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PAGES 329–340

The Big Crunch

PAGES 329, 334

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According to modern cosmology, the universe began with a big bang about 10 billion years ago, and it has been expanding ever since. If the density of mass in the universe is great enough, its gravitational force will cause that expansion to slow down and reverse, causing the universe to fall back in on itself. Then the universe will end in a cataclysmic event known as "the Big Crunch."

I would like to present to you a vaguely analogous theory of the history of science. The upper curve on Figure 1 was first made by historian Derek da Solla Price, sometime in the 1950s. It is a semilog plot of the cumulative number of scientific journals founded worldwide as a function of time.

A straight line with positive slope on this plot is a pure exponential. As you can see, science sprang into being around 1700, probably 1687—the year of Newton's *Principia*—a good candidate for the actual Big Bang. And science increased by a factor of 10 every 50 years, until Price made this curve in the 1950s. The number of journals founded up to then was 100,000. It extrapolates to a million by the end of the century. We are now near the end of the century, but there are only about 40,000 scientific journals in the world today. That accounts for why we scientists often have nothing to read by the time we reach the end of the week. The point is, sometime between the 1950s and now, those 300 years of exponential growth came to an end.

Price said that any quantitative measure of the size of science would look the same. In order to check that and see what has happened since the 1950s, I got some data from the American Physical Society 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. 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 1920s and 1930s, 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.

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But that's not what happened. What happened was that the growth stopped abruptly in 1970 and has been fluctuating around 1,000 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. At the same time, the GI Bill of Rights sent an entire generation of Americans back to college, transforming the United States from a system of elite higher education to a system of mass higher education. Before the war, about 8% of all Americans went to college, about the same as in France or England. Currently, more than half of all Americans receive some sort of postsecondary education.

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 also provided jobs and research opportunities to 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's 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 best to pretend that nothing had changed, even though the Big Crunch had, in fact, already occurred. Around 1970, 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.

The Age of Denial 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. American science had become the best in the world, and young people from everywhere else who wanted to be serious scientists had to come to the United States for part of their education. At the same time, we vastly increased postdoctoral positions, allowing young Ph.D.s to go into a kind

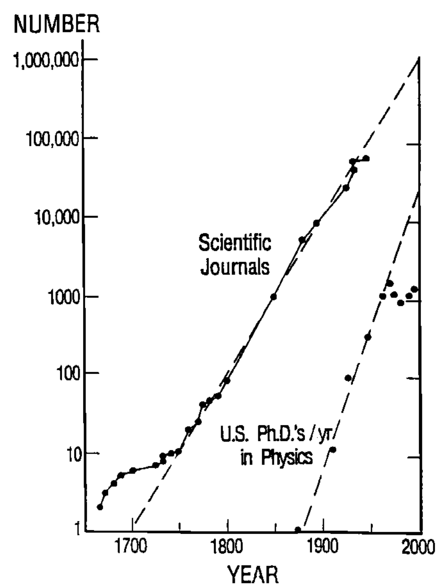

Fig. 1. The number of scientific journals and U.S. Ph.D.s in physics rose exponentially until some time after 1950.

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 1996, 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 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, and service industries like banking and insurance don't support much scientific research.

Anybody who reads the newspaper today understands that the nation is $5 trillion in debt and that scientific research is among the few items of discretionary spending that can be cut. Finally, the immense expansion of the academic world—which soaked up all the new Ph.D.s and 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.

As a result, the institutions of science that evolved during the period of exponential expansion and are optimized for those conditions are beginning to break down. Let me give you some examples.

One example is the institution of peer review, which is an excellent way of distinguishing valid science from nonsense but a very poor way of adjudicating an intense competition for scarce resources. The reviewers, who are among the few genuine experts in the field, have a conflict of interest because they are competing for the same scarce resources. Most scientists are people of high integrity who do their best not to let their conflict of interest cloud their judgment. Nevertheless, every scientist I know has been victimized at one time or another by unfair reviews, and that kind of experience tends to corrode one's high ethical standards. So, peer review, I believe, is in critical danger.

Another example is that the research universities were traditionally the intellectual and economic entrepreneurs of scientific progress. By that I mean they built laboratory buildings with state-of-the-art equipment. To do so, they borrowed money by floating bonds. They also hired tenured professors to fill those laboratories, making long-term commitments to support their salaries. They then expected that those professors will bring in grants that will repay their investments. During the period of exponential expansion, that was a successful business strategy. Today it is suicide. And the universities that are doing this will either learn very quickly to stop doing it or they will go belly up. In either case, the next generation of laboratories will not be built unless we evolve new institutions to promote progress in science.

Our educational system is a kind of mining and sorting operation. At every level, we scientists sift through the human debris that comes our way looking for diamonds in the rough that can be transformed into gleaming gems, just like us, the existing scientists. And we toss away the rest. That creates a paradoxical situation: we have the best scientists in the world, but the public's scientific knowledge is abysmal by any standard. That's because the public consists of all those we've carelessly tossed on the slag heap. This system of training scientists and throwing away everybody else has put us in deep peril. We cannot expect a public that does not understand what we do to go on supporting our enterprise forever.

The mining and sorting operation reaches its pinnacle at the graduate level, where we have the phenomenon of inherited aspirations. The average professor in a research university turns out about 15 Ph.D.s in the course of a career. You can't get very far from that number. If you have an active research group, somebody is bound to graduate every couple of years.

A career lasts about 30 years, so that's approximately 15 Ph.D.s. The only reproductive responsibility of a professor in a research university is to produce one research professor for the next generation. Nevertheless, many of those 15 students have as their ultimate goal becoming a professor in a research university and turning out 15 more Ph.D.s. That is their inherited aspiration.

The real issue is whether science can survive in an age of constraint. In the past, science was a competition against nature. Could we be clever enough to overcome nature, to find out her secrets by doing successful science? That is no longer the case. Science today is a competition for resources, which makes it an economic rather than an intellectual competition. There is no guarantee at all that science will flourish or even survive under these circumstances. The marketplace, people say, will take care of everything and, in truth, the marketplace does work its wonders. The marketplace, after all, is responsible in some sense for the fact that we stopped producing exponentially increasing numbers of Ph.D.s in physics after 1970. But the marketplace does not care about individuals, and it does not care at all whether science survives. If the future size of the scientific enterprise is to be governed by our threshold for pain, that means, very simply, that we will always be in pain.

Funding, of course, is extremely important. A couple of years ago, Leon Lederman, one of the real leaders of American science, wrote a little booklet called *Science: The End of the Frontier*. Its title was a play on the title of a report by Vannevar Bush at the end of World War II called *Science: The Endless Frontier*, which led to the founding of the National Science Foundation and the Golden Age of science that I told you about earlier. Lederman's argument was that we are starving science by not investing enough at the national government level. I have to confess that I am the anonymous Caltech professor in one of the sidebars in that little booklet quoted as saying, in effect, that my principal responsibility is no longer to do science, but rather, to feed my graduate students' children.

Lederman's argument was not well received in Congress, where it was pointed out to him that scientific research was not an entitlement program. It was not well received in the press, either, where the *Washington Post* had fun speculating about hungry children in the halls of Caltech. And it was not well received by my secretary, who pointed out that I had never had a graduate student who had children. (Well, anything for a good line!)

I think that Lederman did us a real service by raising debate about what fraction of our GDP we ought to be investing in scientific research; many like him think we ought to be investing twice as much as we are. But that is a separate issue from the one that I am discussing now. My view is that, if you double the amount of money that we invest in research (in today's climate, that is extremely unlikely to happen, as you know), the result would be to tack on 3 more years of exponential growth, which would leave us exactly in the situation we are in today. That is to say, the problem is not the government; the problem is created by us.

Education, of course, is crucial to this issue. Most people in the academic world who have heard my arguments assume that I am arguing for some sort of intellectual birth control, meaning, to stop the production of Ph.D.s. I do not and cannot believe that the solution to this problem is less education. I do believe that the solution to this problem is more education in science, but it has to be of a different nature.

In 1995, the United States produced about 1,000 Ph.D.s in mathematics. As of last year, just over 10% of them were unemployed. This has produced a firestorm of protest on the Internet. On the other hand, a few months ago, yet another report came out saying that half the math classes in American schools are taught by people who are not qualified to teach them. So, on the one hand we have about a hundred highly qualified unemployed people, and on the other hand we have thousands of positions where those same qualifications are lacking.

In my own field, physics, there are fewer unemployed Ph.D.s, but many complain they cannot find the kinds of jobs they were trained for. Yet, of the 22,000 high schools in America, there are at least 20,000 that do not have a single qualified physics teacher. It seems to me that we have not a surplus of scientifically trained people in this country, but a severe shortage of such people. The problem is that those who have been trained in science are not willing to do what is really needed. Either that, or perhaps we have arranged society so badly that almost nobody is willing to go through the long arduous time it takes to get a scientific education to become a high school teacher. Can you imagine a society in which teaching high school were a respected, prestigious enough occupation that people would be willing to do that? If you can imagine that, you are imagining the solution to many of the problems that I am talking about.

I must stress once again that the institutions of science–the scientific societies, universities, funding agencies, journals, and the structure of how we do science–all evolved during the period of exponential growth. These institutions are optimized for exponential growth, but are poorly suited for the future we face. Above all, the leaders of science (people my age and older who came of age scientifically during that Golden Age I talked about) believe deep down that those were normal times and will return if we just wait long enough. We can say with mathematical certainty that they are wrong. The good times of exponential growth will never return.

As I said before, I do not believe that Ph.D. birth control should be the solution to our problems. For one thing, it takes a lot more than turning out one Ph.D. in a whole career to get to be good at doing it. We also can't solve the problem by lopping off Ph.D. production in the lesser universities, because the vast majority of Ph.D.s are turned out in good universities. But above all, we shouldn't meddle with our Ph.D. programs because producing Ph.D.s is the one thing we really know how to do. It's the only part of our system of education that the rest of the world admires. And, no matter what else happens, we will need to keep producing bright, young scientists in future generations. So rather than do away with it, we must protect and nourish the American Ph.D., no matter what else we do.

Science does have real enemies, ranging from the creationists on the right to the academic postmodernists on the left. These are not worthy opponents. As long as science is healthy and vigorous, they are no threat to us. However, they do serve to remind us of what would happen if we allow science to destroy itself. It would mean nothing less than a return to the dark ages.

We scientists have a grave responsibility to make sure that doesn't happen.

This article is based on a presentation, "New Challenges in Graduate Education I," which was held at the 1996 AGU Fall Meeting and organized by the AGU Committee on Education and Human Resources.

Mountain Building and Active Deformation Studied in New Zealand

PAGES 329, 335–336

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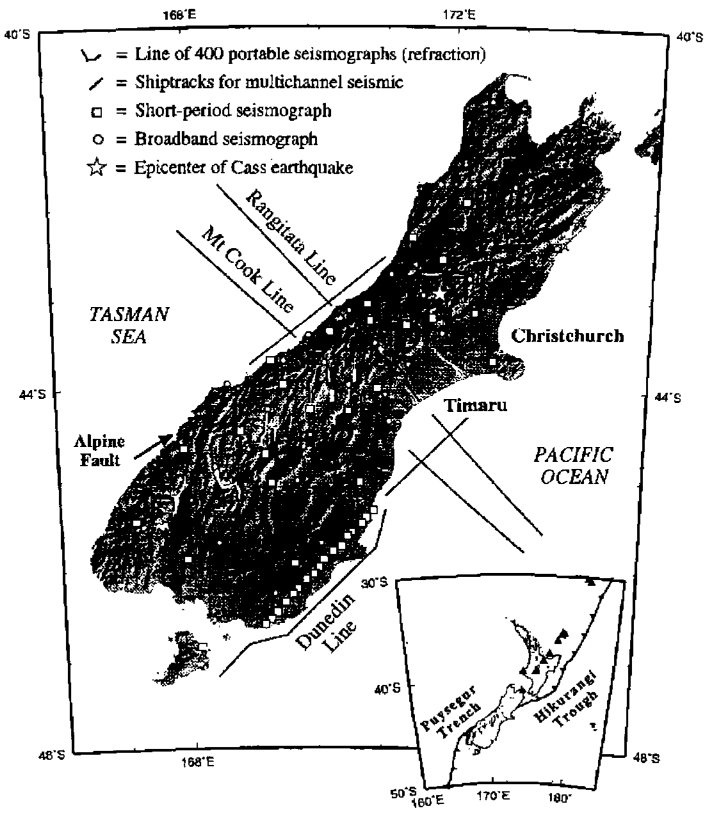

Fig. 1. SIGHT transects shown by solid lines both on- and offshore superimposed on a grayscale representation of topography. Four hundred portable instruments were deployed onshore for the Mt. Cook and Rangitata transects. The distribution of seismo- graphs for the Dunedin line is shown by diamonds. The inset figure shows the location of the South Island with respect to the rest of New Zealand and the subduction zones of opposing polarity at each end of the country. SAPSE onshore recording instruments were broadband seismographs (circles) and short-period seismographs (squares). Epicenter of Mw 6.1 Cass earthquake shown (star).

Strong, eastward dipping (~40°) reflectors found 23 km below the central South Island were recorded by a joint U.S.-New Zealand geophysical project during austral summer 1995-1996. When projected to the surface, the reflectors define a plane that coincides with the surface trace of the Alpine Fault (Figure 1).

Data processing is still at an early stage, but preliminary results, reported at a workshop held at Victoria University of Wellington February 17–19, 1997, give an overall picture of asymmetric crustal thickening and active processes in the mid to lower crust. A jump in crustal thickness of about 20 km is inferred across the Alpine Fault, and the locus of thickening does not occur beneath the highest mountains, but is imaged at least 20 km farther to the east. Low seismic velocities and high electrical conductivity roughly coincide with the strong eastward-dipping reflections in the mid to lower crust. Excess fluids and high pore pressure probably explain both the low seismic velocities and high electrical conductivity.

The central South Island of New Zealand was recently chosen for a series of geophysical experiments. The region's recent mountain building, active transpression, and accessible plate boundary offer many opportunities for scientific study. The project used active source and earthquake seismology, electrical exploration, Global Positioning System, and petrophysics to build a picture, in both space and time, of the structure and active deformation of both crust and mantle at a transpressional plate boundary. Two particular questions we wish to address are: What is the imprint of late Tertiary strike-slip movement on both the crust and upper man-

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