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The Molecular Economy

Pretty much as predicted, the long awaited convergence of nanotechnology and biotechnology has arrived. Can environmental protection, still cleaning up the last Industrial Revolution, avoid the perils while realizing the promises of manufacturing at an atomic scale?

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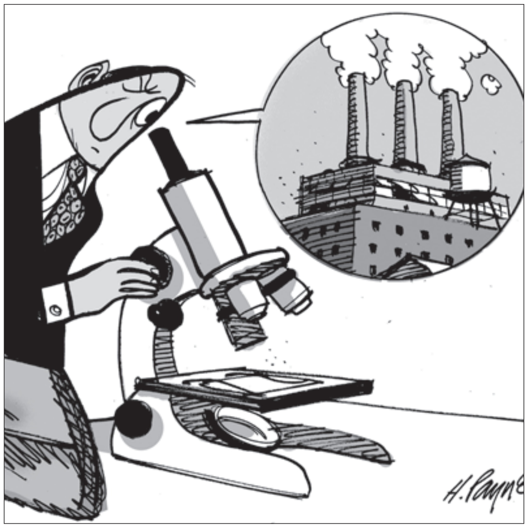
In 1813, a Connecticut arms manufacturer named Simeon North received a contract to produce 20,000 handguns such that "the component parts of the pistols are to correspond so exactly that any limb or part of one pistol may be fitted to any other pistol." To accomplish that task, North replaced the slow, tedious, and imperfect process of hand filing with a milling machine. The advent of interchangeable parts produced a revolution in manufacturing. Slowly the diffusion of machine tools and precision techniques, along with the speed of the assembly line, spread from arms making to other economic sectors, changing how we manufacture everything from sewing machines to bicycles and eventually the automobile and the computer.

The story of the Industrial Revolution is a story about process control — about making things with ever greater precision in less and less time. This mass manufacturing was what helped Henry Ford put a car in every garage at the beginning of the 20th century and, by the beginning of the 21st century, enabled semiconductor manufacturers to pack a billion transistors onto a silicon wafer smaller than a postage stamp. Of course manufacturing systems that produced cars and chips also produced nasty byproducts, and the history of environmental law has been a catchup game of regulating these harms after they are produced. As culture historian C. P. Snow once put it, "Technology . . . is a queer thing. It brings you great gifts with one hand, and it stabs you in the back with the other." Can a new Industrial Revolution avoid these polluting byproducts? Can it help us clean up the detritus of the first Industrial Revolution?

Throughout most of the 19th century, there was a revolution occuring inside the factories and armories in New England. Twenty-five miles from the old mills of Lowell, Massachusetts, relics of the Industrial Revolution's triumph of technology and, later, toxic tragedies, sits Angela Belcher's squeaky-clean laboratory at the Massachusetts Institute of Technology. She and her colleagues are part of a new guild of craftsmen engineering manufacturing at a Lilliputian scale. They are building parts for highly efficient rechargeable batteries by using viruses that have been engineered to coat themselves with iron and then attach to ultra-thin carbon wires to form a conductive network. Across the country, in Berkeley, California, chemical engineer Jay Keasling has created a cellular factory using modified yeast that produces artemisinin, a key ingredient in the drug used to treat malaria. Other researchers are creating custom microbes that will allow highly efficient production of biofuels from a wide variety of feedstocks.

Most people have missed this new Industrial Revolution, but it is the foundation of what business writers Christopher Meyer and Stan Davis call the molecular economy — built on our increasing ability to see and manipulate matter at a nanoscale (a nanometer is one billionth of a meter or about 7,000 times smaller than a red blood cell). This is the continuing saga of making things with ever greater precision, and reproducing that precision at ever greater speeds and at lower cost — atom-by-atom and gene-by-gene. Pretty much as predicted, the long awaited convergence of nano and biotechnology has arrived. As Neri Oxman at the MIT Media Lab recently noted, the biological world at the microscopic level "is displacing the machine as a general model of design." Stan William, who directs quantum science research at Hewlett Packard Labs, observes that "every industry that involves manufactured items will be impacted. . . . Everything can be made in some way better — stronger, lighter, cheaper, easier to recycle — if it's engineered and manufactured at the nanometer scale."



The environmental movement missed the last Industrial Revolution. We have spent decades cleaning up leftover toxins and trying to nudge technological artifacts like the internal combustion engine and steam powered dynamo (both invented in the late 19th century) into a more environmentally friendly state, using a set of laws now 30 to 40 years old. We have had some success but still have a long way to go. Only five percent of the three gigatons of materials flowing through the U.S. economy is renewable and our system to generate electricity still runs at a paltry 30 percent overall efficiency, squandering almost 30 quadrillion BTUs of heat a year (more than the primary energy consumption of Japan). But the environmental possibilities offered by the molecular economy are tantalizing precisely because its impacts will be so pervasive and long lasting and because we are positioned in front of change, rather than behind it — if we choose to be.

If the molecular craftsmen can create new bio-based fuels, cheaper drugs, more efficient solar cells, or better batteries for electric cars — not to mention microbes that turn pollutants into fuels and feedstocks — what's not to like? Innovation in the molecular economy means the ability to build a future with little relationship to the past. But this can also undermine everything from our risk assessment models to regulatory strategies, most designed to deal with legacy issues and products of past production systems. As ecologists and toxicologists are finding out, nanomaterials and synthetic organisms produced in the molecular economy will not necessarily behave like anything produced in the past, and more complex innovations are just over the horizon.

A New Technological Frontier

So we arrive on this new technological frontier burdened with old maps and tools and the need to sort out what will work from what will not. Our very concept of technology has become outmoded. As economist Brian Arthur recently put it, "Modern technology is not just a collection of more or less independent means of production. Rather it is becoming an open language for the creation of structures and functions in the economy." Old distinctions between science and engineering, design and production, the organic and inorganic, and the world of bits (code) and atoms (things) can undermine our conceptual models and the search for solutions. What happens when a high school student can download genetic code to a desktop synthesizer, bought off eBay, and build a new biosensor for heavy metal contamination — or a new biological pathogen? Laws like the Toxic Substances Control Act or the Resource Conservation and Recovery Act will require modernization before they can come to grips with hazards not even contemplatable thirty years ago when they were drafted.

Let's pause and ask some questions. First, is the molecular economy real and how would we know it? Second, how fast will things change? Third, what are the likely environmental consequences of this new economy? And fourth, how can we best prepare in terms of governance strategies?

Some view this tinkering with atoms and genes as old science in a new package, often describing the future in terms of the past, with a dash of hyperbole. So, for instance, the new field of synthetic biology has been described as recombinant DNA (invented in 1973) on steroids. But as Stanford University economist Paul Romer once noted about innovation, "It springs from better recipes, not just more cooking." The molecular economy is based on new recipes. The people writing this cookbook have different backgrounds (chemistry, biology, computer science, and engineering) and the practice has different names (molecular manufacturing, synthetic biology, nano-biotechnology). But what is emerging from this Willy Wonka world of production isn't candy but an amazing array of innovations that are already having significant market impacts worldwide.

In 2007 alone, the global market for goods incorporating nanotechnology totaled $147 billion. The independent consulting firm Lux Research projects that figure will grow to $2.5 trillion by 2015. In the emerging field of synthetic biology, the Utah-based life sciences company Beachhead Consulting estimates that the synbio research market (currently worth around $600 million) has the potential to grow to $3.5 billion over the next decade, while estimates by Lux indicate that one-fifth of the chemical industry (now estimated at $1.8 trillion total) could be dependent on synthetic biology by 2015. Over 1,200 firms and universities in the United States are engaged in nanotechnology research, development, and commercialization and over 200 are working on synthetic biology. So the industrial landscape is growing rapidly along with its economic impacts, but most people have missed this transformation and that is not surprising.

The interesting thing about technological change is its ability to advance below the level of public consciousness. Four years of national polling by Hart Research has found no increase in public awareness of nanotechnology, with around 75 percent of adult Americans having heard "nothing" or "very little." But then again, people living in 1880 were probably not paying much attention to the electric dynamo, the internal combustion engine, or William Perkin's early success with chemical synthesis. Technologies often slip unceremoniously into our lives but can linger for decades, or longer. Our strategic arsenal still relies on the B-52 bomber (in service since 1955), machetes and small arms kill most people in wars, and global warming is driven by a suite of old-fashioned technologies and practices. As the Environmental Protection Agency celebrates its 40th anniversary this year, it is still very much occupied with what English historian David Edgerton called "the shock of the old." But in the future, the success of environmental protection will depend on the ability to shift our attention and sufficient resources in the direction of the new. How much time do we have to prepare? Probably less than 10 years.

There is a tendency to evoke Moore's Law — the 1965 assertion that the performance of integrated circuits would double every 18–24 months — as a metric of today's rapid innovation tempo. However, the distance between research and a viable business is large and the gap littered with failed startups and wasted capital. Bhaskar Chakravorti at Harvard coined the term Demi-Moore's Law to indicate that technology's impact on the market moves at a rate only one half the speed predicted by Gordon Moore, but that is still fast compared to our ability to change the laws, organizations, and mindsets governing our environmental policies. Recently, the OECD, the club of rich industrialized countries, identified a new class of governance challenges they term emerging systemic risks that arise through the interactions between complex social, technological, environmental, and economic systems moving at faster and faster rates. The molecular economy would appear to fit that model perfectly.

We can take a simple, but illustrative, example from the past to gauge how quickly innovation might accelerate in the future. In the 1930s the largest chemical company in the world, A.G. Farber in Germany, was synthesizing approximately 300 new chemicals per year. By the 1970s, a small team of chemists could achieve that rate, and, today, grad students using combinatorial techniques (which integrate robotics and informatics), can synthesize 50,000 chemicals in a few weeks.

The ramp-up of production capacity in emerging areas like nanotechnology will be rapid, and driven by combined advances in instrumentation and informatics, will lead to greater process control. A few years ago, materials like carbon nanotubes were made in gram quantities; now firms like Bayer can produce 60 tons a year, which is a signal that industry is gaining precision control over nanoscale processes. High-yield manufacturing of nanomaterials will allow these new substances to increasingly underpin the mass production of consumer products. The number of manufacturer-identified nano-based products on the market has risen from around 50 in 2005 to over 1,000 in August 2009, with a projected 1,500 products by 2011 from over 25 countries. Increasing capacity to engineer synthetic organisms should yield commercial-level production systems for custom biofuels within five years.

Getting in Front of Change

Getting in front of the emerging molecular economy, if we can do it, will have important strategic implications for decades to come. It means the difference between being able to shape outcomes or having to adapt and respond to them after the fact. Another way of thinking about this is asking the question of whether a dollar spent preparing for this major industrial transformation is worth a hundred dollars spent cleaning up after it. How much, for instance, is EPA dedicating? An optimistic estimate covering both the areas of nanotechnology and synthetic biology is about .2 percent of its fiscal year 2010 budget of $10.5 billion and about .3 percent of the over 17,000 people in the agency. Probably not enough, given what is at stake and the nature of the challenges EPA, and other regulatory agencies, will face.

The molecular economy will be dominated by what Peter Bernstein, in his fascinating history of risk, called the "wildness" — a world of imperfections, outliers, and uncertainties that confounds easy decisions, undermines predictions, and can often lead to embarrassing miscalculations by decisionmakers. Besides rampant uncertainty, this new technological frontier shares one similarity with other frontiers — bad things can and will happen. Accidents are "normal" on the frontier, a point that sociologist Charles Perrow noted years ago.

What could go wrong? The old manufacturing economy produced the first generation of chemical, biological, and nuclear weapons. The molecular economy could produce a new generation of threats which include: resynthesizing diseases affecting humans or livestock that have been eradicated (polio was resynthesized from scratch in 2002 and the deadly Spanish flu in 2005), augmenting the contagiousness of existing viruses such as avian flu, or developing new toxins and ways to deliver bioagents deep into the body though nanoscale engineering.

Early on, the molecular economy may be more brown than green as new processes emerge. Most engineered production systems take time to perfect and are not necessarily optimized for environmental performance. In 1769, the steam engine required 30 pounds of coal per horsepower, but this was reduced to 7.5 pound by 1776 and 2.5 pounds by 1850.

There are presently over 40 processes used to make first-generation nanomaterials, ranging from top-down techniques, such as photolithography, etching, and milling, to bottom-up techniques, such as vapor phase deposition and electrostatic self-assembly. A recent Swedish study found that the production of carbon nanoparticles is highly energy intensive, requiring 2 to 100 times the energy needed to produce aluminum and often requiring high levels of toxic chemical inputs. Industrial biotechnology is still far from optimized in terms of reducing energy requirements, minimizing waste, and avoiding negative land use impacts.

Over time, learning effects reduce cost and improve quality but experimentation can go on for years before a small number of efficient technological solutions emerge and diffuse, many of which become effectively locked in and resistant to change. One important lesson from the last Industrial Revolution is that the winners in this technological race are not necessarily good for the environment. There exists a small window of opportunity where small interventions can have large long-term consequences for the planet. We are in that window but decades of reactive regulatory focus on the outputs of production systems (emissions, wastes, and products) provides little insight or leverage over fundamental transformations in the underlying production infrastructure. The environmental community has fallen into what can be called a "competency trap," applying outmoded tools and skills to emerging challenges. By the time they catch up, competitive forces can create the next competency trap with a new set of actors and technological realities.

So how can we best use an opportunity that scientific advance has placed at the doorstep of environmental protection? Woody Allen once said that, "Eighty percent of success is showing up." In 2007, *Wired* magazine was working on an article called: "Will Synthetic Biology Catch Government By Surprise?" The editors called EPA and the Food and Drug Administration to ask about this emerging area — and the agency people had to ask what synthetic biology is. So the key for regulators, regardless of agency, is to show up, show up early, and show up with the right tools and enough resources.

Directing the Future

One must begin by recognizing that science, left on its own, will not necessarily create new green production systems or effectively address risks to humans and the environment. Survey work with university-based nanoscientists has shown that researchers working on new technologies tend to view their work as not producing any new or substantial risks, while those scientists downstream of development often feel the exact opposite. As one synthetic biologist recently said, "Let's not talk about it, let's actually go do it, and then let's deal with the consequences." There is a very human inclination to be blinded by the excitement and promise of the new. As Princeton historian Edward Tenner once noted, "There is a tendency for advanced technologies to promote self-deception."

If our approach to environmental protection was properly designed to address the future it would do two things well: identify and stop bad things early, and shift the emerging production systems to avoid, or at least minimize, the potential for bad outcomes in the future. In addition, our governing organizations would be purposely designed to enhance learning and flexibility so they could respond quickly to negative surprises and unintended consequences.

We haven't been very effective at spotting risks early and taking action. For instance, concerns about possible inhalation risks of carbon nanotubes first appeared in a letter to *Nature* magazine in 1992 and again in 1998 in an article in *Science* entitled: "Nanotubes: The Next Asbestos?" Fast-forward another decade and more evidence has accumulated that carbon nanotubes can cause asbestos-like pathogenicity in the lung and actually pass directly through the lung lining. Recently, EPA declared it would finally enforce pre-manufacturing reviews for carbon nanotubes, declaring that they "are not necessarily identical to graphite or other allotropes of carbon." In other words, they are, in fact, novel. This represents a minimal gap of over 15 years between early warning and government action. It should have been a relatively easy call, given the structural similarities between carbon nanotubes and asbestos.

We are leaving the world of easy calls. On the horizon are a wide variety of complex molecules and systems that are no longer passive, like nanotubes, but specifically engineered to respond to the external environment (for instance, change structure and behavior in response to light, electromagnetic fields, pH, or other conditions), or actually self assemble into entirely new structures. These applications will be difficult to understand with traditional risk assessment methods and address using the categories that have been key to regulation such as new versus old, organic or inorganic, or even product or process. That is why early warning becomes critical to effective oversight.

Two strategies, both low cost, would help address some failures in early warning. The first is the establishment of a high-level Early Warning Officer, or EWO, with a small support staff at EPA and other agencies, such as FDA, the Department of Agriculture, and the Consumer Product Safety Commission. The EWOs would report directly to the heads of the agencies and provide frequent briefings that focused on both the threats and opportunities posed by the new molecular economy, or other emerging phenomena that could have significant environmental implications. EWOs would also meet to exchange information on a regular basis and build a larger network that encompassed state, local, and international members. This type of strategic reconnaissance is fairly common in the business and intelligence sectors, so models could be easily adapted to oversight organizations.

The second strategy is to develop an open-source tool that tracks an evolving list of known unknowns related to the emerging molecular economy. As empirical evidence is gathered, issues could be modified, taken off the list, or new areas of inquiry added. For instance, in the area of synthetic biology, one unknown at the moment is how best to assess the risks of novel organisms with little or no natural precedents. An evolving list of known unknowns (possibly maintained on a wiki) would also constitute a de facto risk research agenda that could be addressed by national and international funders. Finally, it may reduce the potential for surprises, allowing policymakers the opportunity to consider various scenarios before they occur.

Notice that these strategies are organizational, not legal or regulatory. They are built on well-known principles for managing under conditions of uncertainty where a key quality is becoming mindful of, and embedded in, the world we seek to understand and influence — what biologists would describe as a persistent coevolution strategy. This does not mean abandoning voluntary or regulatory strategies which need to be "stress tested" quickly for adequacy, but in the years it can take to test a voluntary reporting system, technological systems can move rapidly, changing the nature of both the risks and opportunities.

Organizations Responsive to Change

There is no surprise-free future, but we can design organizations to be more responsive to change, providing a backup to traditional regulation, which is slow, expensive, and hard to maneuver in the face of rapid innovation and constant uncertainty. Organizational strategies that increase agility and resilience are well researched and well known and include: learn rapidly from failure, refuse to simplify reality, commit to flexibility, do not over plan (keep options open), and balance specialists with generalists (who will thrive more successfully in complex systems).

Finally, strategies are needed to nudge the emerging molecular economy into a more sustainable state. Within the next decade, dozens of fundamental production processes will be reengineered at a molecular level, ranging from the way we make semiconductors to new batteries and biofuels. During the experimentation period, competing technologies may be particularly susceptible to strategies that push them in the direction of lower energy use, better materials efficiencies, and a reduced environmental footprint. As new production technologies emerge, we want to make sure the green options win, other constraints being equal. Small investments in lifecycle analysis and research on green processes could have large, long-term impacts as production methods are subsequently scaled up and become locked in, often for decades.

From this perspective, it is noteworthy that EPA has shifted its nanotechnology R&D effort into studying risks rather than avoiding them, abandoning an upstream, pollution prevention focus on creating greener products and processes. A serious effort by EPA to avoid, or at least minimize, the potential for bad outcomes in the future would require a "5–10 strategy": 5 percent of its budget (which would be $400-500 million annually across all programs, not just research) and 10 percent of its staff (which would be 1,700 people). Getting the right people onto the technological frontier is more important than funding alone, which can be leveraged from other agencies, but optimizing human resources and talent will require new training and incentive systems for existing staff as well as preparing a new generation of professionals at a university level with the right skill sets. Given the large and looming retirement bulge in many U.S. regulatory agencies, including EPA, we have an opportunity to restructure the workforce in new ways that could address emerging challenges.

In science fiction writer Ben Bova's novels viruses extrude carbon fiber construction materials and nanobots are used to assemble consumer products or patrol blood vessels for arterial plaque. We are a long way from Bova's future but researchers have already moved the promise of the molecular economy off the lab bench and into the marketplace. The challenge for the environmental community is to both understand the changes and capitalize on them.

We need to approach the molecular economy as a major industrial transformation rather than a number of discrete independent technologies (nanotech, biotech, infotech, etc.) and realize that the greatest innovations (and nasty surprises) are likely to spring from the interstitial spaces between these various technological areas. EPA and other environmental agencies have a once-in-a-century opportunity to place environmental policy and protection in front of a major shift in how we produce just about everything. But the agencies needs to show up, turn a cognitive corner, and change their operating metaphors, organizational strategies, and resource commitments to ensure that the coming industrial revolution is planet-friendly and sustainable. •