''Now Boarding: The Flight from Physics'' David Goodstein's acceptance speech for the 1999 Oersted Medal presented by the American Association of Physics Teachers, 11 January 1999

David Goodstein
Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, California 91125

All across the country, the number of students majoring in physics is said to be at its lowest point since Sputnik, 40 years ago. The most important role of the college physics course today seems to be to weed out a few poor souls who might otherwise make it to medical school or some other kind of quasi-scientific training. If the profession of teaching physics were a business, we would be filing for bankruptcy. On the other hand, our assets include nothing less than the wisdom of the ages, the most important part of the body of human knowledge. Mastery of that knowledge, a fundamental grasp of how the world works, ought to be the best possible preparation for the coming century. Rather than being an endangered species, the physics major should be the wave of the future, but it isn't, at least not yet. This talk will analyze how we got ourselves into this fix, and suggest what is needed to get ourselves out of it.

The Oersted Medal has been won by two of my predecessors at Caltech, Robert A. Millikan in 1940, and Richard P. Feynman in 1972. Millikan, in his formal address, pointed out that in the preceding forty years, that is, from 1900 to 1940, some forty-two of the sovereign United States had passed laws requiring all children to attend school up to the age of sixteen to eighteen years. Europeans, he said, find this ''fantastic and ridiculous'' because at least 90 percent of the population must gain its livelihood in ''manual or service pursuits.'' On the other hand, he thought, this situation was a splendid opportunity for physics teachers, essentially because a course in physics was the best possible way of finding out who belonged in the other ten percent.

When it came Feynman's turn, he thought about giving a talk on the philosophy of teaching physics, and realized he had nothing to say but clichés. So, instead, he said, ''I want to talk about the proton under the electron microscope.'' By this he meant his parton theory of electron-proton scattering. Partons would later be identified as quarks and gluons, and although Feynman's talk was never published, it was a characteristically beautiful exposition of profound new ideas in physics.

My own field is Condensed Matter Physics, a business so messy it doesn't lend itself to the kind of elegant exposition that Feynman engaged in for his Oersted address. There's a story making the rounds that makes the point: Two prisoners are brought out to be shot. One says, ''Before shooting me, let me tell you my new theory of high temperature superconductivity.'' The other prisoner says, ''Shoot me first!''

Actually, I'm not a theorist. I don't even *have* a theory of high temperature superconductivity. So, what I would like to do instead is to return to the point of Robert Millikan's address.

When Millikan spoke, before WWII, universal secondary education was just taking hold, and college was reserved for the elite. After the war, prompted in part by the G.I. Bill of Rights, and later the Higher Education Act of 1965, we were very nearly transformed into a nation of universal higher education. Today, nearly two-thirds of all American high school graduates go on to college. This amazing phenomenon entailed an explosive growth of the academic world in the first few decades after the war. However, that growth must be seen in an even larger perspective before it begins to make sense. You may have noticed that we no longer assume that 90 percent of the population will be engaged in what Millikan referred to as ''manual or service pursuits.'' That liberation from menial labor has been the fruit of advances in science and technology. To understand what has happened to our world, we must look to the history of science.

The upper curve in Figure 1 is a plot of the cumulative number of scientific journals founded world-wide as a function of time. This plot was made in the 1950's by an historian named Derek da Solla Price. It is a semi-log plot, and it shows that the number of journals founded increased by a very neat factor of ten every 50 years, from about 1700 until Price made this figure 250 years later. Price asserted that any quantitative measure of science, anything you could count, would behave in this same way. It is pure, positive exponential growth.

Price wisely predicted that this behavior could not go on forever. He was right, of course. The straight line in the plot extrapolates to one million journals by the year 2000. Instead, the number of scientific journals in the world today, as we approach the millennium, 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.

In order to see what has happened since the 1950's, I got some data from the American Physical Society and other sources on the number of physics Ph.D.'s per year produced in the United States, and plotted them on the same scale, represented by the second curve on the slide. The United States started later than Europe. The first Ph.D. in physics was awarded around 1870, after the Civil War, and then the exponential growth began. At the turn of the century, we were up to about 10 a year, and around the 1920's and 1930's, we reached 100 a year. In 1970, we reached 1,000 a year, and it extrapolates to 10,000 a year today and a million a year in the middle of the next century.

But that's not what happened. What happened was that the growth stopped abruptly in 1970 and has been fluctuating

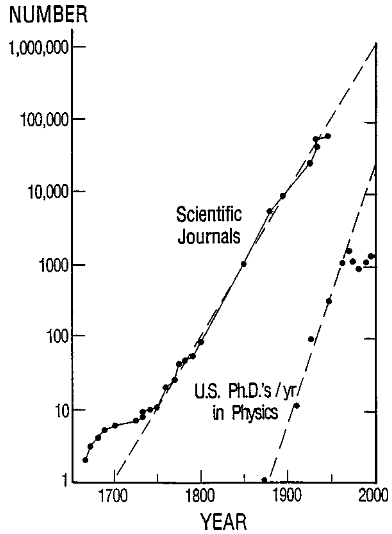

Fig. 1. The upper curve, first plotted by historian Derek da Solla Price in the 1950's, shows the cumulative number of scientific journals founded worldwide versus time on a semi-log scale. The result is a pure positive exponential, with a ten-folding period of 50 years. The lower curve, on the same scale, shows the rate of Ph.D. production in the United States. It shows a century of exponential growth that ended abruptly around 1970.

around 1000 a year ever since. A permanent change occurred in 1970. The Big Crunch occurred, and nobody noticed.

The last 20 years of the exponential growth from about 1950 to 1970 were truly breathtaking. The prestige of science, after helping to win World War II, opened the money pipeline from Washington to the research universities. That was also the era of academic expansion I spoke of earlier. The great corporations decided that they needed central research laboratories, either for solving technological problems or to perform basic research to provide material for future developments. At the same time, we created a superb system of national laboratories that provided more jobs and research opportunities for young scientists. The Soviet Union gave us an enormous boost in 1957 when they launched Sputnik and convinced us all that we weren't educating engineers and scientists fast enough, thus kicking the entire system up to a higher level. This was the Golden Age of American science.

Nevertheless, all of that explosive growth, everything that I have just described, made not even a kink on the curve that you saw. It was simply a seamless continuation of 100 years of exponential growth. That is the nature of exponential growth. The bigger it is, the faster it grows. And those last 20 years were the fastest of all.

The period from 1970 until very recent times is what I like to call the ''Age of Denial,'' in which we did our very best to pretend that nothing had changed, even though The Big Crunch had, in fact, already occurred. The specific events around 1970 were that support for science had gotten big enough to show up on the radar screens of conservative congressmen, while at the same time liberals associated science with the military and the military with the Vietnam war. But the specific events are not important. It occurred because society could no longer sustain that kind of exponential growth. Somewhere around 1970, the fraction of our most highly qualified students enrolling in graduate school started to decline and has been declining ever since. However, American students were replaced by foreign students. One result of the Golden Age was genuine excellence in American science. Just as, before the War, Americans had to go to Europe to complete their educations, and it is said, in ancient times, Romans had to go to Greece, young people from everywhere else who wanted to be serious scientists now had to come to the United States. At the same time, we vastly increased postdoctoral positions, allowing young Ph.D.'s to go into a kind of holding pattern in which they contributed to university research while putting off facing reality for 3 or 6 years, and in some cases, even longer. All of this kept up the level of activities in the American research universities and made it possible for us to pretend that nothing had changed.

Nevertheless, now that we have reached 1999, it is difficult to imagine a situation more radically different from what it was in the last years of the Golden Age.

For one thing, the Cold War has come to an end. This did not create our problems, but it certainly exposed them. It made it impossible for us to go on pretending that nothing had changed. Many of the national laboratories have lost their missions and have not found new ones. We are told that science and technology are essential for our future national economic competitiveness, but the real masters of our economy believe that they know better. The great corporations have decided that central research laboratories are not such a good idea after all, and they have either greatly reduced them or closed them entirely. Furthermore, our national economy has gradually transformed from manufacturing to service, not the kind of service Millikan spoke of, but rather service industries like banking and insurance that don't support very much scientific research. Moreover, the Nation is $5 trillion in debt and scientific research is among the few items of discretionary spending that is available for cutting when the economy goes sour, as it inevitably must. Finally, academic expansion, that immense expansion of the academic world that soaked up all the Ph.D.'s that we were producing and that led to the institution of mass higher education, is over forever. With more than half of our nation's kids already going on past high school, academic expansion will never return.

The big problem with all of this is that the institutions of science, the ways in which we organize our profession, all evolved during the long period of exponential growth. They are optimized for that condition, which means they are poorly adapted for the very different kind of future we must face. Nowhere is that more evident than in the matter that concerns us most here today. That is, in the matter of science education.

Our American system of science education has produced what I like to call The Paradox of Scientific Elites and Scientific Illiterates. The paradox is this: as a lingering result of the Golden Age, we still have the finest scientists in the world in the United States. But science education in America is simply abysmal. There seems to be little doubt that both of these seemingly contradictory observations are true. American scientists, trained in American graduate schools, produce 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% 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? That is what I mean by The Paradox of the Scientific Elites and the Scientific Illiterates.

Science education in American is often referred to as a ‘‘pipeline.’’ The idea is that our young people start out as a torrent of eager, curious minds anxious 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 Ph.D.'s. Thus, our entire system of education is seen to be a leaky pipeline, badly in need of repairs. The leakage problem is seen as particularly severe with regard to women and minorities, but the pipeline metaphor applies to all. 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 figure out 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 Ph.D.'s 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 Ph.D.'s that we wouldn't know what to do with. For another thing, producing Ph.D.'s 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, of contributing to their own and to collective economic well-being. To regard anyone who has achieved those purposes as having leaked out of the pipeline 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 American 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. The more scientists we have looking for diamonds in the rough, the more we find. That's the differential equation for exponential growth. It accounts for the very real problem that women and minorities are woefully underrepresented among the scientists, because it is hard for us, white, male scientists to perceive that once they are cleaned and cut and polished, they will look just 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.

The mining and sorting operation of science education reaches its culmination in graduate school. The last stage in the selection process chooses who among graduating Ph.D.'s will go on to become professors, just like their own mentors. Each professor in a research university turns out, on the average, about 15 Ph.D.'s in the course of a career. A career lasts about 30 years; if you have an active research group someone is bound to graduate every couple of years. You can't get very far from that number. If each of those 15 Ph.D.'s wants to become a professor and turn out 15 more Ph.D.'s, it's easy to see how exponential growth works. In a steady-state world of science, each professor needs to turn out only one professor for the next generation.

Many years ago, when I first started to worry about this problem, I was a young assistant professor of physics, and the President of Caltech was Harold Brown, who would later be Secretary of Defense in the Carter administration. I wrote a white paper, pointing out that the long era of exponential growth had come to an end, and suggesting that Caltech set a dramatic example by cutting back sharply on our rate of production of Ph.D.'s. My colleagues at Caltech accepted my arguments about exponential growth (they had all had courses in differential equations and had learned that the positive exponential is the solution you discard because it is non-physical), but they disagreed with my solution. They thought the proper solution was for everyone else to go out of the Ph.D. business, and for Caltech to continue exactly as it always had. I've had the same reaction at every university where I've spoken about this problem.

Harold Brown, however, had a more creative solution. He thought a Ph.D. in physics should be required as a prerequisite for any serious career, just as classical Latin and Greek had once been required for the British civil service. At least that would put the problem off until some time in the next century, when every man, woman and child in the country would have a Ph.D. in physics. It should be noted, I suppose, that Harold Brown has a Ph.D. in physics, but never practiced the trade, making an entire career instead in administration.

I think you will notice at once a striking similarity between Brown's view, and that expressed 30 years earlier by Millikan, that a course in physics is a proper way to choose those fit to escape a life of menial labor. This point of view may be an occupational hazard of Caltech presidents. I have, I assure you, not the slightest trace of desire to become President of Caltech, but I am, I warn you, going to come to a similar conclusion by the end of this talk.

The depressing situation, in which young Ph.D.'s in physics can't find the kinds of jobs they would like to have has reverberated down through the system. Because the undergraduate physics major is largely perceived as preparation for graduate school, and graduate school in physics is now perceived as the road to oblivion, majoring in physics has gone out of style. (Of course, it was never really in style, but let's ignore that.) My friends and colleagues across the country tell me that the number of students majoring in physics today is at it lowest point since Sputnik, more than 40 years ago. We in the profession of teaching seem to be in a business whose product is no longer in demand. There are just too many scientifically educated people out there.

If you believe what I just said, then, I submit, somebody put something funny in your coffee this morning. There is something starkly, weirdly wrong with the notion that I seem to have arrived at so logically. I think it's time for us to go back to the beginning and reanalyze what our profession is really all about.

A couple of years ago, the U.S. produced about 1000 Ph.D.'s in mathematics. Last year, just over 10% of those new Ph.D.'s, about 100 people, were unemployed. This situation led to a firestorm of protest on the internet, that I somehow got plugged into. Yet, during that same year, a solemn report was issued at the national level saying that half the math classes in American schools were being taught by people who lacked the qualifications to teach them. So here you have, on the one hand, a hundred or so highly qualified people without jobs, and on the other hand, thousands of classrooms where precisely those qualifications are lacking. Surely there must be some rational way to approach this situation.

In physics, people seem to be a bit more versatile, and the absolute unemployment rate is not so high, but nevertheless the internet crackles with the complaints of young Ph.D.'s who are unable to get the jobs doing research in physics that they thought they were being trained for. Once again, on the other hand, there are something like 24,000 high schools in the United States, most of which offer at least one course in physics. Nobody seems to know how many qualified high school physics teachers there are, but the number is small, no more than a few thousand. The vast majority of high school physics courses are taught by what are called cross-over teachers. These are splendid people who do their best to do a good job, but they are teaching a subject they never chose for themselves, and for which they are not adequately trained. I thought when I first got into the business of trying to help out with this problem that I would typically find the high school basketball coach teaching physics (which, after all, comes close to physical education in the alphabet) but that's not the case at all. Usually it's done by someone who majored in biology or chemistry or math, but surprisingly often it's the former home economics teacher who does it. That subject has really gone out of fashion in recent times.

It is utterly absurd to think that we have an excess of scientifically trained people in our society. What we have instead is a desperate shortage of such people. For the relative handful of people who have Ph.D.'s and are unemployed or underemployed, there is no quick fix. Most don't want to teach in high school, and even if they are willing to try, they are unprepared for that demanding occupation, and faced with enormous legal and bureaucratic obstacles besides. But in reality they are just one symptom of what is a very much larger problem that our profession needs to come to grips with.

Let me be blunt. The profession of teaching physics, as it is practiced today, has only two purposes. One is to turn out physicists, and the other is to act as the gatekeeper, keeping the unworthy out of certain other professions such as medicine and engineering. That is what the mining and sorting operation has come down to. We will always need physicists, but not very many of them, and the best ones will succeed no matter how well or poorly we do our jobs. The other role, as gatekeeper, is the dark side of Millikan's vision of nearly 60 years ago. We do indeed get to decide who will be among the elect. Nearly every doctor I've ever had has glanced at that information sheet you fill out on your first visit to the office and said, ''Physics prof! That's what almost kept me out of med school.'' You've probably all had similar experiences. For some reason, it doesn't inspire confidence. (Actually, a couple of my doctors recently have been fans of The Mechanical Universe. That makes me even more nervous.) The simple fact is, we are failing. If teaching physics were a business, we would be filing for bankruptcy.

All right. Let us, for just a moment, pretend that our profession *is* a business, and take stock of our situation the way any good manager would do. We are in deep trouble. Our methods are obsolete, and our product is not in demand. What can we do about it?

The first step is to turn the problem around and ask, do we have any valuable assets that might be worth saving? The answer to that one saves the day. You bet we do! What we have is nothing less than the wisdom of the ages. It's that vast body of knowledge, the central triumph of human intelligence, our victory over mystery and ignorance; and to go with it we have the methods of inquiry and analysis that have produced that body of knowledge. Our assets in fact are so valuable that we have a solemn duty *not* to let our profession go down the drain.

The purpose of teaching physics should not be merely to clone ourselves and to keep a few poor souls out of med school. I believe that a solid education in physics is the best conceivable preparation for the lifetime of rapid technological and social change that our young people must expect to face. The undergraduate physics major is the liberal arts education of the twenty-first century! Every physics department in the country ought to inscribe that motto on its walls and march under that banner. But to make that motto into a reality will take nothing less than a revolution in the way we do our jobs.

Everything about the way we teach physics is useless for the vision I am trying to present to you. The methods, the textbooks, the language we use, all of it is designed more to get rid of the unworthy than to throw open the doors. What we need to change first of all is the mindset with which we approach our subject.

If I knew how to do all of that, or even if I knew just how to take the first step in that direction, I would certainly tell you. But I don't know. What I'm asking for is something truly difficult, much more difficult even than physics itself.

I do, however, know one small thing. The key to teaching anything is to remember what it was like not to understand that thing. That's a very hard thing to do. Every time you come to understand something you didn't understand before, you are transformed. You become a different person from who you were before. The key to teaching someone else to understand that same thing is to remember your former, untransformed self. If you can do that, I think you can teach anything, even physics. Unfortunately, the methods that we actually use to teach physics seem to be based on exactly the opposite point of view: that what we understand ought to be obvious to anyone worth teaching, and if they don't understand it, why we'll drill it into their little heads, or, of course, just flunk them out. That, I think, is not the right way to do it.

So, I have finally come down on the side of Robert A. Millikan and Harold Brown. We physicists have come to understand, in very large measure, how the world works. To live in ignorance of that understanding should be intolerable for an educated person in the next century. I think in the deepest sense, that's what Millikan and Brown had in mind. I'm proud to stand beside them and say the same to you.