DONALD ELLIOTT ON RISK ASSESSMENT AS ULTIMATE IN DEMOCRATIC PROCEDURE

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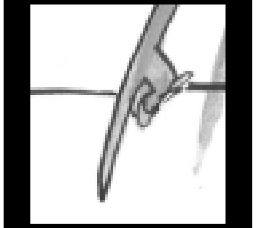
Waking Up To Nanotechnology — Regulators Take Note

EARLY REDUCERS: COMPANIES AND COUNTRIES SAVE MONEY WITH CARBON CUTS

THAT MERCURY RULEMAKING: OUR DEBATE BRINGS TOGETHER THE KEY PLAYERS



COVER STORIES

The Next Small Thing

Nanotechnology is not the next industrial revolution, but it will converge with ongoing revolutions in information technology and biotechnology to create it. The environmental community has a chance to guide the coming Info-Bio-Nano Revolution in ways that avoid the mistakes of the first industrial revolution — and harness this one for environmental improvement

DAVID REJESKI

A recent article in *Scientific American* contained the following statement about nanotechnology: "If the nano concept holds together, it could, in fact lay the groundwork for a new industrial revolution." That is an exciting thought. Penetrating down to a nanoscale level (one billionth of a meter or 1/100,000 the width of a human hair) is like opening up a new scientific universe, a universe where many of the basic properties of matter, from optics to chemistry, are determined. The science of nanotechnology is already here, supported in the United States by a $3.7-billion, four-year government spending plan. Dozens of other countries have launched their own national initiatives, making the nanotech boom a global phenomenon.

Nanotechnology has moved beyond arcane journals and laboratory science. Products utilizing nanotechnology are already on the market, ranging from improved sunscreens to stain-resistant fabrics to ultra-light flat panel displays for cellphones. Carbon nanotubes (an extremely high strength form of carbon discovered in 1991) are used to produce better automobile parts. The liners in Dunlop tennis balls contain clay modified at a nanoscale level to drastically reduce air leakage and maintain bounce. Use that technology in car and truck tires and we could save millions of gallons of gas a year caused by under inflated tires and lower accident rates to boot.

But remember small is not necessarily better, it is just smaller. Many of the molecules that we may end up manipulating at an atomic level are not environmentally benign and, as in all manufacturing processes, they may be manipulated to maximize other properties beside environmental characteristics, such as strength, conductivity, transparency, etc. So what exactly does smallness buy you? Solutions, maybe, if we can produce thin film photovoltaics at one tenth the present cost or find new ways to cheaply desalinate seawater or treat cancer. Problems, maybe, if nanoscale particles can be inhaled deeply into the lungs or cross the blood-brain or blood-placenta barrier. Once the production of anything ramps up, a range of familiar regulatory issues appear related to worker exposure, new chemicals, air and water emissions, and waste disposal. Separating science from science fiction is critical at this stage and it will not be easy. Ensuring that the benefits of such technologies are distributed to people in the world who need them the most will be an even more daunting task.

At the beginning of any new technological wave is what might be called the *hype bubble*, that initial burst of exuberance that is inevitably followed by the painful recognition that we mortals have not escaped the laws of unintended consequences. Remember nuclear energy (power will be too cheap to meter), or biotechnology (we will feed the world), or information technology (the paperless office)? Normally, by the time the hype bubble has passed and we recover our composure, whole new industries have been built, stock options cashed in, and environmental groups mobilized around that tiresome litany of "I told you so." The repetitive nature of this phenomenon deserves some serious attention, and it is finally receiving it thanks to the work of people like Princeton psychologist Daniel Kahneman, winner of the 2002 Nobel Prize in economics. His research has shown how optimism can undermine rational judgment and often results in wild overestimates of the benefits of projects and underestimates of their long-term costs.

The hype bubble dominates technological innovation cycles because it is easy to get people excited (and overly optimistic) about the next big thing. This kills our long-term memory, wipes out our peripheral vision (our guard against surprise), and compromises our judgment. This socially contagious affliction works regardless of whether you are a potential moviegoer, some crazed venture capitalist looking for high-return investment opportunities, a legal firm trolling for new business opportunities, or a newly minted Ph.D. searching for your first job. The problem with riding hype towards the next big thing is that people tend to forget about the last big thing and how that connected to the big things that came before. The media, the fashion industry, and the stock market reward this "art of forgetting" but public policy does not, and should not.

One way to break the hype bubble is to ask some contextual questions. The most interesting question surrounding nanotechnology is whether it will give us an industrial revolution, or just stain-resistant pants. Industrial revolutions do not happen often, so we shouldn't accept this assertion lightly (nor should it be made lightly). Answering this question forces us to view nanotechnology in a larger context and remember things we tend to comfortably obscure or avoid.

Changes already underway in industrial design and production show that regulation isn't going to be anything like it used to be

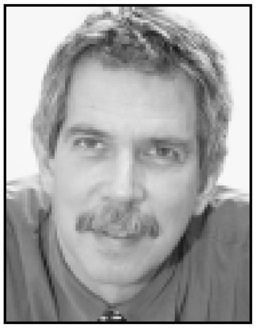
From the standpoint of the environmental community, the answer to this question (or recognition that it even exists) is important. Think about what is at stake. The modern environmental movement came into existence around thirty years ago at the tail end of the first industrial revolution. That revolution unleashed fossil energy for transportation, manufacturing, and power and created the chemical industry — a boon to society but a bane till this day because of accompanying pollution problems. If we are at the threshold of the next industrial revolution, the environmental community is facing its first opportunity to *shape* an emerging social and technological infrastructure in ways that could dramatically improve environmental conditions. This opportunity will be short-lived, given the tendency for technological systems, and their associated institutional infrastructure, to become locked in and hard to change. So if the next industrial revolution is about to happen, we will not have much time to take advantage of a new set of emerging environmental opportunities.

Unfortunately, there does not seem to be much excitement in the air or even the recognition of an industrial sea change in today's discourse on the environment. To be fair, many environmentalists are distracted. Given the ongoing attempts to roll back our existing environmental regulations there is not a lot of time or energy left to focus on prospective revolutions. However, the long-term costs of this distraction may be high as well as our social regrets when we wake up at some future date and gaze in amazement on a transformed industrial landscape. Now is the time to be asking three interrelated questions: First, obviously, Is there an industrial revolution taking place? Then, What are the critical implications for environmental protection and policy? And finally, How do we better prepare to shape the outcomes of this revolution? Let us address these questions one by one.

How would we know an industrial revolution if we bumped into one? Imagine if we could go back in time to the mid-1800s and pass through the last industrial revolution. What transitions — economic, social, or otherwise — would we perceive during our passage through time and are we seeing anything similar today?

Radical shifts in the means of production. The most obvious change would be the emergence of whole new ways of making things. In 1856, the search for a synthetic equivalent of quinine to treat malaria led the young English chemist William Perkins to the discovery of a purple dye and the launching of the synthetic chemical industry. Suddenly, coal went from a fuel to a feedstock for a whole new industry that quickly spread to Germany, France, and beyond. Perkins and his followers learned how to scale up laboratory-based processes to full blown manufacturing enterprises. Synthetic chemistry gave rise to synthetic plastics and then synthetic drugs and the whole synthetic world we inhabit today. Synthetic chemistry converged with other technologies such as the steam engine and electricity and electrification, which freed production from streams, coal mines, and other stationary sources of power. This story could be extended, but the point is that radi-

David Rejeski directs the Foresight and Governance Project at the Woodrow Wilson International Center for Scholars. He is a member of the EPA Science Advisory Board and was recently a Visiting Fellow at the Yale School of Forestry and Environmental Studies.



cally new means of production, based on new scientific discoveries, were a key to the last industrial revolution and will be the key to the next. Photolithography, powder metallurgy, combinatorial chemistry — these are some of the new ways of making things that have recently appeared. Nanotechnology's greatest potential, yet unrealized, will be in its ability to alter the means of production but that doesn't necessarily portend an industrial revolution. Here is why.

Environmentalism's first opportunity to shape an emerging technology in ways that could dramatically improve environmental conditions

Significant changes in communications infrastructure. We often forget that the first industrial revolution was built on radical changes in our communications infrastructure wrought by the telegraph, the telephone, and, in high-density urban areas such as New York City, pneumatic mail systems. To appreciate the extent of these changes, remember that before the advent of the telegraph, it took 10 days to carry a message from Missouri to California via pony express, two days to send a message from New York to Chicago by train, or weeks to go from America to England by ship. Within one decade (1840–1850) the time required to transmit any given word decreased by a factor of 3,000 and the cost by a factor of 100. Suddenly, the possibility of real time or near-real time communication became possible and affordable. What has changed over the last twenty years is not so much the speed of communication (we reached near speed of light rates years ago), but our connectivity, the amount of data available, processing power, and the radically decreasing cost of accessing and using that information. These changes have underpinned what we commonly refer to as the information economy. Nanotechnology may improve computing power, storage, or bandwidth, but the large disruptive changes have already occurred.

Changes in the organization and management of production. Closely associated with new ways of communicating are often new ways of organizing people, work, and commerce in a broad sense. As Peter Drucker once noted, "In a knowledge society, managers must prepare to abandon everything they know." During the last great industrial revolution, managers did abandon everything. By the early part of the 20th century, we witnessed the development and application of modern organizational and management theory. Harvard Business School was founded in 1909, new efficiency theories were applied to Fordist mass production systems, and industrial leaders such as Alfred Sloan rethought and reorganized the organizational structure underpinning business.

Pervasive changes in industrial structure have again occurred over the past decade, beginning in the computer industry and spreading to other areas in the manufacturing sector and finally into the service sector. Many of the changes are hidden behind a thick veil of jargon such as mass customization, contract manufacturing, distributed manufacturing, build-to-order, the real-time enterprise, value-chain modularity, the personalization of production, and free agent workers. Behind this gibberish, however, is the emergence of production systems built on loose, weblike networks rather than the traditional vertical hierarchies that have dominated industry in the past and shaped our past approaches to environmental law and policy. The term *supply chains* (denoting something rigid and linear) is now being replaced by the term *supply networks*. The nature and basis of competition is also in flux with an increasing premium put on speed to market, faster customer feedback loops, and the rapid re-engineering of products and processes. At this point in time, businesses in the nanotech sector have not departed from existing trends in organizational design and management. But what about impacts to the bottom-line?

Accompanying increases in productivity. A classic study by Ram Jaikumar at Harvard Business School examined the changes in labor productivity caused by shifts from the early craft system to mass production and to scientific management techniques and computer-based process control. Each of these changes in the means of production were typically accompanied by a factor of three increase in productivity. Are we seeing anything like this at this point in time? In sectors such as computers and industrial machinery, output per hour worked increased by an average of 15 percent annually between 1995 and 2001 (exceeding a factor two increase). Labor productivity has recently been running at rates of 7–8 percent, and, since the end of 2001, overall productivity has expanded at an annual rate of over 5 percent, reaching a 50-year record. Growth that appeared to be confined to discrete parts of the manufacturing sector has now spread into the service sector, defying a long held assumption attributed to economist William Baumol — that service sector productivity would lag way behind productivity in the manufacturing sector because it required activities that could not be easily mechanized. The most common explanation for this deepening in growth across multiple sectors is that organizations have finally figured out how to adapt to and optimize new technologies, especially information technologies. Nanotechnology may significantly boost industrial productivity, but is it not likely within the next five years. It is also unclear whether and when improvements will flow across sectors (into the dominant service industry, for instance) as they are doing with information technology.

So, looking backward, there were four clear signals, or patterns of signals, that an industrial revolution was upon us, starting a century and a half ago. Each of these factors — how we produce, how we communicate, how we organize production, and accompanying increases in productivity as a result of the first three — has significant environmental implications. Modify these factors and society's environmental footprint shifts, often in ways that are difficult to predict with precision. You will also notice that none of these changes has been impacted to any significant extent by nanotechnology— yet.

As the preceding section shows, an industrial revolution depends not just on the emergence of something new, but on the *convergence* of multiple innovations from multiple sectors and disciplines combined with new organizational forms and management techniques. It wasn't just the steam engine that produced the first industrial revolution, but the contemporaneous invention of the railroad, mass production, chemical engineering, telegraphy, etc. Those who declare that nanotechnology heralds a new industrial revolution are writing headlines, not making good social analysis.

However, looking at the present landscape through the same lens that history provides does show several technologies converging in the same way. We *have* entered a new industrial revolution, but not one based solely or even primarily on nanotechnology. The new industrial revolution began with information technology, which is now converging with biotechnology, and *eventually* will meld with nanotechnology. It is already upon us, and is accelerating. Nanotechology is destined to make it accelerate it even more.

The environmental community now faces a once in lifetime opportunity to get things right, but it will not happen without clarity of perception, moral conviction, and public sector leadership. We have a chance to guide an industrial revolution not only to minimize harm, but perhaps to find ways that industry can radically overhaul technologies, for environmental benefit. So let us stop here for a moment and explore this world from an environmental perspective. This is not some distant future that may appear at our local cinema, but a world at our doorsteps. The goal is to gain a better understanding of just what the hype bubble and other social distractions have obscured from view as our society has been entering, with increasing speed, the next industrial revolution.

Change accelerates. What is different about this industrial revolution versus that last is the rate of change, and this difference has broad implications for governance strategies, including environmental law. We are witnessing a shift from an economy based on long-lived technologies such as locomotives and power plants to one built increasingly on short-lived, constantly improving technologies like computers, DNA chips, or service strategies. It is not just computer processing speeds that are dramatically improving but things like the rate of process changes, the frequency of mergers, and the fundamental speed of innovation. Take, for instance, chemical synthesis, an area with significant environmental impacts. In the 1930s the largest chemical company in the world, A.G. Farber in Germany, could synthesize around 300–400 new chemicals per year. By the 1970s, a small group of chemists could achieve that rate and now, using combinatorial chemistry techniques that combine informatics and robotics, 50,000 new substances can be produced in a couple of weeks. We have moved into what Charles Fine at MIT calls a high "clockspeed" world, dominated by rapid improvements in products, processes, and organizations, all moving at rates that exceed the ability of our traditional governing institutions to adapt or shape outcomes. If you think that any existing regulatory framework can keep pace with this rate of change, think again.

An opportunity not only to minimize harm, but perhaps to find ways that industry can radically overhaul technologies, for environmental benefit

Software rules. The first industrial revolution was about hardware, the physical. It was the production, use, and disposal of this hardware that created the great environmental challenges of the past century. The new industrial revolution has created a world where hardware (atoms) and software (bits) co-exist — where the code determines the hardware. Today, a small design shop in Omaha can produce the production code for a semiconductor chip and send that code via satellite to a fabrication plant in Taiwan or Borneo. Companies are freed to focus their resources on parts of their enterprise where value creation is highest — innovation, product development, and marketing — and outsource the parts of their enterprise that manipulate the atoms — the manufacturing. This is becoming increasingly possible because of robust interfaces that allow software to create hardware (and do this almost anywhere in the world) and the increasing availability of high-quality manufacturing capabilities in low-wage markets throughout the globe. When software rules, environmental considerations will have to become embedded into the production code itself and travel with it, and that means that EPA and other environmental organizations will have to "go virtual," operating a world of simulation, production interface systems, bio-computation, etc.

Environmental regulations were built on the assumption that industrial facilities and associated pollution would stay put

The other change with potentially large environmental implications will be the increasing tendency to extract more and more economic value from the bits, not the atoms, which makes hardware less relevant. Profits will be extracted from selling information and connectivity and not from selling things. Already, companies are giving away cell phones or selling computer and peripherals under cost. Hardware will become increasingly linked to rapid software development cycles providing us with a constant flow of soon-to-be-obsolete products.

Fabrication goes mobile. As we separate bits from atoms, our ability to manipulate those atoms with ever-smaller devices is also dramatically improving. Maybe someday, as the nano prophets predict, we will be able to assemble things atom-by-atom, but long before that manufacturing will move out of big, easy-to-regulate factories and into the world around us just as computation moved from mainframes onto our desktops and into our pockets.

Take the workhorse of the industrial revolution, the hydraulic press. It used to stand many meters tall and weigh several tons. New units, based on powder metallurgy technology, are faster, more powerful, and the size of large filing cabinets. How about putting production on wheels or in cargo holds? Advances in robotics and computer-aided manufacturing now allow self-contained, turnkey manufacturing units for a variety of products, ranging from tires to bagels, to be packaged into 20 or 40-foot containers for shipment and use anywhere in the world.

Office production? Why not? Three-dimensional printers, once expensive devices used for rapid prototyping, can now be rented for under a $700 a month (Hewlett Packard is developing a unit which will sell for about $1,000). Suddenly, we will have the ability to produce "things" (not documents) in an office or workshop using a wide variety of input materials, ranging from chemical polymers to metal powders and cornstarch. But who recycles the "things" or determines the input materials? Such devices are not just gadgets for the idle classes wanting to "fax" a toy to their grandkids (though that will be possible). Researchers at the MIT Media Lab have developed sophisticated, tabletop production facilities known as FabLabs, which they have delivered (along with grad student trainers) to people around the world who would never have access to precision manufacturing. People in India, for example, have used these tabletop factories to produce devices to tune the diesel engines that provide power and water in many villages.

But it is not just the production of bulk items that will be possible with ever-smaller, adaptive systems. Chemical production modules called microreactors are now available in packages ranging in size from a postage stamp to a hockey puck. These devices open up the possibility of shipping reactors and producing, on-site, the exact amount of the substance required. This will change the industrial ecology of chemical production, shifting the routing of precursor chemicals and locations of final production. Analogous to a computer, a hundred or even thousands of microreactors connected in massively parallel arrangements would allow production to be scaled up and matched quite precisely with demand (existing units operating in parallel are already producing 30 tons of pigment annually). Uses could range from chemical synthesis to drug discovery or hydrogen production for fuel cells. A number of researchers are also developing microreactors for biotechnology applications (an area with significant implications for bioterrorism).

So long before we go from large-scale, or so-called "bulk," manufacturing to some futuristic nanoassembler, we will pass through small- and microscale production. The reason this transition is important to understand is that many of our environmental regulations were built on the assumption that industrial production and associated pollution would stay put. EPA has worked for years on the development of facility ID codes to help link data on manufacturers with stationary map coordinates and emissions data. What happens if we put production on wheels, in cargo holds, or in the mail? At that point, manufacturing becomes unteathered and from an environmental standpoint, begins to look more like a non-point, mobile source with the potential to move rapidly across geographic and administrative boundaries. How we deal with such production systems has yet to be studied by the regulatory community.

Production goes biological. Though the environmental press largely overlooked it, the biggest environmental story of the past ten years was the sequencing of the genome — the underlayment of the biotechnology revolution. But in addition to allowing us to alter basic qualities of organisms, essentially we have begun to unravel and understand the ultimate self-replicating production code, DNA, a code that operates at a nanoscale level. As this understanding grows, so does our ability to use biology for manufacturing. This industrialization of biology could radically shift the entire lifecycle of production, impacting everything from feedstocks to emissions to end-of-life strategies for products.

Nexia Biotechnologies in Quebec breeds goats with spider genes that allow the animals to produce milk containing the spider silk protein. The extracted spider silk is, in turn, used to produce a material called BioSteel, which has a tensile strength that is greater than steel and 25 percent lighter than petroleum-based polymers. In the future, we can anticipate an increase in transgenic production capabilities, which could place manufacturing in areas normally associated with livestock breeding. Transgenic modification is also not without risks, a point made in a recent report of the Pew Initiative on Food and Biotechnology.

A deeper understanding of genetics and molecular biology also provides us with a unique opportunity to replace catalytic chemistry based on nonrenewable feedstocks (such as petroleum) with enzyme-based chemistry built on renewable inputs. Polylactic acid (PLA) made from cornstarch is already replacing petroleum-based plastics such as PET, polyesters, and polystyrene, and PLA is carbon neutral and compostable. Enzymes and whole cell systems engineered from bacteria, yeasts, and plants are now being used in metal processing for leaching and refining, in drug development, textile treatment, and paper production (all processes with large environmental and energy burdens).

Finally, we may witness tectonic shifts in existing, and well regulated, production processes. One large and looming example is the production of computer logic, a process with high levels of both chemical and water use. To maintain existing exponential improvements in the per-dollar cost of computing (dictated by Moore's Law), it is highly likely that semiconductor industry will move from traditional photolithography techniques to the biological or chemical production of logic within the next decade or so. Research is already moving in this direction. Witness the work at MIT on the use of viruses to grow wires for the world's tiniest transistors or the recent development in Israel of a nanoscale transistor that assembles itself using DNA proteins. Such shifts would have far-reaching environmental implications, changing the inputs, emissions, and lifecycle management strategies of a variety of products.

Despite the game-changing nature of biological production, which includes a possibility to phase down the petroleum economy, it has received far too little attention in the environmental community, which has focused largely on its negative aspects (genetically modified crops and foods) rather than its pollution prevention potential. Once we start thinking in biological terms, it is a short step to the next major transition worth the attention of the environmental policy mavens.

The industrialization of biology could radically shift the entire lifecycle of production, from feedstocks to emissions to end-of-life strategies

Design becomes evolutionary. If we can assemble using biology why not use biology or biological principles to design? Design, after all, is the beginning of the environmental lifecycle. Before there are any environmental problems, there is a design for a factory, a product, a chemical — a design that is more or less environmentally benign. The problem with using evolution to design things is that it is normally too haphazard and time consuming. Look how many millions of years it took to design us humans.

But what if we can speed up evolution — all that messy, random sorting of traits normally done through trial-and-error and selective pressure? Well, that is exactly what is happening. In the late 1960s, Sol Spiegelman at the University of Illinois succeeded in selectively breeding particular RNA molecules to increase their replication rate by 15 times. By 1992 *Scientific American* featured its first story on what was termed "directed molecular evolution" or what we might call Darwin on steriods. Meanwhile, computer scientists have been conducting similar experiments to create computational ecosystems that breed problem-solving programs in survival of the fittest competitions. The goal is to build desktop innovation machines that will compete with humans. Such devices have already duplicated the invention of more than a dozen seminal patents in the field of electronics. Recently, researchers at Brandeis University have succeeded in selectively "breeding" simple machines in a virtual environment; machines which then "produce" themselves using the three-dimensional printing techniques mentioned earlier. So already, in the fields of biology, computing, and manufacturing, evolutionary processes are being applied to real world problems.

The speed and complexity of science and technology are exceeding the capacity of the environmental community to respond

Now comes the interesting part. If we use directed evolution to design products, molecules, or machines, how will we know if they will emerge with the right environmental characteristics? In some cases we will not. That is the nature of emergence. Many people involved in such experiments admit that they do not fully understand how an "evolved" molecule or computer program works. Essentially, understanding has been sacrificed for variety and speed. For legal scholars this raises an interesting question of who is responsible when environmental characteristics are essentially side effects of evolutionary design processes. On the other hand, one could apply directed evolution to solving environmental problems — to the design of safer chemicals, pesticides, consumer products, etc. Obviously, these scenarios sound far-reaching, yet they are as possible as any scenarios being laid out by the purveyors of nanotechnology and they are built on the last big things, the info and biotech revolutions.

If these trends hold, we are being fast forwarded into a new industrial infrastructure that is flexible, highly adaptive, increasingly based on biology, and driven more and more by evolutionary principles. To paraphrase Peter Drucker, all these developments are visible right outside our window. Waiting for nanotechnology to change this picture is a dangerous procrastination, because the picture is already changing in ways that demand our attention. The types of actions the environmental community needs to take now will prepare it to deal with the already-started industrial revolution and any that follow, nano-based or not. Here are some of the immediate challenges and some no-lose strategies:

First, the pervasiveness, speed, and complexity of the emerging science and associated technologies are exceeding the capacity of the environmental community to respond. Organizations are already being simultaneously pulled in multiple directions by disruptive changes in biology and computer science. Given the enormous public- and private-sector investments in nanotechnology we can expect extremely rapid innovation and unanticipated spillover effects, which will add to, and interact with, effects from the info and biotech realms. Especially hard hit will be the NGOs, who are otherwise occupied fighting unending battles to stop regulatory rollbacks and other stealth maneuvers by the barons of the last industrial revolution. Many local, state, and federal environmental organizations will not fare much better, as they will have to compete with the private sector for people with the skill sets to operate in these new areas or in the interstitial spaces between them (such as in biocomputation). In his 1986 science fiction novel *Count Zero*, William Gibson lays out a future where the battles are not between nations fighting for land, money, or resources, but between organizations vying for talent and creativity. The public sector needs to enter that battleground or become irrelevant. The environmental workforce in government has aged over the past thirty years and needs to be evaluated and restructured to make sure that agencies have the human, not just financial, resources to deal effectively with new challenges both in, and across, these emerging and converging disciplines.

Second, the front line of environmental protection will shift from the legal department to the science and technology functions. If we are at a critical juncture in our industrial evolution, then there is only one viable strategy in this situation, to proactively shape the future, a function that our existing regulatory infrastructure is not well suited for. This does not portend the end of environmental law. However, part of the legal profession must position itself at the front of the technological curve. There is an urgent need to carefully examine the existing regulatory framework in terms of adequacy to deal with emerging science and technology. This will require a deep, not superficial, analysis across the regulatory landscape within agencies, across agencies, and across geographic boundaries (local, state, federal, and international). The task will be made more difficult because innovation will be occurring between, rather than in, the disciplines and sectors where traditional laws and regulations have been developed and tested. Regulatory gaps need to be identified and the transparency of the regulatory system constantly improved, especially for small businesses driving innovation. The Converging Technologies Bar Association was recently launched to address some of these challenges, but more effort will be needed.

Third, agencies such as EPA, and its equivalents around the globe, will need to retool their research strategies. Too much funding is still being spent dealing with the last industrial revolution, its aftermath and byproducts, and not enough on preparatory and anticipatory research. Given the level of scientific and technological innovation taking place at this point in time, funding at EPA for so-called "exploratory" research is unacceptably low (0.8 percent or less of the total R&D budget). Funding should include a robust programs focused on societal and ethical implications in areas such as toxicogenomics.

There is also an urgent need to develop potential breakthrough technologies with R&D funding targeted directly at producing disruptive change (not a 3-percent improvement in efficiency or reduction in cost, but factor 3 or more). This is the way the Defense Advanced Research Projects Agency has traditionally functioned within the Department of Defense. That's the agency that gave us the Internet. Now is the time to create a DARPA-style office within EPA (and EPA equivalents) to tackle the really hard problems with unorthodox approaches. How much money should such an office receive? Between 1995 and 2003, DARPA's funding averaged 5.3 percent of total DOD R&D. A 5-percent figure applied to EPA's existing R&D budget would result in over $30 million devoted to the search for game-changing technologies. The driving ethos of such a project should be, as Apple computer founder Steve Jobs once said, to "put a dent in the universe." Such an office or department should become a magnet for the most creative talent in the world.

Finally, in an era of pervasive scientific change, we need pervasive scientific literacy, and that includes our public, our press, and our policymakers. We can expect the complexity of the science underpinning both environmental problems and solutions to continue to increase, demanding evermore sophisticated understanding transcending multiple disciplines. Over a decade of survey research done by Roper for the National Environmental Education and Training Foundation has shown that as complexity of environmental issues increases, public understanding drops off precipitously. A scientifically illiterate public will be extremely susceptible to various scare campaigns in the press, films, or other media. Nanotechnology has become the poster child for technohype as it creeps into the public consciousness through advertisements, TV shows, books, and films. In this environment, it will be harder for the public to separate science from science fiction. How can we possibly have a rational and informed discussion around issues such as genetic modification or nanotechnology or try to inform policy through multi-stakeholder dialogues involving the public?

Our ability to prepare society for the next industrial revolution is closely related to our ability to perceive and anticipate change and understand its implications for present actions and policies. Frankly, far too few resources in the environmental community are dedicated to understanding the changing context in which policies and strategies will be developed and implemented. Some future historian may well characterize this point in our environmental history as one of tragedy, not only because of the unenlightened attacks on our environmental laws, but also because we missed an opportunity to reshape our industrial infrastructure in ways that would make it far more environmentally benign and sustainable. In a recent interview, former Sun Microsystem's Chief Scientist Bill Joy noted that "we need to encourage the future we want, rather than try to prevent the future we fear." Too many times, environmental protection has been focused on fears rather than aspirations. We need to break that habit, and the opportunity is now. •

> ***The front line of environmental protection will shift from the legal department to the science and technology functions***