LETTERS

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that approach is appropriate for mission agencies, it seems less so for basic research agencies.

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Readers Illuminate Issues of Solid-State Lighting

It is refreshing to find proponents of solid-state light sources (SSLs) addressing the all-important issue of cost, as Arpad Bergh, George Craford, Anil Duggal, and Roland Haitz did (PHYSICS TODAY, December 2001, page 42). It is also gratifying to see the steady progression of reduction in cost per lumen shown in figure 2 of their article. The authors note that white-light SSLs must reach costs of $0.05 per lumen to be economically justified in replacing incandescent light sources for residential use.

For a number of years, I was the director of R&D for a major US lamp company (see PHYSICS TODAY, February 2001, page 38), and am presently an independent consultant specializing in the science and technology of light sources. I would like to make two points. The lesser one is to ask for a better definition of "cost." There are many possible definitions of the cost of a mass-produced, mass-merchandized item. The direct cost of manufacture is the cost of materials plus the cost of labor plus overhead for the manufacturing process. The total manufacturing cost (TMC) also includes the allocated cost of the facilities and automated manufacturing equipment, including capital expenses. To get the retail cost to the consumer, one must add costs for warehousing, transportation, advertising, and distribution to retailers, and the cost of retailing itself. The retailer of incandescent lamps typically keeps $0.25–$0.30 out of every customer's dollar to cover his costs. The net result is that the retail price to the consumer for such a mass-produced and mass-merchandised item is typically 10 or more times the direct cost of manufacture. To which of these costs does figure 2 refer?

My second, and major, point is that a product presently on the market is the functional equivalent of the incandescent lamp in size, lumen output, color, and color rendering, but triple the efficacy, and it is available for $0.05 per lumen retail cost to the consumer: the compact fluorescent lamp (CFL). Its sales are minuscule. Despite elaborate charts demonstrating payback through energy savings in one year, residential customers don't buy them. The market dynamics are simple: The customer goes to the grocery store to buy supplies, with light bulbs on the list. The choice is stark: $2 for a four-pack of incandescent bulbs and steak for dinner or $30–40 for a four-pack of CFLs and beans for dinner. Why should SSLs be any different?

There is a mechanism for overcoming this obstacle, but its use is very limited. My local electric utility purchases CFLs in bulk and leases them at $0.20 per month to its retail customers. The typical customer saves $0.50 in electricity costs per bulb per month, and so achieves a net savings of $0.30 per bulb per month from day one (assuming replacement of 75-watt incandescent bulbs). Total household monthly savings then, without any up-front investment, are $0.30 times the number of bulbs replaced. The utility reduces its peak demand load by 50 watts per unit, and it only pays wholesale cost (say, $5) for the product, thereby increasing its effective capacity at a cost of $100 per kilowatt, instead of more than $1000 per kilowatt to build new generating plants. This ingenious scheme is actually limited to utilities whose peak load occurs on winter nights, which applies to fewer and fewer utilities today.

Articles elsewhere on the subject of SSLs have suggested that government funds of $50 million per year invested in supporting SSL development could greatly assist in meeting the ambitious goals the SSL community has set for itself.

If the government wants to spend money, it can achieve lighting-energy conservation goals with certainty today, not just possibly in the future; it should spend the $50 million to subsidize the lease program for CFLs, purchasing them at wholesale cost and furnishing them to all utilities to lease at nominal costs to their residential customers. The $50 million would buy 15 million CFLs, each saving 50 watts, or 300 kilowatt hours, over its five-year working life in residential service. The program could be self-supporting by means of a 27% tax on the total lease payments of $180 million generated by the 15 million lamps over their lifetime. Such a self-supporting program, continued over several years, could replace incandescent lamps in many homes with CFLs without requiring the retail customer to bear the burden of the up-front cost. A larger annual expenditure would accelerate the conversion.

Supporting the product that today does everything in replacing residential incandescent lamps that is claimed for SSL lamps in the future, and needing only a way to break through the market constraints, would be a much more effective investment for the government. Even if the SSL community achieves every one of its ambitious technical goals on time, it will still need some similar mechanism to penetrate the marketplace.

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I applaud the authors' efforts to present a tutorial and current status of the field of solid-state lighting. However, I feel compelled to point out two omissions. The first is the attribution of credit to only Nick Holonyak and his coauthor[1] for "the first practical demonstration of LEDs in 1962." The paper by Holonyak and S. F. Bevacqua was on semiconductor lasers and has very little to do with LEDs per se. However, if we allow that paper to be a relevant reference for first LEDs, then we must include reference to three other papers[2] published at very nearly the same time as Holonyak and Bevacqua's, as also being "first" practical demonstrations of LEDs. The article by Bergh and coauthors does not distinguish visible LEDs from infrared LEDs. And to be fair about the history of visible LEDs, we should include Henry Round's publication[3] in 1907 of visible electroluminescence from SiC, the material of choice for blue LEDs before the appearance of GaN-based green and blue LEDs.

The second problem has to do with the data presented in figure 1 of the article. The data there for AlGaAs/GaAs red LEDs start in the early 1980s. In fact, data for "practical" AlGaAs LEDs started with a 1967 paper,[4] which was the first report of practical AlGaAs LEDs in the open literature. This paper also represented the first publication of a practical heterojunction.

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Bergh replies: Compact fluorescent lighting is a mature replacement technology for incandescent light, but solid-state lighting offers an entirely new lighting paradigm. John Waymouth missed a number of points in comparing SSL and compact fluorescent lamps.

▶ SSL lights turn on instantaneously and maintain their color when dimmed. Their color is dynamically adjustable and can be easily integrated with silicon integrated circuits to provide "smart lights." None of these attributes is available for CFLs. In addition, CFLs have poor color rendition and a poor form factor in replacing incandescent lamps.

▶ CFL efficiency is around 60 lumens per watt, compared to the expected efficiency of 200 lumens per watt for SSL.

▶ CFLs are isotropic emitters leading to 20–50% light loss within the fixture. In contrast, the quoted LED efficiencies are measured at the output of the fixture and have no additional light distribution losses.

Proponents of the old technology tend to resist the new. However, a testimony on the promise of the new technology is reflected in the position of traditional lighting companies such as OSRAM Sylvania and General Electric Co, which have fully embraced the Next Generation Lighting Initiative, a government–industry partnership to accelerate the development of SSL.

With regard to Jerry Woodall's letter, our article was aimed at lighting and hence at visible LEDs. Holonyak's red emission from GaAsP alloys was an early demonstration of a visible LED.

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Revamping High-School Science: Herding Cats

I am concerned about the discussion in Physics Today dealing with the order in which biology, chemistry, and physics should be taught in high schools (September 2001, page 11; February 2002, page 12). Where in these discussions is geology considered?

I often begin my introductory geology classes with the statement that geology is the most difficult science. My arguments are based on the degree to which the understanding of one science is contingent on understanding the other, the degree to which the basic data of each field are knowable, and the degree to which each science is presently described mathematically. Chemistry relies on physics for understanding, biology on chemistry and physics, and geology on all three. The basic data of physics are largely knowable through experiments whose results are often explained mathematically. This is progressively less true with chemistry, biology, and geology. Consequently, an understanding of geology often starts with existing theories from the other sciences that explain qualitatively the information gleaned from the incomplete 4.6-billion-year record of all the physical, chemical, and biological phenomena that have occurred.

To some scientists and educators, this qualitative nature means geology is an "easy science." However, recognizing that geology will be quantitatively understood only after the other three establishes it as the most difficult of the four. The only argument for geology's ease is the extent to which it can be taught to students with little mathematical ability by using the basic principles of the other three sciences.

I believe that a high-school science course is only the most basic introduction to the field, that principles are more important than mathematical descriptions at that level, and that the principles of the sciences depend on each other in the order I've presented here. On the strength of that belief, I submit that the order of courses in high school should be physics, chemistry, biology, and geology.

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All students should take physics, but should do so even sooner than in the ninth grade, the level that Leon Lederman recommends. Students, though, must know basic algebra before taking physics, because even if one emphasizes concepts, the understanding is deeper when the instructor also introduces quantitative treatments. Thus, any academic revolution needs to change the K–8 traditional math courses and bring in algebra well before the 8th grade. By age 11, the average child is capable of abstract thought and reasoning. In some European countries, students learn algebra in the 5th grade and begin physics in the 6th grade.

We believe that K–12 schools should return to the classical education system in which schools require that every child learn the same core curriculum. Establishing such a common knowledge base is essential; it is how a culture is preserved from one generation to the next.

Numerous experiments and innovations in education during the 20th century were unsuccessful, which implies that basic improvements, not just more gimmicks, are needed. More money and more assessment are certainly important, but educators need to take a stronger stand on specific curricular approaches.

Challenge all children. Whereas the present system tends to focus on the lowest achievers, a more classical system challenges everyone to learn more than they are "comfortable with." As part of their constructive social upbringing, the highest achievers would learn to help those who are initially low achievers. Educators should recognize and appreciate that humans are fundamentally challengers—they enjoy attempting difficult things, especially if the social climate is supportive.

Match learning activity to age. Without being told to do so, young children memorize voluminous data and facts from their environment; it is better that children learn those facts from teachers and parents than from their peers. Memorizing basic essentials like multiplication tables and vocabulary, and practicing reading and writing skills, should be the main activities in early years. At age 11, children can learn the abstractions of algebra; at age 12, they can start learning physics; and at age 13, chemistry. From 7th through 12th grade, every child should take both math and science at every grade level.