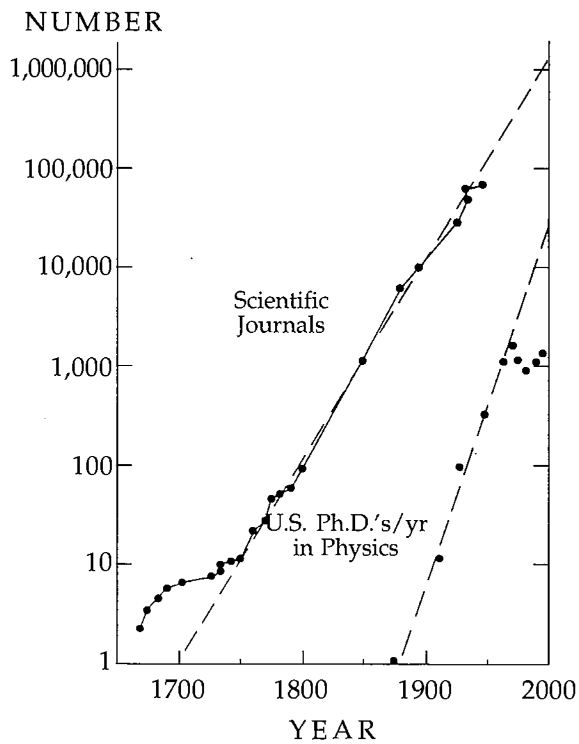
AFTER THE BIG CRUNCH

BY DAVID L. GOODSTEIN

In the beginning, roughly 10 billion years ago according to modern cosmology, was the Big Bang. The universe has been expanding ever since. Whether it will keep doing so forever, we do not know. It may be—if the density of matter in the universe is sufficiently great—that gravitational forces eventually will cause the universe to stop expanding and then to start falling back in upon itself. If that occurs, the universe will end in a cataclysmic event that cosmologists call the Big Crunch.

The history of modern science is somewhat analogous. This science appeared on the scene almost three centuries ago in Europe and slightly more than a century ago in the United States. In each case, it proceeded to grow at an astonishing exponential rate. But while the universe conceivably may expand forever, the exponential enlargement of the scientific enterprise is guaranteed to come to an end.



It is not that scientific knowledge must stop growing. On the contrary, if all goes well, it should continue to expand. But the growth of the profession of science, the scientific enterprise, is bound to reach certain limits. I contend that these limits have now been reached. Many of my scientific colleagues persist in the belief that the future will be like the past and are seeking to preserve the "social structure" of science—the institutions and the patterns of education, research, and funding—that they have come to know so well. If I am right, they won't succeed.

The Big Crunch is here (even if it is actually more like a large whimper than a big bang); indeed, in some fields it has already happened. In physics, it occurred about 25 years ago—and we physicists have been doing our best to avoid the implications ever since. We cannot continue to do so. We must address a question that has never even occurred to the cosmologists: what do you do after the Big Crunch?

The situation can be illustrated by a graph. The upper curve—first published in a book called *Science since Babylon* (1961) by the historian Derek de Solla Price—shows, on a semilogarithmic scale, the cumulative number of scientific journals founded worldwide over the last three centuries. A straight line with a positive slope on this kind of graph means pure exponential growth. If something is increasing that way, then the larger it gets, the faster it grows.

Price's curve, he maintained, is a suitable stand-in for any quantitative measure of the size of science. If so, then modern science appears to have sprung into being around 1700 (the Big Bang might have been the publication of Sir Isaac Newton's *Principia* in 1687) and thereafter expanded exponentially, growing tenfold every 50 years.

Price predicted that this behavior could not go on forever—and, of course, he was right. The straight line in the plot extrapolates to one million journals by the millennium. But the number of scientific journals in the world today, as we near the millennium, is a mere 40,000.

That is only one measure of what is happening, but all the others tend to agree. Consider, in particular, the number of scientists around. It has often been said that 90 percent of all the scientists who have ever lived are alive today. That statement has been true 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 have plotted, on the same scale as Price's curve, the number of Ph.D.'s in physics produced each year in the United States. Like all other quantitative measures of science, this one behaves much like Price's curve. The graph shows that science started later in the United States than in Europe. The first Ph.D. in physics was awarded soon after the Civil War, around 1870. By the turn of the century, the number of doctorates in physics awarded was about 10 per year; by 1930 the annual figure was about 100, and by 1970 it was about 1,000. By extrapolation, there should be one million physics Ph.D.'s given out annually by the mid-21st century, and there now should be about 10,000 awarded per year. But this has not happened. Instead, we have the Big Crunch. The Ph.D. growth stopped cold around 1970, and the number awarded each year has fluctuated around 1,000 ever since. In other fields of science, the timing of the Big Crunch may be a bit different, but not the basic phenomenon. It is inevitable, and it has already begun to happen.

Now, that does not mean that American science has ceased expanding since 1970. It has not. In fact, federal funding of scientific research, in inflation-corrected (1987) dollars, doubled from about $30 billion in 1970 to about $60 billion two decades later. And, by no coincidence at all, the number of academic researchers has also doubled, from about 100,000 to about 200,000. But this rate of growth, controlled by the amount of funding available, is too slow to allow research professors to keep replicating themselves at the same rate as in the past.

If American science were in a steady state condition, the average professor in a research university would need to produce only one future research professor for the next generation. Instead, the average professor, in the course of a typical 30-year career, turns out about 15 students with doctorates—and most such people want to be research professors. As the growth of science slowed in recent decades, it did not take long for the smarter students to realize that not everyone with a Ph.D. could become a research professor. As a result, the number of the best American students who went on to graduate school in science started to drop around 1970, and has been decreasing ever since.

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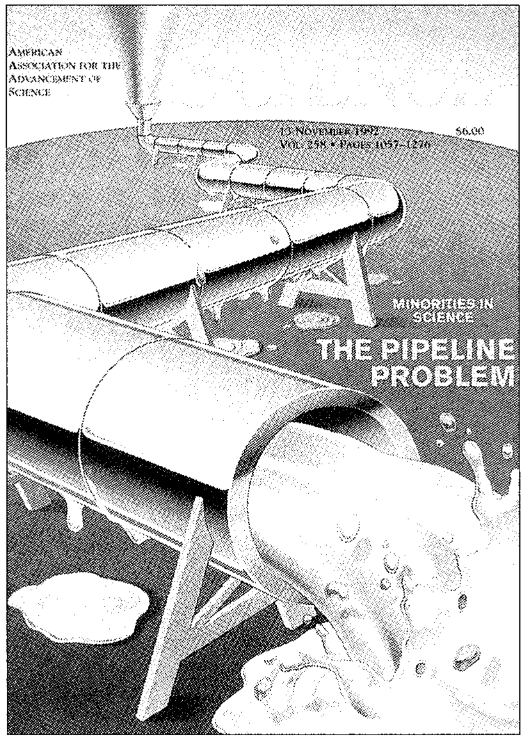
Despite the decline, research professors have been turning out far more scientists than American universities can employ, indeed, far more scientists—now that the Cold War is over and now that the great corporations such as IBM and AT&T have decided to turn away from basic research—than the U.S. government, industry, and academe together can employ.

How have the research professors pulled off this trick? The answer is actually rather simple.

The golden age of American academic science—that is, the 1950s and '60s—produced genuine excellence and made American universities the leaders of the world in scientific training and research. What Europe once was for young scientists in America, America became for young scientists in the rest of the world. They sought to come to the United States, either to obtain an American doctorate or at least to spend a year or more in graduate or postdoctoral study. In short, *foreign* students have taken the places of the missing American students and now constitute roughly half of the Ph.D. holders that American research professors are turning out.

There was one other trick that the professors employed to ward off the effects of the Big Crunch and pretend that it had not occurred. They multiplied the number of postdoctoral research positions, thus creating a kind of holding tank for young scientists that allowed them to put off the unpleasant confrontation with the job market for three to six years, or in some cases even longer.

Since I began with a cosmological analogy, let me now return to one. An unfortunate space traveler, falling into a black hole, is utterly and irretrievably doomed, but that is obvious only to the space traveler. In the perception of an outside observer hovering above the "event horizon," the space traveler's time slows down, so that it seems as if catastrophe can forever be deferred. Something like that has happened in American research universities. The good times ended forever around 1970, but by importing foreign students and employing newly anointed doctors of philosophy as temporary "postdocs," the professors and the universities have stretched time out, allowing them to pretend that nothing important has changed, to think that they need only wait for the good times to return. Only the students realize that they are falling into a black hole.



As this 1992 illustration suggests, leakage in the Ph.D. "pipeline" was widely seen as a major problem.

In spite of all this, only a few years ago, in the early 1990s, many leaders of American science became alarmed that we might not be producing enough scientists and engineers for the future. The problem, they thought, lay with the "pipeline." This metaphor emerged, I believe, from the National Science Foundation, which keeps careful track of science work force statistics, and came to be widely accepted. At the pipeline's entrance was said to be a torrent of youngsters, curious and eager to learn. But as they moved on through the various grades of school, they somehow lost their eagerness and curiosity, and fewer and fewer youths showed any interest in science. The pipeline, in short, was leaking badly, and as a result, there would not be enough Ph.D.'s at the end of the line. The leakage problem was seen as particularly severe with regard to women and minorities. If America is to have all the scientists it will need in the future, we were warned, the leaky pipeline must be fixed. Today, the fear of too few scientists has vanished from the scene, but the pipeline metaphor of science education persists.

I think the pipeline view of our situation is seriously flawed. The metaphor itself leaks—beyond all repair. The purpose of American education is not to produce holders of doctoral degrees in science or in anything else. The purpose is to create knowledgeable citizens of American democracy who can contribute to their own and the common good. To regard such citizens as somehow deficient because they lack advanced degrees in science is silly, not to mention insulting. Moreover, if American education were a leaky pipeline and could be fixed, the problem that many scientists still do not want to face would remain: what to do with the resulting flood of people with advanced degrees in science.

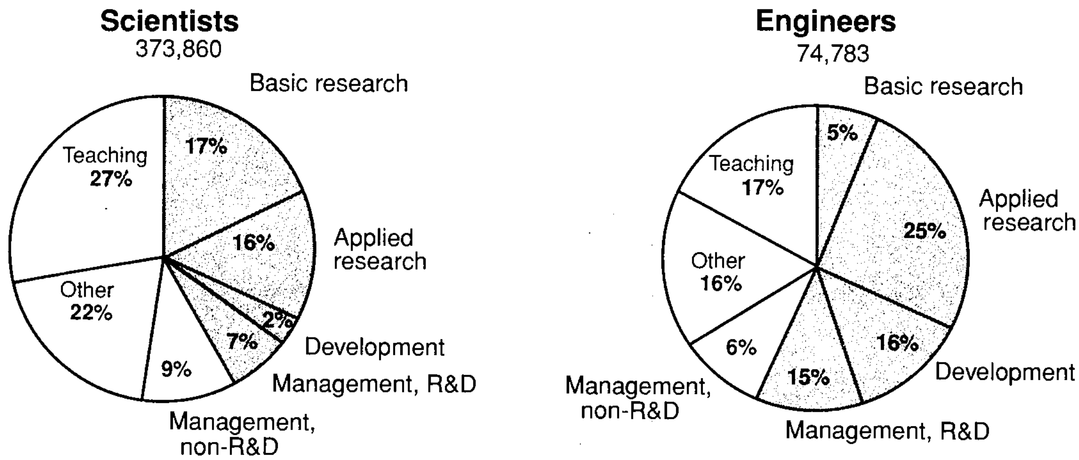
A more realistic way of looking at American science education, as it is now and has long been, is, I suggest, to view it as a mining-and-sorting operation designed to discover and rescue diamonds in the rough, ones capable of being cleaned and cut and polished into glittering gems, just like us, the existing scientists. Meanwhile, all the other human rocks and stones are indifferently tossed aside in the course of the operation. Thus, science education at all levels is largely a dreary business, a burden to student and teacher alike—until the happy moment arrives when a teacher-miner finds a potential peer, a real, if not yet gleaming, gem. At that point, science education becomes, for the few involved, exhilarating and successful.

This alternative metaphor helps to explain why, in all of the industrialized world, the United States has, simultaneously and paradoxically, both the best scientists and the most scientifically illiterate young people: America's educational system is designed to produce precisely that result. At the same time that American scientists, trained in American graduate schools, win more Nobel Prizes than the scientists of any other country, and, indeed, than the scientists in most, if not all, of the other countries combined, the students in American schools invariably rank at or near the bottom of all students from advanced nations in tests of scientific knowledge. America leads the world in science—and yet 95 percent of the American public is scientifically illiterate.

Let us look a little closer at this mining-and-sorting operation that science education is in America. It begins in elementary school, but only sluggishly and almost without conscious direction. Most elementary school teachers are poorly prepared to present even the simplest lessons in scientific or mathematical subjects. In many colleges, elementary education is the only major that does not require even a single science course. Worse, 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 that is true, elementary school teachers are not merely ignorant of science but determined to remain ignorant. That being so, they can hardly be expected to encourage their students to take an interest in science. Moreover, even those teachers who did have some science courses in college are not likely to be well prepared to teach the subject.

Thus, few elementary school pupils

Primary Employment of Scientists and Engineers



Source: National Science Foundation, *National Patterns of R&D Resources: 1992*

The main work of the 448,600 doctoral scientists and engineers in 1989 (43 percent more than in 1979): for 25 percent, teaching; for 17 percent, applied research; for 15 percent, basic research.

come into contact with anyone who has scientific training, and many decide, long before they have any way of knowing what science is about, that it is beyond their understanding. Nevertheless, some students, a relative handful—usually those who do sense that they have unusual technical or mathematical aptitudes—reach middle school and then high school with their interest in science intact.

There, the mining-and-sorting process gets under way in earnest. Most of the 22,000 high schools in the United States offer at least one course in physics. (Because I have some firsthand knowledge of the teaching of physics in high schools, I shall focus on that, but I am quite sure that what I have to say applies to other science subjects as well.) There are only a few thousand trained and fully qualified high school physics teachers in the United States, far fewer, obviously, than there are high schools. Most of the physics courses are taught by people who in college majored in chemistry, biology, mathematics, or—surprisingly often—home economics (a subject that has fallen out of favor in recent years). These teachers are, in many cases, marvelous human beings who, for the sake of their students, work extraordinarily hard to make themselves better teachers of a subject that had never been their first (or perhaps even their second or third) love. Their greatest satisfaction as physics teachers comes from—guess what?—discovering those "diamonds in the rough" that can be sent on to college for cutting and polishing into real physicists.

That process is not completed in college, of course. Mass higher education, essentially an American invention, has meant that nearly everyone is educated, albeit rather poorly. The contrasting alternative in Europe has been to educate a select few rather well. But in the better U.S. graduate schools, elitism is rescued from the jaws of democracy. In about their second year of graduate school, the students (in physics, at least) finally catch up with their European counterparts and thereafter are second to none.

American education, for all its shortcomings and problems, was remarkably well suited to the era in which the scientific enterprise was expanding exponentially. But after about 1970 and the Big Crunch, the gleaming gems produced at the end of the vast mining-and-sorting operation were

Science for Everyone?

What should an educated person know about science? In The Myth of Scientific Literacy *(Rutgers University Press, 1995), Morris Shamos, a professor emeritus of physics at New York University and a past president of the National Science Teacher Association, contends that trying to make everyone scientifically literate is futile. Instead of offering general students the usual medley of scientific disciplines and asking them to memorize terminology and facts, educators, he says, need to provide students with a broad understanding of what science can—and cannot—accomplish.*

The promise of a *meaningful* public literacy in science is a myth. However good our intentions, we have tricked ourselves into believing that what is being done with science in our schools can lead to such literacy. The folly of this position is that not only do we lack agreement as to the meaning of scientific literacy, but more seriously, we also lack any *proven* means of achieving even the lowest level of science understanding in our educated adult population. . . .

Testifying at a hearing of the Senate Armed Services Committee in November 1957 (soon after Sputnik was launched), the physicist and hydrogen bomb expert Edward Teller likened the need for public support of science to that of the arts. "Good drama," he said, "can develop only in a country where there is a good audience. In a democracy, particularly if the real sovereign, the people, expresses lack of interest in a subject, then that subject cannot flourish." Later in the hearing, giving his views on education in science for the nonscience student, he added: "The mass of our children should be given something which may not be terribly strenuous but should be interesting, stimulating, and amusing. They should be given science appreciation courses just as they are sometimes given music appreciation courses."

Teller's message of science *appreciation,* coming at a time when the American public, and particularly the Congress, was highly sensitive to the issue of Soviet competition in space, and just when massive [National Science Foundation] support for precollege science education was in its formative stage, fell on deaf ears as the nation girded itself for a far more ambitious role in science education, namely, to achieve in the educated public what had never before been accomplished—the intellectual state that came to be known as "scientific literacy."

While not clearly defined at the time (nor even now), this objective carried such a comforting pedagogical feel that one could hardly challenge its premise, and for the next quarter-century the science education community sought to [portray] virtually everything it did as bringing us closer to the goal of scientific literacy. It tried valiantly but it failed badly. . . .

The science and engineering communities, and our nation generally, would be better served by a society that, while perhaps illiterate in science in the formal academic sense, at least is aware of what science is, how it works, and its horizons and limitations. . . .

Teller was perfectly correct in his observation that science must have an appreciative audience, meaning in these times a supportive society, one that values science for its intellectual strength as well as . . . the technologies it spawns. Without such support, science and technology . . . could both flounder, and the United States might indeed become a second-rate nation.

produced less often from American ore. Research professors and their universities, using ore imported from across the oceans, kept the machinery humming.

That can't go on much longer. It is hardly likely that the American public, when it apprehends the situation, will agree to keep pumping vast sums of federal and state money into scientific research in order to further the education and training of foreign scientists. Sooner or later—and in today's post-Cold War environment, it is bound to be sooner—we scientists must face up to the reality of the Big Crunch and learn how to deal with it.

That will not be easy. In 1970, as a young assistant professor of physics at the California Institute of Technology, I circulated a memo among my colleagues pointing out that exponential growth could not be sustained and recommending that Caltech set a dramatic example by admitting fewer graduate students. My faculty colleagues accepted my main argument, but they had a different solution: everyone else should get out of the Ph.D. business, and Caltech should go on just as it was. At every other university where I've broached this subject, I've had precisely the same reaction: not that Caltech should go on as before, but that the particular university I was visiting should.

Harold Brown, who when I circulated my memo was president of Caltech (and who later served as U.S. secretary of defense), had a more creative solution to the problem: make a Ph.D. in physics a prerequisite for any serious profession, just as classical Latin and Greek once had been for the British civil service. (He may have been influenced by the fact that he himself has a Ph.D. in physics but never became a practicing physicist.)

Brown was probably joking. But many scientists today seriously put forth a similar solution. They are advising doctoral candidates on other careers they might pursue after earning the degree that certifies their competence to do scientific research. The little matter of *why* they should become elaborately trained to do something that they are not going to do is seldom brought up.

Why are research professors so eager to produce more future research professors? Of course, most are quite certain that the world will need many more splendid people just like themselves. Their main motive, however, is a little less noble: graduate students are a source of cheap labor. They teach undergraduates, thus freeing the professors to concentrate on research, and they also help the professors do their research. And the graduate students' labor is indeed inexpensive: by their third year, those in science are typically performing difficult, technically demanding work at salaries lower than those received by most starting secretaries.

The arrangement is very convenient for the research professors, but it and the mining-and-sorting operation we call science education in this country cannot go on as they have in the past. The Big Crunch will not allow it. For the new era of constraint, we will have to develop a radically different scientific "social structure," for both research and education. That structure will come about by evolution, not radical redesign, because no one knows what form it will eventually take. One thing, however, is clear: reform of science education must be part of our efforts to adapt the scientific enterprise to the changed conditions.

Pure research in basic science does not reliably yield immediate profit. Hence, if it is to flourish, private support will never be enough. Public funds will continue to be essential. If that support from the public purse is to be forthcoming, there must be a broad political consensus that basic science is a common good. It *is* a common good, for two reasons: first, it helps to satisfy the human need to understand the universe we inhabit, and second, it makes new technologies available. The world would be a very different place without, for example, communications satellites or computers. But to get the public—in the absence of a war, hot or cold—to agree that basic science is worth substantial funding, we scientists are going to have to do a much better job of education than we have in the past. It is no longer enough just to educate a scientific elite.

Really teaching science to people who will never be scientists is not going to be easy. The frontiers of science are far removed from most people's everyday experience. Unfortunately, we scientists so far have not found a good way of bringing people in large numbers along as "tourists" on our scientific explorations.

But that leads me to a modest suggestion: perhaps, after all, there is a reason to keep churning out people with Ph.D.'s in science.

As I indicated before, roughly 20,000 U.S. high schools lack even one fully qualified physics teacher. All of the people with physics Ph.D.'s who are now driving taxis could help to meet that need, and they would be just a beginning.

However, let's be realistic. Before large numbers of people will be willing to obtain a Ph.D. in order to teach in high school, the conditions under which American high school teachers work will have to be substantially improved. I am not speaking here primarily of money. After all, the salaries of beginning schoolteachers today are almost competitive with what postdoctoral fellows receive, and experienced teachers earn salaries comparable to what professors at many colleges get. It would help, of course, if high school teachers were paid better, but that is not the main thing. The real problem is that schoolteachers today are not given the professional respect, freedom, and responsibility that people who have earned Ph.D.'s tend to believe they deserve. I have no blueprint for reform, but I see no intrinsic reason why the prestige of schoolteaching cannot be elevated. In Europe, schoolteachers are highly esteemed precisely because of their superior academic qualifications. Perhaps conditions in the United States now are such that improvement along this line is possible.

Even if education can be reformed, however, that will not be enough. Many of the institutions of science that evolved and worked wonderfully during the long era of exponential growth are gradually breaking down in the new age of constraint. For example, universities have been the real entrepreneurs of science. They raise or borrow funds to put up new laboratory buildings and hire tenured professors to work in them, counting on the professors to bring in grants that will pay off the university's investment. That strategy is becoming suicidal, but many universities seem not to have caught on yet. When they do catch on, or else go belly up, who will build the laboratories of the future? Another example is peer review, long considered a pillar of the system. Anonymous peer review becomes a dangerous game when the author and reviewer are locked in an intense competition for scarce resources. The conflict of interests seems to be obvious to everyone except those who are currently running the system. But what alternative is there to peer review?

We scientists who came of age during the 1950s and '60s must finally recognize that the old era is gone and that, no matter what we do, it is not coming back. We are in a new era now, and it is by no means certain that science as we have known it will even survive. But if we are willing to face the new realities and adapt to them, we may be able not only to rescue the scientific enterprise but to give young Americans something that too many of them now do not have: a basic knowledge of what science has thus far revealed about the world they will inherit. If we can accomplish that, the era of constraint for science may turn out to be a new golden age.