SCIENCE:
THE NEXT REVOLUTION?

Sometimes enterprises fail when dazzling successes obscure subtle but fundamental problems. Science may confront such a crisis in this century. Vastly exploding observational capabilities, new computing methods, and growing technological prowess make science look stronger than ever. But these achievements may hide—and in the future will magnify—a growing uncertainty about whether science can answer the most fundamental questions. Some preach the end of science, but a new Scientific Revolution seems more likely.

BEFORE THE REVOLUTION: TECHNOLOGY PRECEDES SCIENCE

Centuries ago, Europe saw an explosion in scientific and technical knowledge. Engineering knowledge grew, particularly in the cutting-edge fields of metallurgy and mechanics. Navigators equipped with new instruments, ship designs, and sailing techniques explored regions of the world that had long been only myth. The invention of linear perspective gave savants the ability to accurately record flora and fauna and engineers the ability to precisely describe innovative machines. Improvements in instruments allowed scientists to measure a wider range of physical phenomena.

Sounds like the Scientific Revolution? It wasn't. All these events occurred in the century before the Scientific Revolution. Late medieval and early Renaissance advances in engineering, geography, art, and instrumentation undercut scientific theories that had been in place for millennia and forced scientists to develop a new understanding of everything from the physics of machines to the structure of the earth and the workings of the cosmos. All of this added up to the modern worldview that still guides our thinking.

THE KNOWLEDGE PARADOX: POST-MODERN TOOLS OF UNCERTAINTY

Today, we may be entering a similar era of basic uncertainty in science. And once again, the very success of our tools for exploring the world, creating and managing knowledge, and crafting intelligence is to blame.

We're beginning to see a mismatch between technical success and scientific knowledge. Evolutionary-design techniques, in which computers "evolve" and test solutions to technical problems are starting to yield designs that work well, but border on the inexplicable.

In emergence, problem solving is running ahead of understanding. Scientists can mimic emergent phenomena across the physical and biological sciences. However, it's not clear why emergence happens and whether it's possible to test theories of emergence using the traditional scientific method. Finally, evolutionary and emergent systems learn from their mistakes, grow stronger and subtler, and eventually could evolve into intelligences as incomprehensible as their designs.

Other branches of science are dealing with a split between the volumes of data produced and the power of the theories used to make sense of them. In high-energy physics, factory-sized instruments are turning out terabytes of data per year, and a new generation of instruments is about to generate an order of magnitude more information. Yet string theory, which attempts to make sense of that information, is still contentious.

THE END OF SCIENCE? NO, BUT ...

These aren't marginal fields that border on pseudoscience. Evolutionary design is used in everything from electronics to biology and animation. Emergence has attracted the attention of Nobel laureates and made contributions in a variety of industries and disciplines. String theory has been at the center of theoretical physics for decades. As was the case 500 years ago, the problem is not that we don't know enough. We know a lot. It's just not adding up.

This doesn't mean that we're reaching an "end of science," as John Horgan put it. Applied science won't come to a halt; innovation and technological change won't cease. But the growing disconnect between our ability to create new technologies, to change our world, and to understand our technologies and anticipate change will create more risk and uncertainty, and ultimately cracks in our consensus of reality.

—**Alex Soojung-Kim Pang**

FUNDAMENTAL UNCERTAINTY, DRIVEN BY THE BASIC TOOLS AND PRACTICES OF SCIENCE, MAY PUSH US INTO A NEW ERA OF "POST-NORMAL SCIENCE"

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Oxford's Jerry Ravetz argues that we're entering a period of "post-normal science," in which the confident technocratic vision of the relationship between science, technology, and society is undergoing profound change. In this interview, Alex Pang helps us understand where this era of change might take us.

Q: WHY DO YOU SAY THAT WE HAVE ENTERED A PHASE OF POST-NORMAL SCIENCE, AND WHAT DO YOU MEAN BY THAT?

Post-normal science contrasts to the "normal science" described by Thomas Kuhn in *The Structure of Scientific Revolutions*. This kind of science is undoubtedly the great driving force of modern global civilization. In the conventional understanding, science discovers nuggets of fact; technology turns them into tools that enable the conquest of nature; and that leads to the improvement of society and human welfare.

But we can no longer separate science, nature, and society. The combination of lifestyles and markets drives innovation in the science-based industries, and their cumulative effect is to further disrupt the complex global natural systems on whose stability we all depend. The degradation and destabilization of the natural environment as a result of globalized science-based industry increasingly threatens the survival of civilization itself.

The situation of science in its social context has become increasingly turbulent in recent years. Science has long established structures that carry great prestige and influence. There's also an institutionalized counter-expertise: for example, major environmental groups can engage in a critical dialog with "official" experts.

Consequently, we've entered a world in which facts are uncertain, values in dispute, stakes high, and decisions urgent. Traditional mechanisms for regulating science are becoming obsolete. With nanotechnology, it's practically impossible; with converging technologies, which are all about linkage, it's inconceivable.

In such contexts of policy making, there is a new role for natural science. Science in the policy context must become post-normal.

Q: WHAT'S NEW HERE? HASN'T THE APPLICATION OF SCIENCE ALWAYS HAD UNCERTAINTY AND UNEXPECTED CONSEQUENCES?

Of course there have always been problems that science could not solve. But increasingly over recent generations, our civilization has been able to tame Nature in so many ways.

Now, however, we are finding that the conquest of Nature is not, and cannot be, complete. As we confront Nature in its disturbed and reactive state, we find extreme uncertainties in our understanding of its complex systems, often at a regional or global scale.

Q: MIXING SCIENCE AND POLITICS USUALLY JUST YIELDS BAD SCIENCE. SO WHY ISN'T BETTER SCIENCE THE WAY TO DEAL WITH THESE PROBLEMS?

The uncertainties of post-normal science will not be resolved by mere growth in our databases or computing power. Increasingly, we live in a world in which we must make hard policy decisions where our only scientific inputs are irremediably soft.

But we're not talking about traditional areas of research and industrial development. These are areas where traditional mechanisms of quality assurance, like peer review and publications, are patently inadequate.

Q: SO WHO IS INVOLVED IN DOING POST-NORMAL SCIENCE?

In the post-normal science context, what might be called "extended facts" can become important in the dialog. These can range from "housewives' epistemology" through pupils' surveys to investigative journalism and leaked scientific documents. Furthermore, particularly at the local level, we've seen that people not only care about their environment, but also can become ingenious and creative in finding ways to improve it.

ALEX SOOJUNG-KIM PANG
is a Research Director at IFTF, currently initiating a new program of research on the long-term future of science.

THE MANAGEMENT OF COMPLEX NATURAL AND SOCIAL SYSTEMS AS IF THEY WERE SIMPLE SCIENTIFIC EXERCISES HAS BROUGHT US TO OUR PRESENT MIXTURE OF TRIUMPH AND PERIL. THE ROLE OF SCIENCE IS NOW APPRECIATED IN THE FULL CONTEXT OF THE UNCERTAINTIES OF NATURAL SYSTEMS AND THE RELEVANCE OF HUMAN VALUES.

So the quality is not merely in the verification, but also in the creation; local people can imagine solutions and reformulate problems in ways for which the accredited experts, with the best will in the world, are not prepared.

Q: ISN'T THIS A PRESCRIPTION FOR DUMBING-DOWN AND ENDLESS GRIDLOCK?

No one can claim that the maintenance of quality through extended peer communities will occur easily and without its own errors. But in the processes of extension of peer communities, we can see a way forward, for science as much as for the complex problems of the environment.

And the post-normal science approach should not be interpreted as an attack on the accredited experts, but rather as assistance. The world of normal science in which they were trained has its place in any scientific study of the environment. But it needs to be supplemented by awareness of the post-normal nature of the problems we now confront. The management of complex natural and social systems as if they were simple scientific exercises has brought us to our present mixture of triumph and peril. We are now witnessing the emergence of a new approach to problem-solving strategies in which the role of science is now appreciated in the full context of the uncertainties of natural systems and the relevance of human values.

Q: AMERICANS ARE STILL FAIRLY POSITIVIST IN OUR THINKING ABOUT SCIENCE-BASED PROBLEMS. IS POST-NORMAL SCIENCE TAKEN MORE SERIOUSLY IN THE UNITED KINGDOM?

My impression is that you have a much more vigorous fringe in America, but the mainstream is decades behind what you have here in Britain. Look at our leading scientists. You've got Martin Rees, who writes a book about science in which he asks whether we'll survive this century—and gives us a 50/50 chance. You have Bob May, who'll tell you that he got into science after joining Greenpeace. You've got the chief scientist, Sir David King, who left South Africa during the days of apartheid. I disagree with him on some issues, like nukes, but he's been out there slugging away on climate change. I wonder, where did these guys come from? What did we do to deserve this?

Q: WHAT IMPACT DOES POST-NORMAL SCIENCE HAVE ON THE WAY SCIENTISTS THINK ABOUT SCIENCE?

I just came back from a meeting in Vancouver, and what emerged there was something remarkable. Lots and lots of nano scientists are worried. We've never before had rank-and-file scientists so worried about the ethics and consequences of what they were doing. You had a sprinkling of atomic scientists during the Cold War, the Asilomar crowd, and the MIT strike in 1968 against military research. I felt it was going to happen sooner or later in some field, and nano is it.

Now, nano scientists have a degree of consciousness, and get really upset at the accusation that they're unethical or uninterested in the consequences of their work. It's not that these people read about post-normal science, but they're part of a different generation, with different career patterns, which means that this is a shift that won't go away. With them, one can imagine things happening in science that were unimaginable before.

EVOLUTIONARY DESIGN: WILL TECHNOLOGY LAP NATURE?

One sign that our current science may still have a ways to go is that we've created a growing list of technologies—and tools for creating new technologies—that we don't entirely understand. Among the most intriguing of these is evolutionary design, which began as a technique for finding optimal solutions to engineering and computer programming problems. With these tools, as James Martin notes, evolution can happen a billion times faster in a computer than in Nature: an ecosystem as complex as the fynbos ecosystem in South Africa can evolve in two days on screen.

As evolutionary design techniques are more widely deployed, the solutions often look radically different from those created by people. University of Sussex scientists using evolutionary programming to design circuits admit "they sometimes don't even understand how their evolved circuits work, despite the fact that they function perfectly as required. It seems that artificial evolution is able to tap into the subtle physical behavior inherent to silicon circuitry." Oxford biologist Richard Dawkins wrote: "Nothing in my biologist's background, nothing in my 20 years of programming computers, and nothing in my wildest dreams, prepared me for what actually emerged" when he created a program that artificially evolved trees. His experience is not unusual.

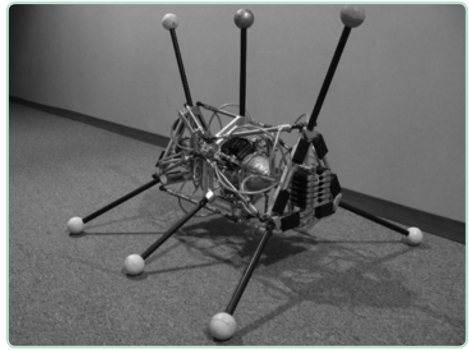
Roboticists at Cornell University use the technique to generate both new robot designs and new ways for those robots to move. The nonaped, for example, has a long, triangular-shaped body with nine legs, six of which touch the ground at any time. (In rugged terrain, this design allows the robot to fall and right itself quickly.) Biological evolution hasn't produced anything like this creature since the Cambrian Era, if then. But evolution doesn't stop there. Because there are no organisms that the nonaped can mimic, scientists have used evolutionary design to generate and test different algorithms for walking.

Evolutionary-design techniques are applied not just to the design of the object, but also to the design of its construction. The Genetically Organized Lifelike Electro Mechanics (GOLEM) project at Cornell is designing programs that evolve creatures that "take advantage of the nature of their own medium—thermoplastic, motors, and artificial neurons" to achieve more efficient means of self-construction. Like the nonaped, these designs have evolved independent of prior ideas about how robots should look; consequently they look nothing like either mechanistic or biomorphic robots. As one NASA scientist says, "We try to give as little antenna knowledge as possible to our software and let evolution be free to design the antenna as it sees fit."

Still more applications: Architects have begun to adopt some of its principles in the design of buildings and industrial infrastructure. Bioscientists have begun to use it as a methodology for creating novel drug molecules. Even game designers are starting to use evolutionary-design processes to generate unique aspects of game worlds and characters.

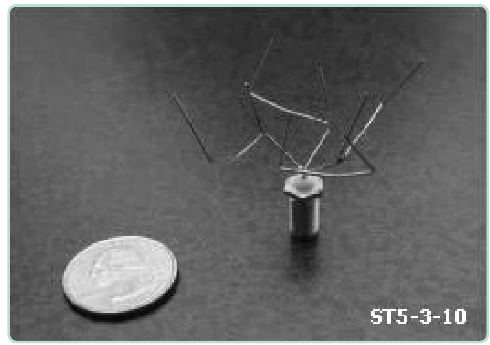
The next step for evolutionary design looks to be co-evolutionary design, relying on competition and cooperation between two or more different populations to accelerate and enhance the evolutionary process.

1 THE NONAPED HAS EVOLVED NINE LEGS AND NEW ALGORITHMS FOR WALKING



Source: http://ccsl.mae.cornell.edu/research/nonaped/images/FullRobot.jpg

2 A NASA ANTENNA THAT HAS EVOLVED ITS OWN FORM



Source: http://ic.arc.nasa.gov/people/jlohn/

EMERGENCE: EXPLANATORY RULES OR CREATIVE TOOLS?

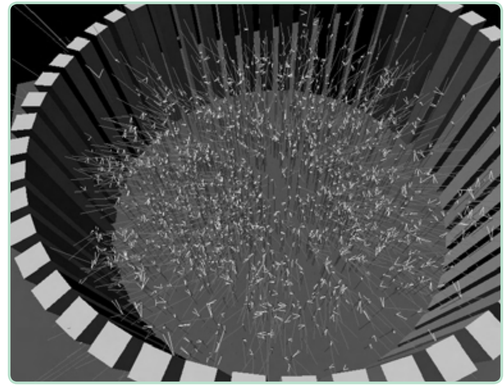
The rapid growth in computing and graphics power has transformed the study of emergence and of the mathematics of self-organization. More powerful computers have been able to run the agent-based models that reveal emergent phenomena in the interactions of large populations. Once you know about them, emergent phenomena seem to be everywhere you look: they appear in chemistry, with compounds that are unexpectedly stable; in biology, in everything from physiology to animal behavior; and in virtually every aspect of social life. But emergence is dogged by two fundamental questions.

First, do agent-based models (or other simulations) reveal the underlying rules governing real physical and social phenomena? Emergence can do a good job of modeling natural phenomena and displaying results that look fairly accurate. But do birds actually avoid collisions using the rules written into flocking programs (to take but one example)? As philosophers and historians of science point out, the ability to conduct experiments that verify or disprove the existence of phenomena or accuracy of theories has long been central to the progress of science. Direct experiments are difficult to conduct on emergent phenomena. Some researchers have argued for similarities between, for example, rat pups and robot dogs. But while suggestive, such comparisons remain speculative.

Second, why does emergence happen? Researchers on emergence are split on how to explain emergent phenomena. Supporters of "weak emergence" argue that emergence can be explained as a consequence of physical and chemical actions (much as thought can be explained as a consequence of neural activity). As Tufts cognitive scientist and weak emergence proponent Daniel Dennett puts it, emergence is "not in principle unpredictable or irreducible or anything like that." Proponents of "strong emergence," in contrast, contend that emergence cannot be explained in terms of lower-order phenomena. Australian astrophysicist Paul Davies has suggested an experiment involving quantum entanglement to determine if emergent phenomena are reducible to physical phenomena. Scientists should have the equipment to perform the experiment within the next few decades, he estimates.

We may not understand emergence completely, or even be able to have confidence that what goes on in the simulation is really similar to what happens in the world, but that hasn't stopped scientists from applying agent-based models to everything from economics to movie animation—often with compelling results. If emergence doesn't explain the world, it still provides a good basis for creating new ones.

3 3D COMPUTATIONAL MODEL OF FLOCKING BEHAVIOR



Source: http://www.cs.princeton.edu/~jhalderm/courses/boids.gif

FROM BYTES TO EXABYTES: TOO MUCH OF A GOOD THING?

Science has always been about data. Satellites orbiting the earth beam down 100 gigabytes of data every day. The U.S. government's National Oceanographic and Atmospheric Administration (NOAA) has over 650 terabytes of basic scientific data on 364,000 magnetic tapes. In 2002, the Stanford Linear Accelerator Center's BaBar project gathered its 500th terabyte of data and declared itself the world's largest collection of scientific data. NASA's Center for Computational Science has nearly 100 terabytes of data and receives over 200 gigabytes per month.

The challenges are going to become even more severe when the Large Hadron Collider (LHC), the world's largest scientific facility, becomes operational. The LHC, located at CERN on the Swiss–French border, will employ thousands of scientists. Its two major detectors, ATLAS and CMS, will have 2,000 scientists each, organized into complicated hierarchies: subsystem groups, an experimental Executive Board, and an LHC-wide Collaboration Board. The LHC is expected to generate some 10–15 petabytes of data per year. As one CERN scientist puts it, this will be "more than 1,000 times the amount of information printed in book form every year around the world."

Put another way, the LHC will generate, on average, about 1.7 terabytes of data every hour, 41 terabytes a day, and 288 terabytes a week. In one hour, it will generate 15 times as much information as all the satellites orbiting the earth beam down in a day. In less than three weeks, it will generate as much information as NOAA currently stores. That information will be stored and processed in the world's largest computing grid, stretching across over 100 sites in Europe, North America, and Asia.

Still these numbers pale by comparison to the human exchange of information through e-mail and telephone—and these interactive media may more closely resemble the future of scientific machine-to-machine communication as computing grids share resources and as programs become increasingly context aware, searching more or less autonomously for new patterns in content that has been processed in other contexts by other machines. The question is whether there will come a point where that machine-generated knowledge passes verification tests designed by humans but is based on theories that only machines can understand.

4 MEASURES OF INFORMATION

	Number of bytes	Equivalent
Kilobyte	1,000	Half a typewritten page
Megabyte	1,000,000	6 seconds of high-fidelity sound
Gigabyte	1,000,000,000	2 CD-ROMs of digital data
Terabyte	1,000,000,000,000	NOAA climate database
Petabyte	1,000,000,000,000,000	3 years of Earth Observing System data
Exabyte	1,000,000,000,000,000,000	Half of all the information generated in 1999

Source: Adapted from P. Lyman and H. Varian, *How Much Information? 2003*, http://www2.sims.berkeley.edu/research/projects/how-much-info-2003/execsum.htm.

5 COMPARISON OF INFORMATION FLOWS

	Bytes per year
NASA's Center for Computation Science	24,000,000,000
Earth-orbiting satellites	365,000,000,000
CERN's Large Hadron Collider	1,500,000,000,000,000
E-mail (worldwide)	400,000,000,000,000,000
Telephone calls (worldwide)	17,000,000,000,000,000,000

Source: P. Lyman and H. Varian, *How Much Information? 2003*, http://www2.sims.berkeley.edu/research/projects/how-much-info-2003/execsum.htm.

GRAND THEORIES: AT THE LIMIT?

In addition to the challenges of dealing with petabytes of data, more robustly connecting agent-based models to the physical and biological world, or making complex decisions in an era of post-normal science, some observers have made the argument that we're witnessing a larger crisis in science.

Most notably, science writer John Horgan's *The End of Science* contends that the era of new big theories and discoveries may have come to a close. Big theories like Darwinian evolution, electromagnetism, and quantum mechanics have been refined but not replaced. The cost of making fundamental new discoveries is growing tremendously: today's particle accelerators are vastly more expensive than the instruments physicists used to discover the quantum nature of light or map atomic orbits. At the same time, the cost of extending existing knowledge or developing science-based applications is falling: for example, genome sequencing is much cheaper now than when the Human Genome Project began a decade ago. Together, Horgan argues, these trends suggest that all the really big discoveries in science have been made, and we're now just filling in the gaps.

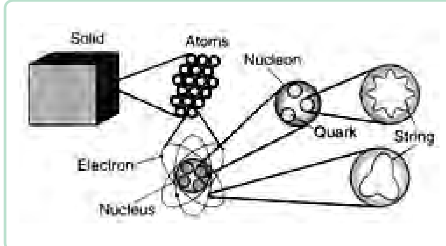
Others note that some scientific questions that once seemed within reach have proven surprisingly elusive. Neuroscience has seen a number of significant advances in instrumentation and application over the last several decades. Magnetic resonance imaging and positron emission tomography let us watch the brain in action. Cochlear implants route around profound deafness by connecting electronics directly to the nerves that link to the brain's hearing centers. More recently, direct brain–computer interfaces have taken this work further, demonstrating that humans and monkeys can learn to control computer cursors and robotic arms through thought. Nonetheless, these advances in *techne* have not been matched by equally profound advances in *theoria*: we can see much more of what happens in the brain but seem no closer to answering the big questions about the nature of consciousness or thought.

Another example of a grand theory that has resisted definitive proof is string theory. Lee Smolin argues in *The Trouble with Physics* that string theory, which promised to provide a unified explanation for the forces of gravity, electromagnetism, and subatomic attraction, has become unverifiable. There are a number of variants of string theory, which have produced an enormous number of predictions—too many to ever be tested thoroughly. More practically, while high-energy particle accelerators at CERN, Fermilab, and elsewhere have managed to create a whole family of subatomic particles by smashing together atoms and electrons, one would need an accelerator 1,000 light years in circumference to generate enough energy to reveal the existence of strings.

The combination of fast-moving experiment and application, on one hand, and slower-moving theory, on the other, has often signaled a coming crisis in science. The early 20th-century revolution in quantum physics and relativity sought to explain anomalies in classical physics observed after decades of experimenting with radiation, crafting electrical devices, and working with power and radio networks. The similarities to today's situation are striking and perhaps foreshadow a 21st-century reorganization of equal or greater proportions.

6 HOW STRINGS MAKE UP MATTER

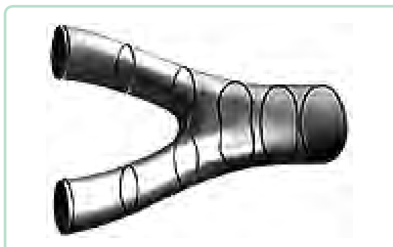
Beyond direct observation, strings are theorized to be tiny loops of vibrating energy that make up subatomic particles



Source: Virgil Renzulli, "A Universe of At Least 10 Dimensions," *Columbia University Record*, March 27, 1998, http://www.columbia.edu/cu/record/23/18/14.html.

7 HOW STRINGS INTERACT

Two string loops interact by joining together into a third string



Source: Virgil Renzulli, "A Universe of At Least 10 Dimensions," *Columbia University Record*, March 27, 1998, http://www.columbia.edu/cu/record/23/18/14.html.

WHAT TO DO

EDUCATION:

TEACH THE CONTROVERSY, LEVERAGE SUPERCOMPUTING, BUILD TRANSDISCIPLINARITY

Whether or not we're headed for the end of science, uncertainty will increasingly dog basic science. To prepare, science institutions should not retreat from the controversy, but rather, incorporate the many controversies posed by the potential limits of scientific investigation into student curricula at all levels and prepare the next generation to think beyond the so-called limits of science. Universities in particular should provide future scientists with a new literacy of abundant computing: as we move toward a world where abundant supercomputing power will be readily available, researchers will have new tools to apply to solve a whole range of problems. Finally, academic, research, and corporate R&D institutions need to move beyond *interdisciplinarity* to *transdisciplinarity*. Where the former focuses on collaboration among experts with different expertise, the latter emphasizes researchers who are trained in more than one discipline. Ultimately, the potential is to bring a more sophisticated perspective to research—perhaps analogous to the advance from CAT scans to MRIs. This more sophisticated view will elevate the discourse on what science is, what research can and can't do, and what should be included in the scope of the R&D project. Companies should start now in their quest to hire people with transdisciplinary skills and encourage R&D groups to build trandisciplinary teams.

R&D:

HARNESS EVOLUTIONARY DESIGN AND EMERGENCE IN HUMAN SCIENTIFIC EFFORT

With abundant computing power and an increasingly networked world, there is a potential for sharing the burden of solving our most vexing scientific problems with a wider universe of scientists—and doing it in a way that consciously mimics the principles of evolutionary design and emergence. Such tools and processes don't just mean better collaboration or schemes for sharing and analyzing data across more institutional boundaries, although those will be important. This approach also goes beyond applying the tools of evolutionary design and emergence to more problem spaces. It is fundamentally an organizational problem: how to redesign the organization of R&D to harness the invisible intelligence in these processes. If people are learning agents of the kind that iterate and evolve in evolutionary programs, how do we organize them to evolve in the same way—and ultimately contribute to an unexpected collective solution?

CULTURE:

ANTICIPATE TRANSHUMANIST STRATEGIES TO DEAL WITH THE PERCEIVED LIMITS OF SCIENCE

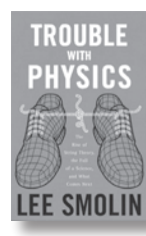
Individuals will deal with perceived limits of science in different ways. For example, some may seek more answers from religion. Others are likely to turn to what we call X-People attitudes and behaviors—the extension of human capacity to sense, to think, to interact. A new generation is already turning to drugs that enhance cognitive performance and tools that capture vast stores of data for later access in a kind of "external wearable memory." Whether or not these practices will produce the transcendent insight that launches the next scientific revolution, they cut to the quick of human identity and are precisely the kinds of behaviors that are likely to incite religious backlash.

WHERE TO LOOK

John Horgan's
The End of Science,
Abacus, 1998

Horgan argues that all the really big discoveries in science have been made, and we're now just filling the gaps.

Lee Smolin's
The Trouble with Physics,
Houghton Mifflin, 2006



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