (infrared)	50 minutes
Extraterrestrial life ("SETI")	Special relativity	100 minutes
Pseudoscience, creationism	Radioactive dating (geol ages), or SETI	10 minutes
Biological effects of radioactivity	Nuclear physics	30 minutes
Quantitative risk assessment	Nuclear physics (biol effects of radiation)	10 minutes
Nuclear weapons	Fission, fusion	30 minutes
Nuclear power	Fission	50 minutes
Renewable energy sources	Energy, thermodynamics	30 minutes
Energy efficiency/conservation	Energy, thermodynamics	20 minutes

An Example: Teaching About Transportation and Energy

The transportation mode that consumes the most energy, and that has the greatest environmental impact, is the automobile. As an eye-opening exercise that demonstrates the power of simple numerical estimations, ask students to estimate the rate at which a typical automobile consumes energy, beginning from the fact that calorimetry experiments show that 1 liter of gasoline, when burned, creates about 35 million joules (J) of thermal energy. As additional hints, a typical car travels about 12 km on one liter of gasoline, at a typical speed of 80 km/hr. The answer is about 70 kW--the power consumed by 700 bright 100-W lightbulbs! This assumes constant speed. Acceleration multiplies the power by about 5.

Figure 1 shows the energy transformations in a typical automobile. Such "energy-flow diagrams" are quite useful in explaining physical processes. They illustrate, at a glance, the two great laws of energy: conservation of energy (equivalent to the first law of thermodynamics), and the second law of thermodynamics. Being always conserved, energy can be pictured as a fluid that changes form but maintains its volume: The amount flowing into any energy transformation is the same as the amount flowing out.

Figure 1 also illustrates the second law of thermodynamics, in the overall transformation from non-thermal energy to mostly thermal energy, and also in the portion labeled "engine," where only a small fraction of the energy emerges as mechanical work.

Because energy resources are finite, and energy use creates pollution, the question of a device's "energy efficiency" is socially important. The second law tells us that any device using thermal energy to do work must be less than 100% efficient. Quantitatively, the "energy efficiency" (work done divided by total energy input) cannot be greater than $(T_1\text{-}T_2)/T_1$, with T_1 and T_2 the input and exhaust temperatures in Kelvin. With a typical T_1=600 K and T_2=300 K, this maximum energy efficiency is 50%. In fact, the actual engine efficiency indicated in Figure 1 is only 17/69=25%. Worse yet, the "overall energy efficiency" of the entire car in moving itself and its occupants down the road is only 9/70=13%, or about 1/8. In other words, of every 8 liters of gasoline put into a car, only 1 liter actually gets the car down the road!

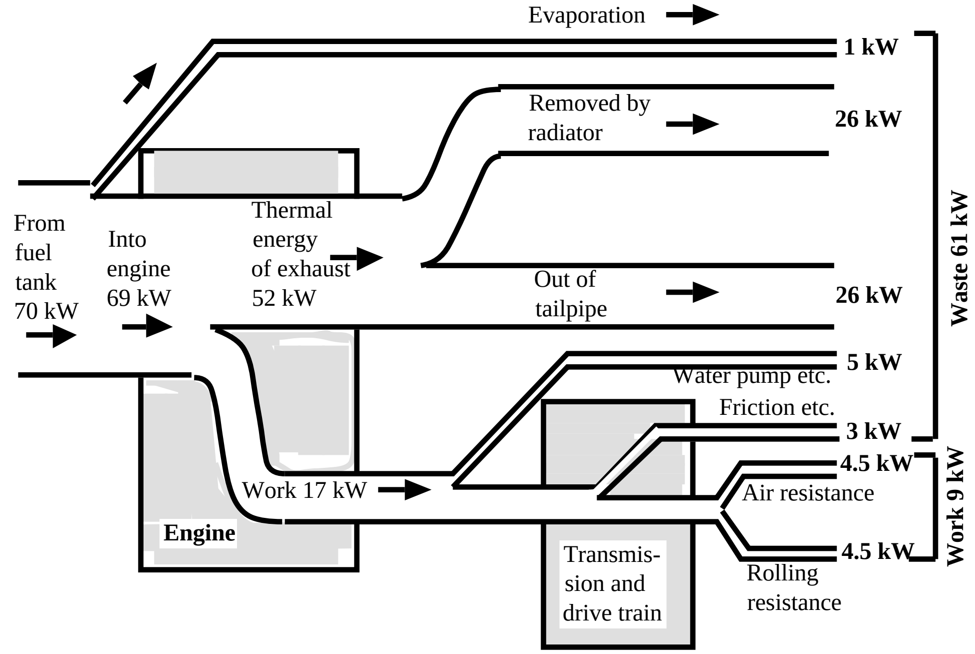

FIGURE 1. Typical Energy Flow Rate In An Unaccelerated Car At Highway Speed.

But this is not the end of the story, because the human purpose of a transportation vehicle is not to move the *vehicle* down the road, but rather to move *people* down the road. So we need another, more socially appropriate, measure of efficiency. Maintaining the general notion that the "efficiency" of a device represents the "useful output" obtained from the device divided by the "total input" needed to operate the device, we define "passenger-moving efficiency" as the number of passenger-kilometers moved (number of passengers multiplied by kilometers moved), per megajoule (MJ) of energy consumed. This definition allows us to compare transportation modes (Table 2).

We can even compare the passenger-moving efficiencies of different animals and machines, but in this case we need an efficiency measure that accounts for the quite different masses of different animals. Thus our efficiency measure is *kilograms* (of passengers)-kilometers per MJ (Table 3).

TABLE 2. Passenger-Moving Efficiencies Of Different Human Transportation Modes, In Passenger-Kilometers Per Megajoule

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
Commuting auto (average occupancy = 1.15)	0.2

TABLE 3. Passenger-Moving Efficiencies Of Animals And Machines In Kilogram-Kilometers Per Megajoule.

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
Mouse	5

By far the most efficient passenger mover, not only among human transportation modes but also among the entire animal kingdom, is the human on a bicycle. There are two fundamental physical reasons for this: First, bicycles run on wheels, which take advantage of *the law of inertia* (Newton's First Law) by continuing to roll once set into motion. Second, the bicycle is far more efficient than other wheeled vehicles, namely autos, buses, trains, and airplanes, because of *the second law of thermodynamics:* Vehicles that employ heat engines must obey the second law's severe restriction on efficiency.

Vehicles can also move freight. An appropriate measure of freight-moving efficiency is kilograms of freight multiplied by kilometers moved, per MJ (Table 4).

TABLE 4. Freight-Moving Efficiencies, In Kilograms-Kilometers Per Megajoule

Railroad train (freight)	3100 kg-km/MJ
Truck (heavy)	490
Airplane (freight)	74

Here, trains are 6 times more efficient than trucks, and 42 times more efficient than airplanes (Table 4). Furthermore, trains are about twice as efficient as buses, four times more efficient than airplanes, and eight times more efficient than commuter autos, at moving people (Table 2). Again, there are basic physical reasons for this. All of these vehicles do most of their work against air resistance and rolling resistance (Figure 1). Trains reduce air resistance by presenting only a single frontal surface while carrying a large load. Rolling resistance results from heat generated by the tires compressing the air inside when each portion of the tire contacts the road. Steel wheels on steel tracks avoid this loss. Trains are "good rollers." Bicycles with very hard, high-pressure tires are also good rollers, as any experienced bicycle rider can tell you.

One Earth, One Chance

Industrial democracy cannot work without scientifically literate citizens. Relevant science is essential not only for the sake of science, but also for the planet.