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Physics literacy, energy and the environment

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Abstract

Socially aware science literacy courses are sorely needed in every nation that is industrialized and democratic. This article puts societal topics into the more general context of science literacy, suggests that socially significant topics can fit comfortably into a physics literacy course, looks at energy and environment issues, and discusses how one might teach three such issues: energy use in transportation, global ozone depletion and global warming.

Physics literacy for all citizens

According to the American Association for the Advancement of Science's (AAAS) project *Science for All Americans* (Rutherford and Ahlgren 1990), "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."

Indeed, industrialized democracies will not survive unless their citizens are scientifically literate. This is true for the very simple reasons that, in industrial nations, many of the most crucial decisions concern science and technology, and in democracies, citizens decide. Citizens really do need to know about energy, the environment and a host of other science-related topics.

But today's industrialized democracies are far from scientifically literate. For example, 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" (Goodstein 1992).

Jon Miller, Director of the International Center for the Advancement of Scientific Literacy and Professor of Journalism at Northwestern University, is a leader in the measurement and analysis of the public understanding of science. He defines 'civic scientific literacy' as (1) an understanding of basic scientific concepts such as the molecule and the structure of the solar system, (2) an understanding of the nature of scientific inquiry, and (3) a pattern of regular information consumption, such as reading and understanding popular science books. By this measure, Miller reports that approximately 10% of American adults qualified as civic scientifically literate in the 1980s and early 1990s, but that this proportion increased to 17% by 1999. He goes on to report that, rather surprisingly, the proportion of scientific literacy is even lower than this in Canada, Japan and the EU. Miller comments that these levels may be too low for the requirements of a strong democratic society in a new century of accelerating scientific development (Miller 2002 and references therein).

All of this points to a need for science literacy courses at every educational level. But few if any nations offer anything that comes close to fulfilling this requirement, especially in physics. Certainly this is true in the USA, where the great

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majority of secondary school graduates have never studied physics, and if they have studied physics then it is likely to have been in a narrowly focused technical course that doesn't mention the scientific literacy issues needed by citizens in a democratic society. The ailing state of US public school science education is borne out by the results of international science and mathematics tests that generally show US students to be performing behind their counterparts in other industrialized nations and, indeed, in many developing nations.

As one possible bright spot in all of this bad news, it is interesting to ask why US *adults* are actually *more* scientifically literate than their counterparts in other industrialized nations, while US secondary school students perform more poorly than those in other nations. Analysing his data, which included each individual's age, educational attainment, college science courses completed and other factors, Miller concluded that by far the strongest indicator of adult scientific literacy was the number of *college*-level science courses taken. More specifically, the slightly higher proportion of scientifically literate adults in the US is explained by the larger number of so-called 'general education courses' ('cultural enlightenment' courses that are entirely outside the student's major field of study) in science that US non-scientists take as college students. As Miller notes, it is not well known in the scientific community that the US is the only major nation that requires general education courses for its university graduates.

Given the need for science literacy courses at both the public school and university level, how should we structure them? Briefly (see Hobson 2000 for details), general physics courses for non-scientists should be taught in a manner that inspires student understanding and enthusiasm, and is relevant to the cultural and social needs of students and society. More specifically, the course should:

- be conceptual (non-algebraic) but numerate (powers of ten, metric system, graphs, percentages, estimates, probabilities, proportionalities);
- use 'interactive-engagement' or 'inquiry' techniques that cause students to engage, with other students, the instructor, a computer screen or a textbook, in the scientific thought process;
- be focused on a few themes rather than encyclopedic;
- instil scientific habits of mind by means of a recurrent theme such as 'how do we know?'
- devote 50% or more of its time to so-called 'modern' (i.e. since the beginning of the *preceding* century) physics and contemporary physics; and
- include societal topics such as energy resources and the environment.

The remainder of this article will focus on the last of these points.

Societal topics appropriate to physics literacy courses

A wide variety of socially significant topics can fit comfortably into a physics literacy course. My teaching typically includes these:

- scientific methodology (a recurrent theme),
- materialism and the Newtonian mechanical universe,
- the automobile (discussed below),
- transportation efficiency (discussed below),
- the steam–electric power plant (how it works, energy flow, energy efficiency),
- resource use and exponential growth (including the population explosion),
- global ozone depletion (discussed below),
- global warming (discussed below),
- the search for extraterrestrial intelligence and Fermi's questions (where is everybody? will technological civilizations endure?)
- the interpretation of quantum physics, and contrasts with Newtonian physics,
- radioactive dating and the geological ages,
- human exposure to ionizing radiation,
- dealing with risk in a technological society,
- the history of fission energy,
- the Manhattan Project (the first fission bomb),
- fusion weapons,
- evidence for the big bang, and details of the big bang inflationary origin of the universe,
- the energy future (fossil, nuclear and renewable energies, and energy efficiency).

This is a long list, and certainly one does not need to include all of it in any particular course. In fact, one can increase student enthusiasm and demonstrate the social relevance of physics by simply including one or two such topics. On the other hand, science literacy courses do not need to, and indeed should not, include the traditional algebra-based physics problems that occupy so much time in other courses, and should not try to cover the plethora of narrow 'classical' topics usually included in traditional courses. Instead, the course should limit itself to the few most general physical principles, such as Newton's first law, conservation of energy, the second law of thermodynamics, fields, the constancy of the speed of light and quantization, that are fundamental to understanding the physical universe.

You can present many societal topics briefly as illustrations and applications of the major principles of physics. Rather than adding them on at the end of the course, integrate these topics into the course as soon as students have learned the physics principles needed to understand that topic. For example, teach transportation issues as applications of mechanics and thermodynamics, and teach global warming following energy and electromagnetic radiation.

Always emphasize general scientific principles, so that students can see that physics really is relevant to important social issues. Present plenty of evidence, employ critical thinking and emphasize scientific methodology, especially if the issue is a controversial one such as global warming or nuclear power. Keeping in mind that, for students, the exams define your real course goals, be sure to include societal topics on examinations.

Energy and society[1]

Energy makes a wonderful recurrent theme in science literacy courses. Energy concepts are more useful than are the Newtonian force concepts to which we usually devote so much time. This is because energy enters into a first-order differential equation involving speed whereas force enters into a second-order equation involving acceleration, and because energy survives nearly unscathed (but quantized, and equivalent to mass) in modern physics. The essentials of nearly every physical process can be understood in terms of 'energy transformations'.

For example, when a book falls without air resistance from some height onto the floor, energy transforms from gravitational energy (of the raised book), to kinetic energy (of the falling book) to thermal energy (of the book and the floor and the surrounding air) created upon impact with the floor. Air resistance can be included as thermal energy created by interactions with air molecules during the book's fall. Through all of this, the total energy is the same at every instant. One can see the second law of thermodynamics in the conversion of mechanical energy (gravitational or kinetic) into thermal energy. This simple and common process would be quite difficult, and strictly speaking impossible (because thermal energy is a non-Newtonian microscopic concept), to describe with Newtonian force concepts.

Besides its scientific utility and generality, energy has great societal significance because it is what can make things go (i.e. the ability to do work), because of shortages of the technologically convenient forms of energy and because of the environmental impact of most energy-transforming devices.

As an example, consider transportation devices. 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 experimental fact that 1 litre of gasoline, when burned, creates about 35 million joules (J) of thermal energy. As hints, a typical car travels about 12 km on one litre of gasoline, at a typical speed of 80 $\mathrm{km\,h^{-1}}$. The answer is about 70 kW—the power consumed by 700 bright 100 W lightbulbs! This assumes constant speed. Acceleration multiplies this power by about five.

Figure 1 shows the energy transformations in a typical automobile. Such 'energy-flow diagrams' are useful in explaining a wide variety of 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.

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[1] A portion of this section is reprinted, with permission, from *Proceedings of the 1999 International Conference of Physics Teachers & Educators*, edited by Luo Xingkai and Zhao Kaihua (Guilin, China: Guangxi Normal University Press, 2000).

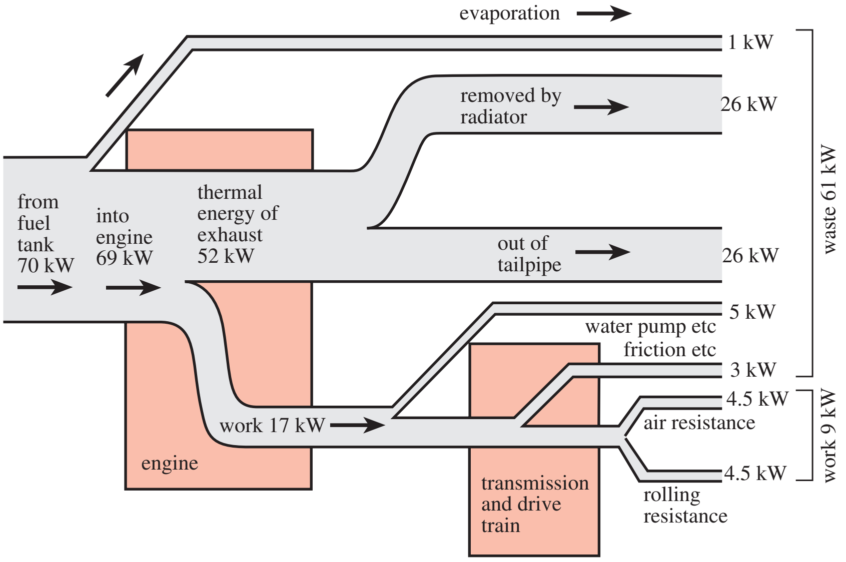

Figure 1. Typical energy flow rate in an unaccelerated car at highway speed.

Figure 1 illustrates the second law of thermodynamics in the overall transformation from microscopically more organized non-thermal energy to less organized thermal energy, and also in the portion labeled ‘engine’, where only a small fraction of the energy emerges as mechanical work and the rest emerges as lower-temperature thermal energy because entropy must increase. It is this tendancy of thermal energy to flow from higher temperatures to lower temperatures, and thus to increase its entropy by equilibrating, that drives heat engines.

Because energy resources are finite, and energy use creates pollution, the question of a device’s ‘energy efficiency’ is socially significant. The second law tells us that any device using thermal energy to do work must be less than 100% efficient. Quantitatively, for an automobile engine operating at a typical 600 K and exhausting at a near-atmospheric temperature of about 300 K, the second law allows a maximum ‘energy efficiency’ (useful work output divided by total energy input) of 50%. In fact, the typical real 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 eight litres of gasoline put into a car, only one litre actually gets the car down the road!

All of this should be communicated to students via interactive engagement. In my large classes, I typically put up a transparency of figure 1 and then go through a series of multiple-choice questions on transparencies, in order to guide the class, through in-class discussion with peers plus a feedback mechanism (Meltzer and Manivannan 1996), toward proper answers.

But our automobile’s 13% efficiency is not the end of the story, because the purpose of most transportation vehicles 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-kilometres moved (number of passengers multiplied by kilometres moved) per megajoule (MJ) of energy consumed. This definition allows us to compare transportation modes (table 1). In table 1, the energy input for humans is food calories. Business majors, for example, need to know such things as table 1 if we are to develop rational transportation systems.

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*

Table 1. Passenger-moving efficiencies of different human transportation modes, in passenger-kilometres per megajoule.

Mode	Efficiency (pass-km MJ^{-1})
Human on bicycle	18
Human walking	5
Intercity 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 2. Mass-moving efficiencies of animals and machines in kilogram-kilometres per megajoule.

Mode	Efficiency (kg km MJ^{-1})
Human on bicycle	1100
Typical fish	600
Horse	500
Human walking	300
Typical bird	200
Intercity train	100
Urban bus	55
Hummingbird	50
Carpool auto	40
Commercial airplane	40
Fly, bee	20
Commuting auto	12
Mouse	5

(of animals and vehicles) times kilometres per MJ (table 2).

It is striking that the most efficient mass mover by far, not only among human transportation modes but also among all animals, is the human on a bicycle. There are two excellent 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 the other wheeled vehicles because of the second law of thermodynamics: whereas animals convert chemical energy directly to work, mechanical devices that convert thermal energy to work must conform to 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 kilometres moved per MJ (table 3).

Table 3. Freight-moving efficiencies, in kilogram-kilometres per megajoule.

Mode	Efficiency (kg km MJ^{-1})
Train (freight)	3100
Truck (heavy)	490
Airplane (freight)	74

Here, trains are six times more efficient than trucks, and 42 times more efficient than airplanes. Again, this stems from physical principles. These vehicles do most of their work against air resistance and rolling resistance (figure 1). Trains reduce air resistance by presenting a small single frontal surface while carrying the amount of freight that would be borne by about 200 trucks. Rolling resistance results from the backward torque of the force couple that is created by the partial flattening of the tyre on the road (Doménech *et al* 1987). Steel wheels on steel tracks avoid this loss by flattening only slightly, making trains 'good rollers'. High pressure bicycle tyres are also good rollers, as any experienced cyclist can tell you.

The environment

Global ozone depletion and global warming are exemplary physics-packed environmental topics. I devote one 50 minute period to each, immediately following the electromagnetic spectrum and the solar spectrum. Many physics and societal lessons become obvious when one presents ozone depletion followed immediately by global warming. Both topics involve regions of the electromagnetic spectrum (ultraviolet and infrared, respectively). Both problems are caused by specific human-made chemicals released into the atmosphere, mainly chlorofluorocarbons (CFCs) and carbon dioxide, respectively. It is not surprising that these are the first environmental issues of truly global reach, in the sense that the CFCs or carbon dioxide released by a spray can or automobile in Chicago soon creates problems in Africa and Antarctica. After all, the atmosphere mixes around the globe in just a few years. The two problems amplify each other because CFCs are potent greenhouse gases, and global warming actually cools the stratosphere, which heightens the upper atmospheric frigidity that is a prerequisite for polar ozone depletion.

The human release of ozone-depleting chemicals is essentially finished history. International treaties banning these chemicals include about all that one could hope for, and atmospheric concentrations are finally turning downward. It remains for us only to wait out the 50 years during which nature will provide her answer to our unintended global experiment with CFCs.

Ozone depletion should be presented just before global warming, because the ozone story brings good news that can instil the courage we need to confront global warming. The ozone story is an ‘existence proof’ that solutions to such problems are possible. For further details on these topics, see Hobson (1993, 2000).

Summary

Energy use in transportation, global ozone depletion and global warming are just a few examples of the many societal and cultural topics that can and should be incorporated into science literacy courses for all students. Such courses are sorely needed at both the public school and university level in every nation that is industrialized and democratic.

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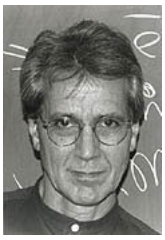

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