The End of Science Revisited

John Horgan

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One of my most memorable moments as a science journalist occurred in December 1996, when I attended the Nobel Prize festivities in Stockholm. During the white-tie banquet for 1,500 presided over by Sweden's King and Queen, several prizewinners stood to give brief speeches. David Lee of Cornell University, a winner in physics, decried the "doomsayers" who were claiming that science is ending; the work for which he and his colleagues had been honored showed just how vital physics is.

As the audience applauded, several people at my table whispered and jabbed their fingers at me. They knew Lee was alluding to my book, *The End of Science* (Addison-Wesley, 1996), which had been stirring up trouble since its release six months earlier. The book argued that science—especially pure science, the grand quest to understand the universe and our place in it—might be entering an era of diminishing returns. As the *New York Times* put it in a front-page review, "The great days of scientific discovery are over; what science now knows is about all it will ever know."[1]

The book was denounced by eminences such as Bill Clinton's science advisor, the British minister of science, the heads of NASA and the Human Genome Project, the editors of *Science* and *Nature*, and dozens of Nobel laureates. These denunciations usually took the form not of detailed rebuttals of my arguments but of declarations of faith in scientific progress. Scientists need a certain degree of faith to bolster their confidence in the arduous quest for truth; lacking such faith, science would not have come so far so fast. But when researchers reflexively deny any evidence and arguments that challenge their faith, they violate the scientific spirit.

Perhaps recognizing this fact, some pundits reacted thoughtfully to my book. Moreover, I suspect that more than a few scientists who publicly assailed my views privately acknowledged their merit. David Lee was a case in point. When I introduced myself to him at the Nobel banquet to tell him how flattered I was that he had mentioned my book, he said he hoped that I hadn't been offended. He had enjoyed the book and had agreed with much of it, particularly the argument that achieving fundamental discoveries is becoming increasingly difficult. He just felt that the only way for scientists to truly know the limits of science is to keep trying to overcome them.

BUMPING UP AGAINST LIMITS

Today, scientists and nonscientists alike still find it hard to accept that science may be bumping up against limits. I can understand why. We have grown

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up in a period of explosive scientific and technological progress, reflected by such measures as Moore's law. When I started working as a journalist in 1983, I wrote on an IBM Selectric typewriter. I literally cut and pasted (actually Scotch-taped) manuscripts, and slathered Whiteout on like housepaint. My first computer, a "portable" Kaypro, was as bulky as a filing cabinet and had a 64K memory. Ten years later, I was writing *The End of Science* on a Macintosh laptop. Talk about progress!

Because science has advanced so rapidly over the past century or so, we assume that it can and will continue to do so, possibly forever. But science itself tells us that there are limits to our knowledge. Relativity theory prohibits travel or communication faster than light. Quantum mechanics and chaos theory constrain our predictive ability. Evolutionary biology keeps reminding us that we are animals, designed by natural selection not for discovering deep truths of nature but for breeding. Perhaps the most important barrier to future progress in science—especially pure science—is its past success.

Postmodernist philosophers will find this a terribly naive comparison, but scientific discovery in some respects resembles the discovery of the Earth. The more we know about the Earth, the less there is to discover. We have mapped out all the continents, oceans, mountain ranges, and rivers. Every now and then, something interesting turns up. Scientists find a new species of lemur in Madagascar or exotic bacteria living in deep-sea vents. But at this point we are unlikely to discover something truly astonishing, like the lost continent of Atlantis or dinosaurs dwelling inside the Earth.

In the same way, scientists might be unlikely to discover anything surpassing the big bang, or quantum mechanics, or relativity, or natural selection, or DNA-based genetics. Nobel Prizes reflect the trend toward diminishing returns. The Russian physicist Pyotr Kapitsa discovered superfluidity in liquid helium in 1938 and won a Nobel Prize for that finding 40 years later. David Lee and his two colleagues won the 1996 prize for showing that superfluidity also occurs in a helium isotope, He-3.

If we accept that science has limits—and science tells us that it does—then the only question is when, not if, science reaches them. The American historian Henry Adams observed a century ago that science accelerates through a positive feedback effect.[2] Knowledge begets more knowledge; power begets more power. This so-called acceleration principle has an intriguing corollary: If science has limits, then it might be moving at maximum speed just before it hits the wall.

NANOTECH AND FUSION

Some researchers grant that the basic rules governing the physical and biological realms may be finite, and that we may already have them more or less in hand. But they insist that we can still explore the consequences of these rules forever and manipulate them to create an endless supply of new materials, organisms, technologies. Proponents of this position often compare science to chess. The rules of chess are quite simple, but the number of possible games that these rules can give rise to is virtually infinite.

This point is reasonable, but some enthusiasts—particularly in the trendy field of nanotechnology—take it too far. As espoused by evangelists such as Eric Drexler, nanotechnology resembles a religion more than a field of science.[3] Drexler and others proclaim that we will soon be able to reconstruct reality from the atomic scale on up in ways limited only by our imaginations. Our alchemical power to transform matter will help us achieve infinite wealth and immortality, among other perks.

Nanotechnology has also inspired some entertaining science fiction about nanobots running amok, such as Michael Crichton's novel, *Prey* (Harper Collins, 2002), and an essay by Bill Joy of Sun Microsystems titled "Why the Future Doesn't Need Us" (*Wired,* Apr. 2000). But to the extent that researchers have experimental experience at the nanoscale level, they tend to doubt the more far-fetched claims—positive or negative—that nanotechnologists make. "The level of hard science in these ideas is really low," the Harvard chemist George Whitesides remarked recently.[4] After all, nanotechnology is just a glossy wrapping for nitty-gritty work done in chemistry, molecular biology, solid-state physics, and other fields that investigate nature at small scales. Experiments often reveal that what should work in principle fails in practice.

Take nuclear fusion. Physicists such as Hans Bethe elucidated the basic rules governing fusion—the process that makes the sun and other stars shine—more than 60 years ago. By the 1950s, this knowledge had spawned the most fearsome technology ever invented: thermonuclear weapons. Next, physicists hoped to harness fusion for a more benign application: a clean, economical, boundless source of energy.

When my career began in the early 1980s, fusion-energy research was a staple of the science beat: Keep the money coming, researchers promised, and in 20 years we will give you energy too cheap to meter. Twenty years later, the US has drastically reduced its budget for magnetic-confinement fusion, formerly the leading candidate for power generation.

Inertial-confinement fusion—in which giant lasers blast tiny fuel pellets—has fared better, but only because its main application is nuclear-weapons research. Surveys of sustainable-energy methods rarely even give fusion a courtesy mention any more—and please don't bring up cold fusion. Diehards may still cling to the dream, but realists acknowledge that fusion energy is effectively dead, the victim of technical, economic, and political constraints.

COMPUTERS AND CHAOPLEXITY

Of course, technological advances often enable researchers to overcome seemingly insurmountable obstacles. Computers in particular have vastly increased scientists' capacity for data acquisition, analysis, storage, and communication. Innovations such as optical and quantum computing may extend the reign of Moore's law indefinitely—although, as the astute computer theorist Rolf Landauer often warned, quantum computers may be so sensitive to thermal noise and other disruptions that they remain a laboratory curiosity.[5]

But adherents of certain computer-driven fields—notably artificial life, chaos, and complexity—seem to view computers not as tools but as wands that will magically solve even the toughest puzzles. In *The End of Science* I lumped chaos and complexity together under a single term, *chaoplexity*, because, after talking to scores of people in both fields, I realized there is no significant difference between them.

Chaoplexologists have argued that with more powerful computers and mathematics they can solve conundrums resistant to conventional scientific reductionism, particularly in "soft" fields such as ecology, psychology, economics, and other social sciences. Stephen Wolfram recently reiterated these claims in his magnum opus, *A New Kind of Science*, which touts cellular automatons as the key that will unlock all the riddles of nature.[6]

As many critics have noted, Wolfram's "new" science actually dates back at least to John von Neumann, the inventor of cellular automatons. Von Neumann and many others have shown that simple rules, when followed by a computer, can generate patterns that appear to vary randomly as a function of time or scale. Let's call this illusory randomness "pseudonoise." Two paradigmatic examples of pseudonoisy systems are the Mandelbrot set, discovered by Benoit Mandelbrot, and "Life," a cellular automaton devised by John Conway.

Chaoplexologists such as Wolfram assume that much of the noise that seems to pervade nature is actually pseudonoise, the result of some underlying, deterministic algorithm. This hope has been nurtured by certain genuinely significant findings, such as Mitchell Feigenbaum's discovery more than 20 years ago that gushing faucets and similar turbulent systems, although they seem hopelessly noisy, actually adhere to a rule called period doubling.

But a gushing faucet is laughably simple compared to a stock market, a human brain, a genome, or a rain forest. These hideously complex phenomena—with their multitudes of variables—have shown no signs of yielding to the efforts of chaoplexologists. One reason may be the notorious butterfly effect, elucidated by Edward Lorenz in the 1960s. The butterfly effect limits both prediction and retrodiction, and hence explanation; specific events cannot be ascribed to specific causes with complete certainty. This is something that has always puzzled me about chaoplexologists: According to the butterfly effect—one of their fundamental tenets—achieving many of their goals may be impossible.

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SEEKING ARTIFICIAL COMMON SENSE

One would think that chaoplexologists would also be chastened by the failure of artificial intelligence to live up to expectations. AI researchers have come up with some useful inventions, including devices that can translate languages, recognize voices, judge loan applications, interpret cardiograms, and play chess. But these advances pale beside the hopes that AI pioneers once had for their field.

In 1984, I edited an article for *IEEE Spectrum* in which AI expert Frederick Hayes-Roth predicted that expert systems were going to "usurp human roles" in professions such as medicine, science, and the business world.[7] When I called Hayes-Roth recently to ask how he thought his predictions had held up, he cheerfully admitted that the field of expert systems, and AI generally, had stalled since their heyday in the early 1980s.

Not all AI'ers have conceded defeat. Hans Moravec and Ray Kurzweil still prophesize that machines will soon leave flesh-and-blood humans in their cognitive dust.[8,9] (In *The End of Science*, I called this sort of speculation "scientific theology.")

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These cyberprophets cite Garry Kasparov's loss to the IBM computer Deep Blue in 1997 as a portent of AI's impending triumph.

Actually, that contest underscored the limitations of artificial intelligence. Chess, with its straightforward rules and tiny, Cartesian playing field, is a game tailor-made for computers. Deep Blue, whose five human handlers included the best chess programmers in the world, was a prodigiously powerful machine, capable of examining hundreds of millions of positions each second. If this silicon monster had to strain so mightily to beat a mere human at chess, what hope is there that AI engineers will ever create HAL, the lip-reading killer in the film *2001*?

Some prominent AI'ers acknowledge that computers will probably never be as smart as HAL. Although computers excel at tasks that can be precisely defined, such as chess, they will never acquire the flexible, all-purpose intelligence—the ordinary common sense—that every normal human acquires by the age of five or so.

In *HAL's Legacy: 2001's Computer as Dream and Reality*,[10] a recent collection of essays by AI experts, David Kuck stated flatly, "Under any general definition ... AI so far has been a failure." Roger Shank declared that HAL "is an unrealistic conception of an intelligent machine" and "could never exist." The best that computer scientists can hope to do is to create machines "that will know a great deal about what they are supposed to know about and miserably little about anything else." Even Marvin Minsky, who had predicted in the mid-1960s that computers would be as smart as humans within three to eight years, admitted that "we really haven't progressed too far toward a truly intelligent machine."

One AI'er still pursuing the original vision of a computer with an all-purpose rather than highly specialized intelligence is Douglas Lenat. For 20 years, he has been trying to create a software program that mimics common-sense knowledge. Lenat's goal was for this program, called Cyc, to become more or less autonomous, capable of acquiring new knowledge by scanning newspapers, books, and other sources of information. In 1997, Lenat predicted that by 2001 Cyc would become a "full-fledged creative member of a group that comes up with new discoveries. Surprising discoveries. Way out of boxes."[11]

The world is still waiting. Rodney Brooks of MIT has complained that Cyc's intelligence has nothing in common with the human variety; far from interacting with the world in flexible or creative ways, Cyc is really just a fancy dictionary. When I interviewed him in 1997, Brooks said, "Ultimately you have to ground it out. You have to attach it to some other sensory motor experience, and that's what I think he's missing."

THE END OF MATHEMATICS?

Some of the harshest attacks on *The End of Science* came from scientists whose fields I hadn't bothered to denigrate.

When I encountered him at a New York Academy of Sciences meeting in November 1996, chemist and Nobel laureate Dudley Herschbach commented that not only had I failed to include a chapter on chemistry, my index included only two measly references to the subject. I didn't have the heart to tell Herschbach that chemistry just seemed too passé to dwell on. In a 1992 interview, Linus Pauling assured me that he had laid out the basic principles by 1930, and who was I to disagree with Linus Pauling? (Also, to be honest, I have always found chemistry excruciatingly dull.)

Similarly, the mathematician John Casti complained in *Nature*[12] that I had neglected to include a chapter titled "The End of Mathematics." Actually, I had planned to include such a chapter; I just ran out of gas. I would have agreed with Casti that there are no limits, in principle, to mathematics, because mathematics is a process of invention rather than of discovery; in that sense, mathematics resembles art or music more than pure science.

Moreover, Kurt Godel's incompleteness theorem established that any moderately complex system of axioms gives rise to questions that cannot be answered with those axioms. By adding to their base of axioms, mathematicians can keep expanding the realm within which they play, posing new conjectures and constructing new proofs, forever. The question is, how comprehensible will these proofs be?

There are clear signs that mathematics is already outrunning our limited cognitive capabilities. The largest conventional proof ever constructed is the classification of finite simple groups, also called "the enormous theorem." In its original form, this theorem consisted of some 500 separate papers, totaling more than 20,000 pages, written by more than 100 mathematicians over a period of 30 years. It has been said that the only person who really understood the proof was Daniel Gorenstein of Rutgers University, who served as a kind of general contractor for the project. Gorenstein died in 1992.

A growing number of mathematical proofs are constructed with the help of computers, which can carry out calculations far beyond the capability of mere mortals. The first such proof, constructed in 1976, demonstrated the truth of the four-color theorem, which states that four hues are sufficient to color even an infinitely broad map so that no identically colored countries share a border. The proof depended on a calculation that took a computer 1,000 hours to complete.

Mathematicians like to wax rhapsodic about the elegance, beauty, and depth of proofs. But computer proofs yield truth without insight or understanding. So yes, mathematics can, in principle, continue forever. The problem is that no mere human will be able to understand it. In 1997, the mathematician Ronald Graham said to me, "We're not very well adapted for thinking about the space-time continuum or the Riemann hypothesis. We're designed for picking berries or avoiding being eaten."

THE UNDISCOVERED MIND

Some criticism of *The End of Science*, I admit, was on target. When I met the eminent British biologist Lewis Wolpert at a biology conference in London in 1997, he declared that my book was "appalling, absolutely appalling!" He was particularly upset by the chapter titled "The End of Neuroscience." How dare I dismiss all the vast and vital research on the brain in a single chapter, which focused not on genuine neuroscientists but on Francis Crick, a molecular biologist, and Roger Penrose, a physicist? Neuroscience was just beginning, not ending!

Wolpert stalked away before I could tell him that I thought his objection was fair. I had already decided that mind-related science had so much potential to alter our world, both intellectually and materially, that it deserved a more serious, detailed critique than it got in *The End of Science*. I offered such a critique in my second book, *The Undiscovered Mind: How the Brain Defies Replication, Medication, and Explanation* (Free Press, 1999). As the subtitle suggests, this book looks at attempts to explain the mind, treat its disorders, and replicate its functions in computers. In addition to neuroscience, this book also covers psychiatry, psychopharmacology, behavioral genetics, evolutionary psychology, and artificial intelligence.

My conclusion was that these fields have largely failed to live up to their advertising. In spite of all this investigation, the mind remains largely undiscovered. In *The End of Science*, I coined the term "ironic science" to describe science that never gets a firm grip on reality and thus doesn't converge on the truth. Ironic science is more like philosophy, literary criticism, or even literature than like true, empirical science. Ironic science crops up in the so-called hard sciences, such as physics and cosmology. Superstring theory is my favorite example of ironic science. It's science fiction with equations.

But ironic science is most pervasive in fields that address human cognition and behavior. Theories of human nature never really die—they just go in and out of fashion. Often, old ideas are simply repackaged. The 18th-century pseudoscience of phrenology is reincarnated as cognitive modularism. Eugenics evolves into behavioral genetics. Social Darwinism mutates into sociobiology, which in turn is reissued as evolutionary psychology.

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One astonishingly persistent theory is psychoanalysis, which Freud invented a century ago. Once defined as "the treatment of the id by the odd," psychoanalysis has been subjected to vicious criticism since its birth. Some Freud-bashers imply that while French philosophers and other fuzzy-brained sorts may still fall under Freud's spell, real scientists are immune to his charms. Actually, many prominent neuroscientists—such as Nobel laureates Gerald Edelman[13] and Eric Kandel[14]—still defend Freudian theory.

Freud's ideas have persisted not because they have been scientifically confirmed but because a century's worth of research has not produced a paradigm powerful enough to render psychoanalysis obsolete once and for all. Freudians cannot point to unambiguous evidence of their paradigm's superiority, but neither can proponents of more modern paradigms.

THE HUMPTY DUMPTY DILEMMA

Neuroscience was supposed to deliver us from this impasse. Neuroscientists have acquired an astonishing ability to probe the brain with microelectrodes, magnetic resonance imaging, positron-emission tomography, and other tools. Neuroscience is clearly advancing. It's getting somewhere. But where? So far, neuroscience has had virtually no payoff in terms of diagnosing and treating such complex mental illnesses as schizophrenia and manic depression. It has failed to winnow out all the competing unified theories of human nature, whether psychoanalysis, behaviorism, connectionism, or evolutionary psychology.

Neuroscience's most important discovery may be that different regions of the brain are specialized for carrying out different functions. For example, the visual cortex contains one set of neurons dedicated to orange-red colors, another to objects with

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high-contrast diagonal edges, and still another to objects moving rapidly from left to right. The question is, how does the brain coordinate and integrate the workings of these highly specialized parts to create a mind? Neuroscientists have no idea. This is sometimes called the binding problem, but I prefer to call it the Humpty Dumpty dilemma. Neuroscientists can take the brain apart, but they can't put it back together again.

Particle physicists once faced a similar dilemma. In the 1950s, the number of particles detected in accelerators proliferated wildly. Theorists trying to make sense of it all were baffled. Then a brilliant young physicist named Murray Gell-Mann showed that all these different particles were made of a few more fundamental particles called quarks. Order emerged from chaos.

But in terms of sheer complexity, particle physics is a child's game compared to neuroscience. All protons, neutrons, and electrons are identical; a theory that applies to one particle applies to all. But each brain is unique, and it changes every time its owner is spanked, learns the alphabet, reads *Thus Spake Zarathustra*, takes LSD, falls in love, gets divorced, undergoes Jungian dream therapy, or suffers a stroke. Scientists cannot simply ignore each individual's uniqueness, because it is central to our humanity. This fact immensely complicates the search for a unified theory of the brain and mind.

Some scientists have reluctantly concluded that science may never fully solve the mysteries of the brain and mind. This position is sometimes called "mysterianism." One well-known mysterian is the psychologist Howard Gardner, who contends that neither psychology, neuroscience, nor any other field has provided much illumination of such perennial riddles as consciousness and free will.[15] These subjects "seem particularly resistant to [scientific] reductionism," Gardner said. He suggests that psychologists may advance by adopting a more "literary" style of investigation and discourse—the style that Freud exemplified.

A surprising number of scientists have proposed that investigations of mystical states of consciousness—such as those induced by meditation, prayer, or psychedelic drugs—might yield insights into the mind that complement or transcend those of science. This notion has inspired a series of highly publicized meetings—most recently at MIT last September—between prominent scientists and the Dalai Lama, the leader of Tibetan Buddhism. I explore this possibility in my most recent book, *Rational Mysticism* (Houghton Mifflin, 2003). While researching the book, I spoke to a wide variety of scholars studying mysticism, including neuroscientists, psychologists, and anthropologists.

Early on, one of these sources warned me that you can't comprehend mystical experiences if you've never had one. With that in mind, I learned Zen meditation. I had my temporal lobes electromagnetically tickled by a device called the "God machine." I consumed a nauseating psychedelic brew called ayahuasca, which serves as a religious sacrament for Indians in the Amazon. I concluded that mystical experiences can't give us the kind of absolute knowledge that we crave. Quite the contrary. Mystical experiences do not give us The Answer to the riddle of our existence; rather, they let us see just how truly astonishing the riddle is. Instead of a big "Aha!" we get a big "Huh?"

WHAT'S MY POINT?

After I gave a talk on the limits of science at Caltech, a neuroscientist in the audience angrily asked me what my point was. Did I think he and his colleagues should simply give up their research? Should Congress take its funding away? Good questions.

I hope I don't sound disingenuous when I say that I would hate to see my prophesies become self-fulfilling—not that there is any chance of that anyway. I always encourage young people to become scientists, and I would be delighted if my children pursued that path someday.

Grant for a moment that I am right—that science will never again yield revelations as monumental as the theory of evolution, general relativity, quantum mechanics, the big bang theory, DNA-based genetics. For example, physicists will never discover a unified theory that reveals "the mind of God," as Stephen Hawking once put it.[16] And grant that some far-fetched goals of applied science—such as immortality, superluminal spaceships, and superintelligent machines—may forever elude us.

I nonetheless have no doubt that researchers will find better treatments for cancer, schizophrenia, AIDS, and other diseases; more benign sources of energy (other than fusion); and more convenient contraception methods. In the realm of pure science, scientists will surely gain a better understanding of how galaxies formed, how life began on Earth, how Homo sapiens became so smart so fast, how neural processes generate awareness, how a single fertilized egg turns into a fruit fly or a congressman.

But I would like to see a greater recognition of science's limitations—particularly in mind-related fields, where our desire for self-knowledge can make us susceptible to pseudoscientific cults such as Marxism, social Darwinism, eugenics, and psychoanalysis. Science is never more dangerous than when it seeks to tell us what we are, what we can be, and even what we should be.

My goal is to foster an attitude that I call "hopeful skepticism." Too much skepticism culminates in a radical postmodernism that denies the possibility of achieving any truth. Too little skepticism leaves us prey to peddlers of scientific snake oil. But just the right amount of skepticism—mixed with just the right amount of hope—can protect us from our lust for answers while keeping us open-minded enough to recognize genuine truth if and when it arrives. ■

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***John Horgan**, a former senior writer at* Scientific American, *has written for the* New York Times, Discover, Slate, Time, *and other publications. He has posted essays, articles, and profiles at www.johnhorgan.org. Contact him at jhorgan@highlands.com.*