discoveries. But only real experiments can be used to validate these discoveries; pseudo-experiments are not acceptable because, when one is dealing with an unexplored phenomenon, their basic postulates can never be trusted.

This can be contrasted with many engineering investigations, where major factors controlling a process are already well known, but practical solutions are, nevertheless, difficult because of the many factors involved, their complex interconnections and, often, their probabilistic nature. Here simulations are highly reliable and one can often make valuable predictions. Nuclear scientists or engineers may use simulations in trying to find an optimum distribution of fuel elements in a reactor, but they must know in advance the cross sections for the processes involved, and only real experiments can generate such data.

Simulation programs used in teaching[2,6–9] should also be highly reliable, because we base them on solid postulates such as Newton's laws or spectral wavelengths of chemical elements. Consequently, games like "pretend you are Kepler" or "pretend you are Bohr" can be very useful—at least as motivators, and often as exploratory tools in the "what if" situations. We just have to learn when and how to play such games to optimize the efficiency of learning. I would like to thank Susan Marchand for useful comments, which helped shape the ideas expressed in this note.

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Ending scientific illiteracy

Your September editorial (page 144) could lead one to despair. It stated, "... we can only expect substantial improvement ... when the members of the school board and the people ... who elect them are ... convinced of the unique importance of science ..."

Mark Twain and H. L. Mencken took the measure of school boards and voters, respectively. Twain wrote, "In the beginning God made idiots. This was for practice. Then he made school boards." Mencken noted that no one ever went broke underestimating the intelligence of the American voter. Your suggestion—to convince the scientifically illiterate of the importance of science—requires nothing short of a cultural revolution. Of course we must try.

The problem is exacerbated by the scientific illiteracy—frequently compounded by arrogance—of many who are supposedly educated. The newspaper editor who wrote that "the calorie is not a metric unit" probably never took a course in physics. I cannot recall, in my 22 years of teaching high-school physics, ever having a student who was interested in journalism. Convincing these influential people of the importance of physics is likely to be a formidable task.

Much of what has been proposed for improving schools—more hours, more days, more homework—is likely to be counterproductive. It would seem that the first priority should be to convey to students a positive image of science, that is, the notion, attributed to Alfred North Whitehead, that science is a delightful intellectual activity. We all know (or do we?) that science is a structure of ideas based on observations. There is no good reason why students should not be encouraged to invent some of those ideas for themselves.

We also know that the most basic as well as the simplest phenomena, requiring the simplest apparatus, are taught in physics. That is why, if we are to turn out students who are not only literate in science but also happy about it, we must revise the curriculum to teach physics before biology and chemistry. Those subjects contain a number of topics that can only be taught as dogma, sans understanding, to students who have no knowledge of physics.

These needed changes are difficult to effect on the local level. Strong leadership is sorely needed at the state and national levels.

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