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Scientific Elites and Scientific Illiterates

How can our miserable system of education have produced such a brilliant community of scientists?

by David L. Goodstein

Is American science education like mining? Here Georgius Agricola illustrates the process of mining and sifting copper ore in the Carpathians in *De Re Metallica*, 1556.

Scientific papers often begin by posing a paradox, even if it is one that had not previously seemed particularly disturbing. Having posed the paradox, the author then proceeds to resolve it. At first glance, we don't seem to make much progress that way. A paradox that was previously unnoticed is now no longer unexplained. Such exercises, however, can sometimes be useful. For example, Albert Einstein's famous 1905 paper introducing the theory of relativity was very much of this form. He began by pointing out that when a magnet induces an electric current in a loop of wire, we attribute that effect to entirely different causes depending on whether the magnet or the wire is in motion. Finding this paradox intolerable, he proceeded to resolve it, giving new meanings to time and space along the way.

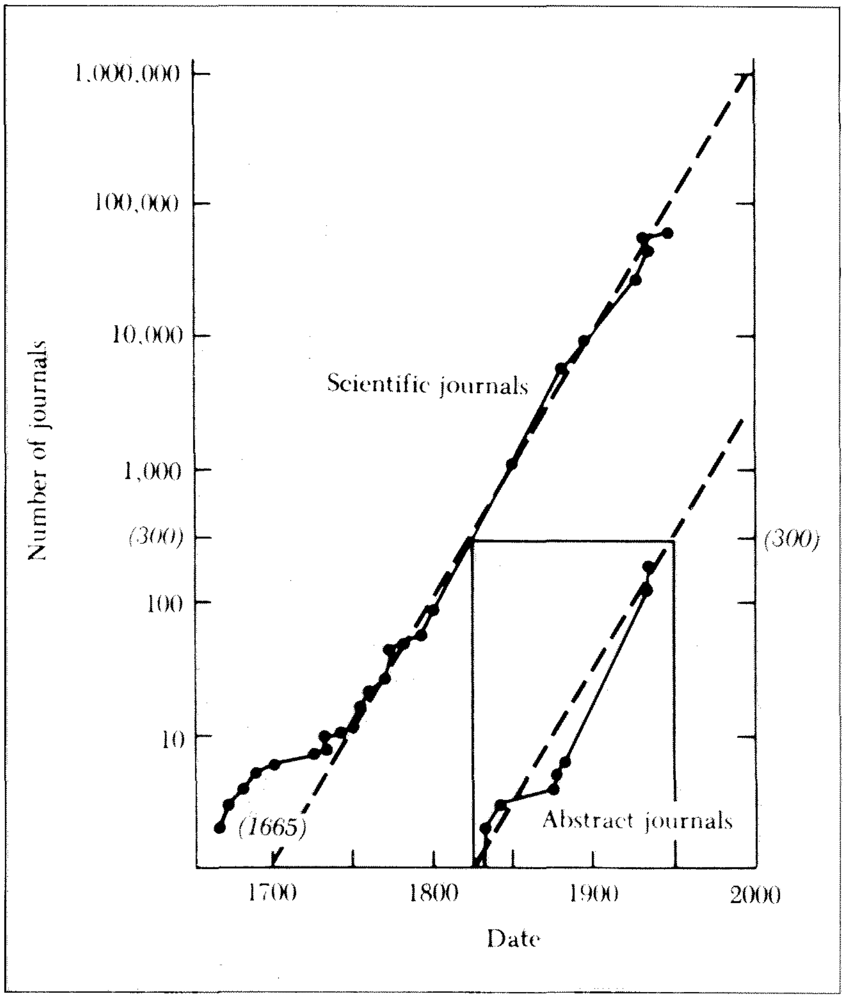
Today, with my customary modesty, I would like to follow in Albert's bicycle tracks and begin this talk by posing a paradox. The paradox is that we, here in the United States today, have the finest scientists in the world, and we also have the worst science education in the world, or at least in the industrialized world. American scientists, trained in American graduate schools, produced more Nobel Prizes, more scientific citations, more of just about anything you care to measure, than any other country in the world; maybe more than the rest of the world combined. Yet, students in American schools consistently rank at the bottom of all those from advanced nations in tests of scientific knowledge; and furthermore roughly 95 percent of the American public is consistently found to be scientifically illiterate by any rational standard. How can we possibly have arrived at such a result? How can our miserable system of education have produced such a brilliant community of scientists? I would like to refer to this situation as the Paradox of the Scientific Elites and the Scientific Illiterates.

In my view, these two seemingly contradictory observations are both true, and they are closely related to one another. We have created a kind of feudal aristocracy in American science, where a privileged few hold court, while the toiling masses huddle in darkness, metaphorically speaking, of course. But I think inexorable historic forces are at work that have already begun to bring those conditions to an end—not that light will be brought to the masses necessarily, but that *our* days at court are clearly numbered. To understand all this, and before we get more deeply mired in dubious metaphors, it may help to go back to the beginning. I mean literally The Beginning.

In modern cosmology, the accepted theory of the beginning of the universe goes something like this: at a certain instant around 10–15 billion years ago, the universe was created in a cataclysmic event called the Big Bang. It has been expanding uniformly ever since. What we do not know is whether the density of matter in the universe is great enough to reverse that expansion eventually, causing the universe to slow down, come to a stop, and then finally fall back upon itself. If that does happen, the cosmologists are prepared with a name for the final cataclysmic moment when the universe ends. It will be known as the Big Crunch.

I would like to offer a somewhat analogous

The number of founded scientific journals plotted as a function of year grew at an exponential rate between 1750 and 1950, leading to a somewhat tongue-in-cheek prediction of a million journals for a scientist to consume by the year 2000.



From Derek da Solla Price, *Science Since Babylon* (Yale University Press, 1961). Reprinted by permission.

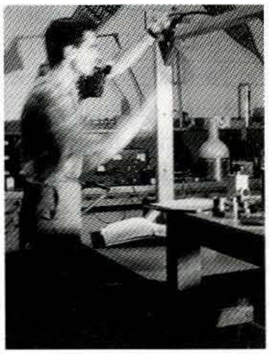
theory of the history of science. According to this theory, science began in a cataclysmic event sometime around the year 1700. (The publication of Newton's Principia in 1687 is a good candidate for the actual event.) It then proceeded to expand at a smooth, continuous exponential rate for nearly 300 years. Unlike the universe, however, science did not expand into nothing at all. Instead, the expansion must come to an end when science reaches the natural limits imposed on it by the system it was born into, which is called the Human Race.

I don't mean that scientific knowledge is limited by the human race; in fact, I don't think scientific knowledge is limited at all, and I hope it will go on expanding forever. What I'm talking about here is what you might call the profession of science, or the business of science. It is my opinion that the size of the scientific enterprise, which began its exponential expansion around 1700, has now begun to reach the limits imposed on it by the size of the human race. Thus, the expansion of science is now in the process of ending, not in a Big Crunch, but in something much more like a whimper, that may or may not leave some residue of science still existing when it is all over.

I think that the beginning of the end of the exponential expansion era of science occurred, in the United States at least, around the year 1970. Most people, scientists and otherwise, are unaware that it is coming to an end (in fact, they probably never knew it existed) and are still trying to maintain a social structure of science (by which I mean research, education, funding, institutions and so on) that is based on the unexamined assumption that the future will be just like the past. Since that is impossible, I believe, we have some very interesting times ahead of us. I would like to explain why I believe all this, and what we might try to do about it.

The graph at left is borrowed from a book called *Little Science, Big Science* by Derek da Solla Price. Price may be identified as the Edwin Hubble of the expansion of science. (Hubble discovered the expansion of the universe.) The figure, a plot of the number of scientific journals founded, worldwide, as a function of year, is a suitable stand-in for any other quantitative measure of the size of science. It shows that the cumulative number of journals founded increased by a factor of 10 about every 50 years, from 1750 to 1950. This is a different, faster kind of growth than a free expansion like that of the universe. Here the rate of growth of the system keeps increasing as the size of the system increases. In other words, the bigger it is, the faster it grows.

It is a simple mathematical fact that if scientists keep multiplying faster than people, there will soon be more scientists than there are people.



The author during the Golden Age of 1962.

Anyone observing this so-called exponential curve would conclude that science was born (roughly) in the year 1700, and that a million journals would have been founded by the year 2000. Price, who pointed out this phenomenon in the early 1960s, was clever enough to know that neither of these conclusions would be correct. On the one hand, both scientific knowledge and the scientific enterprise have roots that stretch all the way back to antiquity, and on the other hand the number of scientific journals in the world today, as we approach the year 2000, is a mere 40,000. This sorry failure of the publishing industry to keep up with our expectations often leaves us scientists with nothing to read by the time we reach the end of the week.

The point is that the era of exponential growth in science is already over. The number of journals is one measure, but all others tend to agree. In particular, it applies to the number of scientists around. It is probably still true that 90 percent of all the scientists who have ever lived are alive today, and that statement has been true at any given time for nearly 300 years. But it cannot go on being true for very much longer. Even with the huge increase in world population in this century, only about one-twentieth of all the people who have ever lived are alive today. It is a simple mathematical fact that if scientists keep multiplying faster than people, there will soon be more scientists than there are people. That seems very unlikely to happen.

I think the last 40 years in the United States have seen the end of the long era of exponential growth and the beginning of a new era we have not yet begun to imagine. These years will be seen in the future as the period in which science began a dramatic and irreversible change into an entirely new regime. Let's look back at what has happened in those 40 years in light of this historic transformation.

The period 1950–1970 was a true golden age for American science. Young PhDs could choose among excellent jobs, and anyone with a decent scientific idea could be sure of getting funds to pursue it. The impressive successes of scientific projects during World War II had paved the way for the federal government to assume responsibility for the support of basic research. Moreover, much of the rest of the world was still crippled by the aftereffects of the war. At the same time, the G.I. Bill of Rights sent a whole generation back to college. The American academic enterprise grew explosively, especially in science and technology. Even so, that explosive growth was merely a seamless continuation of the exponential growth of science that had dated back to 1700. It seemed to one and all (with the notable exception of Derek da Solla Price) that these happy conditions would go on forever.

By now, in the 1990s, the situation has changed dramatically. With the Cold War over, national security is rapidly losing its appeal as a means of generating support for scientific research. To make matters worse, the country is $4 trillion in debt, and scientific research is among the few items of discretionary spending in the national budget. There is much wringing of hands about impending shortages of trained scientific talent to ensure the nation's future competitiveness, especially since by now other countries have been restored to economic and scientific vigor. But, in fact, jobs are scarce for recent graduates. The best American students have proved their superior abilities by reading the handwriting on the wall and going into other lines of work. Half the students in American graduate schools in science and technology are from abroad.

Both periods, the euphoric golden age, 1950–1970, and the beginning of the crunch, 1970–1990, seemed at the time to be the product of specific temporary conditions rather than grand historic trends. In the earlier period, the prestige of science after helping win the war created a money pipeline from Washington into the great research universities. At the same time, the G.I. Bill of Rights transformed the United States from a nation of elite higher education to a nation of mass higher education. Before the war, about 8 percent of Americans went to college, a figure comparable to that in France or England.

Now more than half of all Americans receive some sort of post-secondary education, and nearly a third will eventually graduate from college. To be sure, this great and noble experiment in mass higher education has failed utterly and completely in technology and science, where between 4 and 5 percent of the population can be identified as science and technology professionals, and the rest may as well live in the pre-Newtonian era. Nevertheless, the expanding academic world in 1950–1970 created posts for the exploding number of new science PhDs, whose research led to the founding of journals, to the acquisition of prizes and awards, and to increases in every other measure of the size and quality of science. At the same time, many great American corporations decided they needed to create or expand their central research laboratories to solve technological problems, and also to pursue basic research that would provide ideas for future developments. And the federal government itself established a network of excellent national laboratories that also became the source of jobs and opportunities for aspiring scientists. As we have already seen, all this extraordinary activity merely resulted in a 20-year extension in the U.S. of the exponential growth that had been quietly going on since 1700. It was to be the last 20 years, however. The expansionary era in the history of science was about to come to an end, at least in America.

Actually, during the second period, 1970–1990, the expansion of American science did not stop altogether, but it did slow down significantly compared to what might have been expected from Price's exponential curves. Federal funding of scientific research, in inflation-corrected dollars, doubled during that period, and, by no coincidence at all, the number of academic researchers also doubled. Such a controlled rate of growth (controlled only by the available funding, to be sure) was not, however, consistent with the lifestyle that academic researchers had evolved. The average American professor in a research university turns out about 15 PhD students in the course of a career. In a stable, steady-state world of science, only one of those 15 can go on to become another professor in a research university. In a steady-state world, it is mathematically obvious that the professor's only reproductive role is to produce one professor for the next generation. But the American PhD is basically training to become a research professor. American students, realizing that graduate school had become a training ground for a profession that no longer offered much opportunity, started choosing other options. The impact of this situation was obscured somewhat by the growth of postdoctoral research positions, a kind of holding tank for scientific talent that allowed young researchers to delay confronting reality for three to six or more years. Nevertheless, it is true that the number of the best American students deciding to go to graduate school started to decline around 1970, and it has been declining ever since.

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In the meantime, yet one more surprising phenomenon has taken place. The golden age of American academic science produced genuine excellence in American universities. Without any doubt at all, we lead the world in scientific training and research. It became necessary for serious young scientists from everywhere else either to obtain an American PhD, or at least to spend a year or more of postgraduate study here. America has come to play the role for the rest of the world, especially the emerging nations of the Pacific rim, that Europe once played for young American scientists, and, it is said, that Greece once played for Rome. We have become the primary source of scientific culture and learning for everyone. Almost unnoticed, over the past 20 years the missing American graduate students have been replaced by foreign students. This has permitted the American research universities to go on producing PhDs almost as before.

It should be clear by now that with half the kids in America already going to college, academic expansion is finished. With the Cold War over, competition in science can no longer be sold as a matter of national survival. There are those who argue that research is essential for our economic future, but the managers of the economy know better. The great corporations have decided that central research laboratories were not such a good idea after all. Many of the national laboratories have lost their missions and have not found new ones. The economy has gradually been transformed from manufacturing to service, and service industries such as banking and insurance don't support much scientific research. Although each of these conditions appears to be transient and temporary, they are really the immediate symptoms of a large-scale historic transformation. For us in the United States, the expansionary era of science has come to an end. The future of American science will be very different from the past.

Let's get back now to the Paradox of Scientific Elites and Scientific Illiterates. The question of how we educate our young in science lies at the heart of the issues we have been discussing. The observation that for hundreds of years the number of scientists had been growing exponentially means, quite simply, that the rate at which we produced scientists has always been proportional

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to the number of scientists that already existed. We have already seen how that process works at the final stage of education, where each professor in a research university turns out 15 PhDs, most of those wanting to become research professors and turn out 15 more PhDs.

Recently, however, a vastly different picture of science education has been put forth and has come to be widely accepted. It is the metaphor of the pipeline, illustrated above on the cover of an issue of *Science* magazine from last November. The idea is that our young people start out as a torrent of enthusiastic, curious minds eager to learn about the world, but as they pass through the various grades of schooling, that eagerness and curiosity is somehow squandered, fewer and fewer of them showing any interest in science, until at the end of the line, nothing is left but a mere trickle of PhDs. (The artist for *Science* didn't get the idea of a trickle quite right.) Thus, our entire system of education is seen to be a leaky pipeline, badly in need of repairs. As the cover of *Science* indicates the leakage problem is seen as particularly severe with regard to women and minorities (even the "trickle" at the end is milky white), but the pipeline metaphor applies to all. I'm not quite sure, but I think the pipeline metaphor came first out of the National Science Foundation, which keeps careful track of science workforce statistics (at least that's where I first heard it). As the NSF points out with particular urgency, women and minorities will make up the majority of our working people in future years. If we don't find a way to keep them in the pipeline, where will our future scientists come from?

I believe it is a serious mistake to think of our system of education as a pipeline leading to PhDs in science or in anything else. For one thing, if it were a leaky pipeline, and it could be repaired, then, as we've already seen, we would soon have a flood of PhDs that we wouldn't know what to do with. For another thing, producing PhDs is simply not the purpose of our system of education. Its purpose instead is to produce citizens capable of operating a Jeffersonian democracy, and also if possible capable of contributing to their own and to the collective economic well being. To regard anyone who has achieved those purposes as having leaked out of the pipeline is worse than arrogant; it is silly. Finally, the picture doesn't work in the sense of a scientific model: it doesn't make the right predictions. We have already seen that, in the absence of external constraints, the size of science grows exponentially. A pipeline, leaky or otherwise, would not have that result. It would only produce scientists in proportion to the flow of entering students.

I would like to propose a different and more illuminating metaphor for science education. It is more like a mining and sorting operation, designed to cast aside most of the mass of common human debris, but at the same time to discover and rescue diamonds in the rough, that are capable of being cleaned and cut and polished into glittering gems, just like us, the existing scientists. It takes only a little reflection to see how much more this model accounts for than the pipeline does. It accounts for exponential growth, since it takes scientists to identify prospective scientists. It accounts for the very

Rather than a pipeline, science education could be compared to a mining and sorting operation, separating from the huge mass of ore diamonds that can be cleaned, cut, and polished—into, say, physicists. At far left is the diamond treatment plant at the Auchas Mine in Namibia.

Our colleagues abroad can take what scant comfort they can find in the promise that our dilemmas in science and education are on the way, along with Big Macs and designer jeans.

real problem that women and minorities are woefully underrepresented among scientists, because it is hard for us white, male scientists to perceive that once they are cleaned, cut, and polished they will look like us. It accounts for the fact that science education is for the most part a dreary business, a burden to student and teacher alike at all levels of American education, until the magic moment when a teacher recognizes a potential peer, at which point it becomes exhilarating and successful. Above all, it resolves the paradox of Scientific Elites and Scientific Illiterates. It explains why we have the best scientists and the most poorly educated students in the world. It is because our entire system of education is designed to produce precisely that result.

It is easy to see the sorting operation at work in the college physics classroom, where most of my own experience is centered, but I believe it works at all levels of education and in many other subjects. From elementary school to graduate school, from art and literature to chemistry and physics, students and teachers with similar inclinations resonate with one another. The tendency is natural and universal. But, if it is so universal, you might ask, why is America so much worse off than the rest of the world? The answer, I think, is that in education and in science, as in fast food and popular culture, America is not really worse than the rest of the world; we are merely a few years ahead of the rest of the world. What we are seeing here will happen everywhere soon enough. Our colleagues abroad can take what scant comfort they can find in the promise that our dilemmas in science and education are on the way, along with Big Macs and designer jeans.

Getting back to America, the mining and sorting operation that we call science education begins in elementary school. Most elementary school teachers are poorly prepared to present even the simplest lessons in scientific or mathematical subjects. In many places, elementary education is the only college major that does not require even a single science course, and it is said that many students who choose that major do so precisely to avoid having to take a course in science. To the extent that this is true, elementary school teachers are not merely ignorant of science, they are preselected for their hostility to science, and no doubt they transmit that hostility to their pupils, especially young girls for whom elementary school teachers must be powerful role models.

Even those teachers who did have at least some science in college are not likely to be well prepared to teach the subject. Recently, I served on a kind of visiting committee for one of the elite campuses of the University of California, where every student is required to have at least one science course. The job of the committee was to determine how well this requirement was working. We discovered that 90 percent of the students in majors outside science and technology were satisfying the requirement by taking a very popular biology course known informally as "human sexuality." I don't doubt for an instant that the course was valuable and interesting, and may even have tempted the students to do voluntary "hands on" experimentation on their own time (a result we seldom achieve in physics). But I do not think that such a course by itself offers sufficient training in science for a university graduate at the end of the 20th century. These students, some of whom will go on to become educators, are themselves among the discards of the science mining and sorting operation.

In any case, the first step of the operation is what might be called passive sorting, since few elementary school pupils come into personal contact with anyone who has scientific training. Certainly, we all know that many young people decide that science is beyond their understanding long before they have any way of knowing what science is about. Still, a relatively small number of students, usually those who sense instinctively that they have unusual technical or mathematical aptitudes, arrive at the next level of education with their interest in science still intact.

But we too have rescued elitism from the jaws of democracy, in our superior graduate schools.

The selection process becomes more active in high school. There are about 22,000 high schools in the United States, most of which offer at least one course in physics. Physics is my own subject, and I have had some influence on the teaching of physics in American high schools because a remarkably large fraction of them use "The Mechanical Universe," a television teaching project I directed some years ago. Because I have some first-hand knowledge about physics in high schools, I'll stick to that, although I suspect what I have to say applies to other science subjects as well. Anyway, there are just a few thousand trained high school physics teachers in the U.S., far fewer than there are high schools. The majority of courses are taught by people who in college majored in chemistry, biology, mathematics, or, surprisingly often, home economics, a subject that has lost favor in recent years. I know from personal contact that these are marvelous people, often willing to work extraordinarily hard to make themselves better teachers of a subject they never chose for themselves. My greatest satisfaction from making "The Mechanical Universe" comes from the very substantial number of them who have told me that I helped make their careers successful. Their greatest satisfaction comes from—guess what?—discovering those diamonds in the rough that can be sent on to college for cutting and polishing into real physicists.

I don't think I need to explain what happens in college and graduate school, but I'd like to contribute a story of my own because I think it helps to illustrate one of my main points. By far the best course I had in college was not in physics, but rather it was a required writing and literature course known as Freshman English. The professor was my hero, and I was utterly devoted to him. He responded just as you might expect: he tried hard to talk me into quitting science and majoring in English. Nevertheless, the thought of actually doing that never crossed my mind. I knew perfectly well that if I were ever going to make anything of myself, I was going to have to suffer a lot more than I was doing in Freshman English. Physics, I was already sure, would provide the necessary suffering. The story illustrates that we scientists are not the only ones who engage in mining and sorting. But the main point is that for most of us in the academic profession our real job is not education at all; it is vocational training. We are not really satisfied with our handiwork unless it produces professional colleagues. That is one of the characteristics that may have to change in the coming brave new world of postexpansion science.

American education is much maligned, and of course it suffers from severe problems that I need not go into here. Nevertheless, it was remarkably well suited to the exponential expansion era of science. Mass higher education, essentially an American invention, means that we educate nearly everyone, rather poorly. The alternative system, gradually going out of style in Europe these days, is to educate a select few rather well. But we too have rescued elitism from the jaws of democracy, in our superior graduate schools. Our students finally catch up with their European counterparts in about the second year of graduate school (this is true, at least, in physics), after which they are second to none. When, after about 1970, the gleaming gems produced by this assembly line at the end of the mining and sorting operation were no longer in such great demand at home, the humming machinery kept right on going, fed by imported ore.

To those of us who are professors in research universities, those foreign graduate students have, temporarily at least, rescued our way of life. In fact we are justly proud that, in spite of the abysmal state of American education in general, our graduate schools are a beacon unto the nations of the world. The students who come to join us in our research are every bit as bright and eager as the home-grown types they have partially replaced, and they add energy and new ideas to our work. However, there is another way of looking at all this. Graduate students in the sciences are often awarded teaching assistantships, for which they may not be well qualified because their English is imperfect. In general, through teaching or research assistantships or fellowships, they are paid stipends, and their tuitions are either waived or subsidized by the universities. Thus our national and state governments find themselves supporting expensive research universities that often serve undergraduates poorly (partly because of those foreign teaching assistants) and whose principal educational function at the graduate level has become to train PhDs from abroad. Some of these, when they graduate, stay on in America, taking some of those few jobs still available here, and others return to their homelands taking our knowledge and technology with them to our present and future economic competitors. It doesn't take a genius to realize that our state and federal governments are not going to go on forever supporting this playground we professors have created for ourselves.

To most of us professors, of course, science no longer seems like a playground. Recently, Leon Lederman, one of the leaders of American science, published a pamphlet called *Science—The End of the Frontier.* The title is a play on *Science—The Endless Frontier,* the title of the 1940s report by Vannevar Bush that led to the creation of the National Science Foundation and helped launch the golden age described above. Lederman's point is that American science is being stifled by the failure of the government to put enough money into it. I confess to being the anonymous Caltech professor quoted in one of Lederman's sidebars to the effect that my main responsibility is no longer to do science, but rather it's to feed my graduate students' children. Lederman's appeal was not well received in Congress, where it was pointed out that financial support for science is not an entitlement program, nor in the press, where the *Washington Post* had fun speculating about hungry children haunting the halls of Caltech. Nevertheless, the problem Lederman wrote about is very real and very painful to those of us who find that our time, attention, and energy are now consumed by raising funds rather than doing research. Although Lederman would certainly disagree with me, I firmly believe that this problem cannot be solved by more government money. If federal support for basic research were to be doubled (as many are calling for), the result would be merely to tack on a few more years of exponential expansion before we'd find ourselves in exactly the same situation again. Lederman has performed a valuable service in promoting public debate of an issue that has worried me for a long time (the remark he quoted is one I made in 1979), but the issue itself is really just a symptom of the larger fact that the era of exponential expansion has come to an end.

We must find a radically different social structure to organize research and education in science.

The crises that face science are not limited to jobs and research funds. Those are bad enough, but they are just the beginning. Under stress from those problems, other parts of the scientific enterprise have started showing signs of distress. One of the most essential is the matter of honesty and ethical behavior among scientists. The public and the scientific community have both been shocked in recent years by an increasing number of cases of fraud committed by scientists. There is little doubt that the perpetrators in these cases felt themselves under intense pressure to compete for scarce resources, even by cheating if necessary. As the pressure increases, this kind of dishonesty is almost sure to become more common.

Other kinds of dishonesty will also become more common. For example, peer review, one of the crucial pillars of the whole edifice, is in critical danger. Peer review is used by scientific journals to decide which papers to publish, and by granting agencies such as the National Science Foundation to decide what research to support. Journals in most cases and agencies in some cases operate by sending manuscripts or research proposals to referees who are recognized experts on the scientific issues in question, and whose identities will not be revealed to the authors of the papers or proposals. Obviously, good decisions on what research should be supported and what results should be published are crucial to the proper functioning of science.

Peer review is usually quite a good way of identifying valid science. Of course, a referee will occasionally fail to appreciate a truly visionary or revolutionary idea, but by and large, peer review works pretty well so long as scientific validity is the only issue at stake. However, it is not at all suited to arbitrate an intense competition for research funds or for editorial space in prestigious journals. There are many reasons for this, not the least being the fact that the referees have an obvious conflict of interest, since they are themselves competitors for the same resources. It would take impossibly high ethical standards for referees to avoid taking advantage of their privileged anonymity to advance their own interests, but as time goes on, more and more referees have their ethical standards eroded as a consequence of having themselves been victimized by unfair reviews when they were authors. Peer review is thus one among many examples of practices that were well suited to the time of exponential expansion, but that will become increasingly dysfunctional in the difficult future we face.

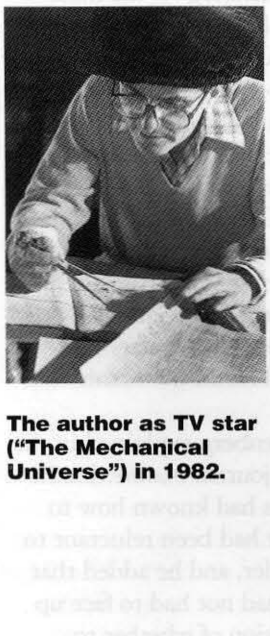
We must find a radically different social structure to organize research and education in science. That is not meant to be an exhortation. It is meant to be simply a statement of a fact known to be true with mathematical certainty, if science is to survive at all. The new structure will come about by evolution rather than design, because, for one thing, neither I nor anyone else has the faintest idea of what it will turn out to be.

Unfortunately, we have never developed a way to bring people along as informed tourists of the vast terrain we have conquered, without training them to become professional explorers.

And, for another, even if we did know where we are going to end up, we scientists have never been very good at guiding our own destiny. Only this much is sure: the era of exponential expansion will be replaced by an era of constraint. Because it will be unplanned, the transition is likely to be messy and painful for the participants. In fact, it already is. Ignoring the pain for the moment, however, I would like to look ahead and speculate on some conditions that must be met if science is to have a future as well as a past.

It seems to me that there are two essential and clearly linked conditions to consider. One is that there must be a broad political consensus that pure research in basic science is a common good that must be supported from the public purse. The second is that the mining and sorting operation I've described must be discarded and replaced by genuine education in science, not just for the scientific elite, but for all the citizens who must form that broad political consensus.

Basic research is a common good for two reasons: it helps to satisfy the human need to understand the universe we inhabit, and it makes new technologies possible. It must be supported from the public purse because it does not yield profits if it is supported privately. Because basic research in science flourishes only when it is fully open to the normal processes of scientific debate and challenge, the results are available to all. That's why it is always more profitable to use someone else's basic research than to support your own. For most people it will also always be easier to let someone else do the research. In other words, not everyone wants to be a scientist. But to fulfill the role of satisfying human curiosity, which means something more than just our own, we scientists must find a way to teach science to nonscientists.



The author as TV star ("The Mechanical Universe") in 1982.

That job may turn out to be impossible. Perhaps professional training is the only possible way to teach science. There was a time long ago when self-taught amateurs could not only make a real contribution to science, but could even become great scientists. Benjamin Franklin and Michael Faraday come to mind immediately. That day is long gone. I get manuscripts in the mail every week (attracted, no doubt, by my fame as a TV star) from amateurs who have made some great discovery that they want me to bring to the attention of the scientific world. But they are always nonsense. The frontiers of science have moved far from the experience of ordinary persons. Unfortunately, we have never developed a way to bring people along as informed tourists of the vast terrain we have conquered, without training them to become professional explorers. If it turns out to be impossible to do that, people may decide that the technological trinkets we send back from the frontier are not enough to justify supporting the cost of the expedition. If that happens, science will not merely stop expanding, it will die.

Tackling in a serious way the as-yet remote task of bringing real education in science to all American students would have at least one enormous advantage: it would give a lot of scientists something worthwhile to do. On the other hand, I'm not so sure that opening our territories to tourism will bring unmixed blessings down upon us. For example, would the scientifically knowledgeable citizens of our Jeffersonian republic think it worth $10 billion of public funds to find out what quarks are made of? I don't know the answer to that question, but I am reasonably sure that a scientifically literate public would not have supported President Reagan's Star Wars program, which in its turn, did help for a while to support at least a small part of my own research. In other words, keeping the tourists away has some advantages that we may have to give up.

Nevertheless, I'm willing to take the gamble if others are. I don't think education is the solution to all our problems, but it does seem like a good place to start. Besides, I really don't know what else we can do. □

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