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Nanoscience, Green Chemistry, and the Privileged Position of Science

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This chapter compares two cases of forefront science. The first, nanoscience, is a classic hot research arena: scientists rush into each niche as soon as it opens; conferences and professional publications buzz with the latest results; pundits offer glowing predictions of benefits to environment, world hunger, and medicine; government officials generously dole out taxpayers' money; and voices even arise to counsel the need for prudent foresight.[1] A very different profile characterizes the second case, that of "green chemistry," which aims at redesigning molecules and chemical production processes to make them more benign: research is coming nearly a century later than it could; conferences are few in number; funding is niggardly; public attention is slight; and little fame accrues to participants.[2] What can we learn from these polar opposite cases about the influence relations in and around contemporary science?

The first section describes nanoscience and technology R&D and the social forces impelling the activities, both within the scientific community and more broadly. Section two explains some of what is and is not occurring in green chemistry, traces the factors that have caused it to lag, and discusses a recent surge that may ultimately bring green chemistry onto mainstream chemical agendas. The remainder of the chapter analyzes implications of the two cases for our understanding of scientists as participants in a system of power, including their roles as allies of business, and my analysis is intended as a contribution to reinvigorating the interests tradition in the sociology of knowledge. As the title of the chapter suggests, however, I do not see forefront technoscientists primarily as pawns of political-economic elites, but argue that they also use these connections to enjoy a structurally privileged position in contemporary social life -- exercising considerable discretion over matters of great public consequence, and themselves being among the foremost beneficiaries of science funding and technological innovation.

Although I start from the constructivist assumption that social forces have shaped the nanoscience-technology juggernaut and the green chemistry laggard, and although I inquire into what those forces have been, I aim to move beyond social construction of science and technology toward reconstructivist scholarship aimed at clarifying alternative possibilities, both substantive and procedural.[3] I think there are lessons in the juxtaposition of the two cases for those who seek to reconstruct scientific research and technological practice along fairer, wiser, more democratic, or otherwise "better" lines. If technoscience in some respects constitutes a form of legislation that reshapes the everyday lives of billions of persons, is it not about time to develop procedures capable of holding the scientists and technologists doing the legislating a good deal more accountable for their actions?[4]

Nanoscience and Nanotechnology

Nanoscience and nanotechnology are "the art and science of building complex, practical devices with atomic precision," with components measured in nanometers, billionths of a meter.[5] This is not a typical scientific field inasmuch as researchers do not pursue common substantive knowledge: "smallness" is the unifying attribute, so it may be more appropriate to term research and development at the nanoscale as an approach rather than a field. Indeed, in private some scientists go so far as to suggest that "nano" functions more as a label to legitimate receiving grant monies than as a coherent set of research activities.

Nobelist Richard Feynman is generally credited with calling attention to the possibility of working at the atomic level on non-radioactive materials in a 1959 lecture at Cal Tech titled, "There's Plenty of Room at the Bottom,"[6] and he no doubt was a source of inspiration for at least some of the nanoscience that gradually began to develop. Most such research now being conducted is relatively mundane (see below), whereas the hype and concern about nanotechnology are due more to the dramatic notions first presented in then-MIT graduate student K. Eric Drexler's *Engines of Creation: The Coming Era of Nanotechnology*.[7] This visionary/fictional 1986 account for non-technical readers sketched a manufacturing technology that would construct usable items from scratch by placing individual atoms precisely where the designers wanted. This he contrasted with contemporary manufacturing, which starts with large, preformed chunks of raw materials, and then rather crudely combines, molds, cuts, and otherwise works them into products. The current approach uses far more energy than "molecular manufacturing" (MNT) would require, while leaving enormous quantities of waste products that molecular manufacturing would not.

Moreover, Drexlerian molecular manufacturing would become self-sustaining, with tiny factories building tiny factories to build tiny machines. However, because some of these might escape their designers' control, Drexler warned from early on that special controls would be needed: "Assembler based replicators could beat the most advanced modern organisms….Tough, omnivorous 'bacteria' could out-compete real bacteria: they could spread like blowing pollen, replicate swiftly, and reduce the biosphere to dust in a matter of days."[8] This warning was reiterated to a larger audience in Bill Joy's April 2000 *Wired* magazine article, "Why The Future Doesn't Need Us," describing a world of self-replicating, exponentially proliferating "nanobots" that could drown the planet in an uncontrollable "gray goo."[9] Michael Crichton gave the warning a more explicitly sci-fi spin in his 2002 novel *Prey*, featuring swarms of intelligent, predatory, nearly unstoppable nanobots.[10] Crichton of course could be dismissed, but it was impossible to brand Joy a Luddite, given his role at the time as chief scientist at Sun Microsystems, and his standing as an architect of the world's information infrastructure. Nevertheless, the research and technology communities quickly mobilized like antibodies to neutralize him, as discussed in a later section.

More ordinary, but still potentially transformative, aspects of nanoscience include work projected to accelerate present trends toward faster computing by aiding in miniaturization and by providing new ways to store information at the atomic level, as by facilitating "quantum" computing.[11] One effort concerns developing micro chip-like functionality from single molecules, enabling tiny, inexpensive computers with thousands of times more computing capacity than current machines, perhaps introducing a second computer revolution.[12] New materials include carbon nanotubes and other very strong and very light advanced materials. Nanomix Corporation is working to develop "new hydrogen storage systems that will power the fuel cell revolution, by using nanostructured materials to store solid-state hydrogen for automotive and portable power applications" for what is being touted as the coming "hydrogen economy."[13]

Other endeavors attempt to replicate biological functions with synthetic ones, such as designing and synthesizing organic molecules and supramolecular arrays that can mimic green plants' photosynthetic processes—perhaps opening the way for solar energy in a more fundamental sense than what the term so far has meant.[14] Most of the research presently is at a pre-commercial stage, although nanoparticles are beginning to come onto the market (e.g., titanium dioxide in sunscreens), and health and environmental concerns around nanoparticles may come to be the first specific point of contention among environmental groups, business, and government regulatory bodies.[15]

Along with tangible investments and research trajectories comes a good deal of hype of the sort that commonly shows up in the early years of new cycles of innovation. “Imagine highly specialized machines you ingest, systems for security smaller than a piece of dust and collectively intelligent household appliances and cars. The implications for defense, public safety and health are astounding.”[16] Even normally staid government reports burst with promotional fervor,[17] and a university web page says that “Our world is riddled with flaws and limitations. Metals that rust. Plastics that break. Semiconductors that can’t conduct any faster…. Nanotechnology can make it all better – literally – by re-engineering the fundamental building blocks of matter. It is one of the most exciting research areas on the planet, and it may lead to the greatest advances of this century.”[18]

Another R&D pathway is nanotechnology applied to biotechnology, nano-bio for short. A mundane example is the use of nanoscale bumps on artificial joints in order to better mimic natural bone and thereby trick the body into accepting transplants. Pharmaceutical manufacturing increasingly will rely on nanoscale techniques, according to some observers. More generally, as one advocacy organization puts it, “Recent developments in nanotechnology are transforming the fields of biosensors, medical devices, diagnostics, high-throughput screening and drug delivery - and this is only the beginning!”[19]

Although relatively routine at present, some of the potential consequences are profound, especially the joining of nanotechnology with biotechnology to blur the dividing line between living and non-living matter. For example, neural implants could make machine intelligence directly available biologically, and tiny machines may live (if that is the right word) in the body either just as sensors or also to treat incipient illness. An example in this category is the development of sensors "that could detect minute quantities of all biological and chemical hazards and provide appropriate safety measures if detected;" and devices "as small as the tip of a hypodermic needle" that "could detect thousands of diseases."[20] These innovations may continue the trend of increasing costs, widening the divide between medical haves and have-nots, and accentuating tendencies to substitute medicine for a healthy lifestyle.

Nanotechnology has been embraced enthusiastically by government officials. The Japanese Ministry of International Trade and Industry in 1992 launched the first major nanoscience initiative funded at what seemed a generous amount -- $185 million over ten years. That has now been dwarfed, with U.S. government support for civilian nanoscience and technology research at approximately $900 million annually under the 21st Century Nanotechnology Research and Development Act, which in 2003 formalized a variety of programs and activities undertaken by the Clinton Administration's National Nanotechnology Initiative. European and Japanese funding likewise is increasing rapidly.

As occurred with the so-called War on Cancer launched by the Nixon Administration, researchers have repackaged their work to jump on the nanotech funding bandwagon. Many are actually revising their research interests as they become involved in nanoscience, and new graduate students and postdoctoral researchers of course are able to move into the hot new areas of study without much loss of accumulated intellectual capital. Is this simply a response to ready availability of funding, or is there more to it?

We lack good methodologies for sorting out such matters, and even participant interviewing has not yet been done. However, I think anyone who has been around nanoscientists can attest to the genuine enthusiasm prevalent among them. Conferences already abound devoted specifically to nanoscience and technology, and large international meetings of chemists, physicists, and others include increasing numbers of papers with nano themes and methods. A sampling: Nanotechnology Growth Opportunities for the Biotech and Medical Device Sectors, Irvine, CA, April 2004; Nanomechanics: Sensors and Activators, Reno, May 2004; Second International Conference of Microchannels and Minichannels, Rochester, NY, June 2004; European Micro and Nano Systems Conference, Paris, October 2004.

Nanotechnology relationships are tight among university, industry, and government, continuing the triple-helix trend of the past generation. Several of the above conferences have obvious commercial themes, and other conferences are even more targeted toward nano-oriented businesses. nanoSIG™, part of NASA/Ames and sponsored in part by the business sector, says it is "the leading Northern California based membership organization focused on the commercial development of nanotechnology." The organization's NanoBio Forum works "at the interface of biotechnology and nanotechnology," sponsoring discussions on topics such as nanoparticles in proteomics, genomics and cellomics. A December 2003 forum was organized specifically to provide "advice on how to start a nanobiotechnology company, get government funding, and work with local government agencies."[21]

IBM and Xerox are among an increasing number of large corporations engaged in nanotechnology R&D, and start-up firms hoping to mimic the explosive success of Silicon Valley are racing to get products onto the market. Carbon Nanotechnologies, Inc., for example, claims to be a "world leading producer of single-wall carbon nanotubes . . . the stiffest, strongest, and toughest fibers known." Their most advanced product, "BuckyPlusTM Fluorinated Single-wall Carbon Nanotubes," was selling for $900 per gram in 2004, many times the price of gold.[22]

In sum, nanoscience and technology R&D consists of myriad minor, relatively useful and harmless trajectories combined just about inextricably with some fascinating, potentially helpful, and potentially disastrous radical innovations. Although interest is high among business executives and elected officials, it would be a mistake to overlook what Kleinman and Vallas in chapter two refer to as scientists themselves "mobilizing lines of action that can modify, mediate, or contest aspects of the emerging knowledge regime," a theme to which I return later in the chapter.

Brown Chemistry Versus Green Chemistry

Twentieth-century chemists, chemical engineers, and chemical industry executives made fundamental choices that substantially shaped humanity's experiences with chemicals. Most educated people know the main facts about some of those choices, such as DDT, PCBs, and chemical waste dumps. However, hardly anyone yet understands the deeper story behind the social construction of chemicals: It turns out that there was far greater technological malleability than almost anyone appreciated, and that chemicals as we know them by no means constitute the only path that chemistry and the chemical industry could have taken.[23]

One of the choices was that of relying on petroleum-based feedstocks instead of on fatty/oily or woody plant materials from which chemicals also can be made. Research on lipid chemistry and carbohydrate chemistry has a long history, with a number of journals devoted entirely to it. But the bulk of chemists' attention went first to coal-tar derivatives, and later to natural gas.

A second choice was that of opting for wet chemistry. Most contemporary chemical reactions occur in solution, and to get chemicals into solution requires solvents. There is a minority tradition of dry synthesis, but it received little attention in the past century. The result is that solvents played a huge role in the chemical industry, and many of those solvents such as benzene and toluene are extremely toxic.

A third choice was to emphasize "stoichiometric" processes, where two or more chemicals are combined to produce an output, one that goes on to interact with another chemical in a subsequent stage. Eventually, after as many as thirty steps in the "synthesis pathway," a final product emerges. Along the way, "byproducts" are produced at each step – outputs not directly usable in further steps toward a desired final product. Some byproduct chemicals can be used elsewhere, but some are just wastes – hazardous wastes. For example, formaldehyde and cyanide were among the byproducts that used to be created during production of the painkiller Ibuprofen. Since the mid 1970s in most nations, chemical companies have had to track these wastes from cradle to grave, paying huge sums for paper work, trucking, incineration, deep well injection, and other methods of disposal. Prior to that date, the hazardous wastes were treated more haphazardly, with some finding their way into water supplies at places such as Hooker Chemical Company's former site, Love Canal, and at Woburn, Massachusetts.[24] Estimates vary, but it is clear that brown chemistry has produced millions of tons of hazardous wastes.

A fourth distinguishing feature of the 20th-century chemical industry was rapid scale-up from original synthesis, through pilot plants, to full-scale production -- a process that rarely required as much as a decade. The result was megaton quantities of pesticides, plastics, finishes, and myriad other chemical products and processes, and few people hesitated to release the synthetic organic chemicals into ecosystems and human environments. Many of those involved did not know better, one assumes, and yet not knowing depended on selective attention, perception, or recall, because warning signs began to accumulate early on. For example, when orchardists sprayed fruit trees, massive die-offs of bees occurred until those doing the spraying learned to wait until well after flowering had finished.[25] Eggshell thinning and other more subtle signs took longer to observe, but there were enough early warnings and enough farmers with old-fashioned distrust of new-fangled inventions that chemists and others on the lookout for warnings would have found them. Instead, industrial chemists and their bosses and customers skipped the gradual scale-up that would have allowed lower- cost learning from experience.

Following Rachel Carson's cogent criticisms and the rise of the environmental movement, of course everything began to change in chemistry and in chemical engineering….Well,…no,… actually it did not. Indeed, even after passage of bookshelves of environmental legislation, more than 100,000 chemical researchers worldwide continue to collaborate with purveyors and purchasers of chemicals within the brown chemistry paradigm. Although the synthetic organic chemical industry is now in its second century, with many tens of thousands of chemicals in commerce and considerable opportunity to learn from the bad experiences, some of the world's brightest and most highly trained experts continue to poison their fellow humans and the ecosystem without fundamental reconsideration of whether there is a better way to do things. More strangely yet, although environmental organizations of course have worked hard to get governments to reduce toxic emissions in air and water, most environmentalists have not yet realized that it might make sense to change the basic dynamics creating toxins in the first place.

There have been selected exceptions, such as a push for less persistent pesticides, a reduction of volatile organic compounds in paints and coatings, and efforts in a few countries to phase out a handful of the worst chemicals. But the basics of brown chemistry remain intact, not only in chemical practice but in human thinking. The reason is pretty simple: Almost everyone assumes that there is no realistic alternative. Faced with a choice between better living through chemistry and back-to-the-cave, post-moderns may bitch about the uncaring executives in the chemical industry, but few of us seriously entertain the notion of doing without our plastics, chrome plating, leather seating, gasoline additives, lawn and garden chemicals, inexpensive food raised with pesticides, and other products produced via chlorinated and other synthetic chemicals.

It turns out we have been wrong, however, to assume that chemicals are chemicals, and there's nothing much to be done about it. Very, very slowly, over enormous cognitive, institutional, and economic momentum, has begun to emerge an alternative, green-chemistry paradigm:

* Design each new molecule so as to accelerate both excretion from living organisms and biodegradation in ecosystems;

* Create the chemical from a carbohydrate (sugar/starch/cellulose) or oleic (oily/fatty)

feedstock;

* Rely on a catalyst, often biological, in a small-scale process that uses no solvents or benign ones;

* Create little or no hazardous waste byproducts,

* Initially manufacture only small quantities of the new chemical for exhaustive toxicology and other testing,

* If preliminary results are favorable, follow up with very gradual scale-up and learning by doing.

The chemical research community belatedly has begun to experiment with aspects of this second formula. Sometimes called “sustainable chemistry” or “benign by design,” the organizational heart of the enterprise has been located not at major universities but in a tiny program in the Pollution Prevention and Toxics branch of the U.S. Environmental Protection Agency. Rather than focusing on cleanup and correction of problems already existing, the emphasis there since 1994 has been on prevention of problems before they occur – partly by redesigning chemical production processes and products at the molecular level to make them radically less dangerous.

There are very few historians of 20th-century chemistry, and most of these work on medicinal chemistry and/or on the World War I (“chemists’ war”) era, with none I know of studying the origins of green chemistry or barriers to it. Hence, we have no scholarship based on lab notes, internal industry memos, or other archival sources. With that caveat, my research suggests that at least four small tributaries of chemical investigation came together in the 1990s to create a rivulet of activities with enough coherence to be labeled “green chemistry.”

The first contributing element is supercritical fluids (SCFs).[26] Discovered more than a century ago was the fact that certain substances “exist in a hybrid state between liquid and gas above a critical temperature and pressure and as such have some bizarre and very useful solvent properties.”[27] Supercritical carbon dioxide ($scCO_2$), for example, is non-flammable, non-toxic, and has extremely low viscosity – and it is very inexpensive. Decaffeination of coffee supercritically began in the 1960s, but only since the mid 1990s have chemists begun taking advantage of SCF properties for chemical synthesis of ordinary industrial chemicals. Industry sometimes actually can save money; instead of becoming contaminated by the chemicals being processed as do ordinary solvents (think of used paint thinner), $scCO_2$ can be re-used repeatedly because it simply boils off for collection once the pressure is reduced. For similar reasons, it is being championed as an alternative to the dangerous solvent perchloroethylene now widely used for professional dry cleaning, for industrial degreasing operations, and for microelectronics fabrication facilities.

Opinions differ on why the delay in making use of SCFs. Some point to the complexity of the equipment, but 4000 pounds per square inch and temperatures ranging up to a few hundred degrees certainly are within the range often found in industrial practice. Other observers nominate maintenance difficulties and costs of the equipment as the culprit. Still others argue that safety is harder to assure when dealing with pressurized systems. No doubt there is some validity in these claims, but given the life cycle costs and environmental-social costs of many petroleum-based solvents, it seems pretty clear that a huge number of chemists in and out of industry have for decades not been paying appropriate attention to the potential advantages of $scCO_2$ and other supercritical fluids. As Kleinman and Vallas put it in chapter two, “deeply entrenched norms and practices…constrain actors in their efforts to remake” their fields.

A university professor working on SCF in the UK suggests that the explanation rests partly with the faddish way new techniques sometimes are approached. There have been recurrent cycles, he says, in attention to SCF potentials. Typically the potential is oversold as enthusiasts propose and try out fancy schemes far beyond the existing state of knowledge; when these fail, interpretations hold that SCF has not worked out, and attention turns to some other hot topic. An obvious alternative would be patient, steady exploration of whatever fundamental questions remain, coupled with modest chemical and other engineering innovations designed to apply relatively simple SCF technology in relatively simple manufacturing and other processes. For example, one entrepreneur is now utilizing SCFs to make building materials out of fly ash from a coal-burning power plant – a low-level application of no interest to most forefront researchers.

Nevertheless, through conferences and professional networks, the idea is spreading of using SCFs for the relatively mundane task of replacing dangerous solvents such as benzene and toluene, of which millions of pounds are used annually. Environmentally conscious chemists and engineers had already been worrying about solvents because of their obvious health and environmental risks – for example, the paint industry has greatly reduced volatile organic compounds in paints, thinners, varnishes, and other coatings, partly by building on the techniques used in latex, water-based paints. The confluence of these other solvent activities with the new push in supercritical fluids stimulated a mini-boom in the late 1990s. A credible, but not peer reviewed, plan emerged at a University of Massachusetts workshop predicting that within two decades it should be possible to replace all solvents and acid-based catalysts that have adverse environmental effects with solids, water-based replacements, or other green alternatives.[28] Among other approaches, the solvent replacers began turning toward dry chemistry – probing the technical feasibility of skipping altogether one of the first and messiest steps in the brown-chemistry formula: that of dissolving the compounds prior to reacting them. No dissolution, no need for solvents.

Another progenitor of green chemistry was Stanford Chemistry Professor Barry Trost, who first proposed the concept of "atom economy" in 1973. Rather than judging a chemical process successful if it produced usable product at a satisfactory cost – the mainstream standard -- Trost argued for elegant efficiency, for using the highest possible percentage of input atoms in the usable output, ideally leaving zero waste. This originally seemed a utopian concept, but an increasing number of bio-catalytic and other chemical processes now are being explored that achieve exactly such an outcome.[29] What Trost contributed, I think, was not a concrete method like supercriticality, nor a goal such as solvent replacement, but a vision that the would-be green chemists could use to construct a counter-narrative to the dominant approach – which now could be labeled as messy, inefficient, inelegant, and otherwise outdated.[30]

A fourth contributing factor was the work of a few renegades who continued to probe alternatives to the use of fossil fuels as chemical feedstocks. These researchers lacked funding or standing to make a real difference in their day, but they kept the flame going by training a few students and by winning at least brief mentions in the field's texts and in chemists' peripheral consciousness. The research took place under two main headings – carbohydrate chemistry (i.e., cellulose and other plant materials) and oleic chemistry (fatty and oily substances, mostly also from plants). A vivid illustration of how this type of research differs from conventional organic chemistry is that it actually is possible to obtain the necessary research materials from an ordinary grocery store! This minority tradition gained a bit of new life during the recurrent energy crises late in the last century, and won a measure of vindication when Cargill Dow opened in 2002 the world’s first commercial-scale plant to make polyaspartic acid for plastics out of corn.

Why didn’t these and other sources for green chemistry come together sooner, and more powerfully? One answer is that the brown chemistry formula was technically just too sweet, economically too attractive, and institutionally too convenient. Fossil feed stocks became plentiful, reliable, and cheap at just about the same time that chemists were discovering lots of ways to combine chlorine molecules with carbon and hydrogen to create chlorinated hydrocarbons such as DDT, PCBs, dieldrin, polyvinyl chloride, and others. These new products had the great virtue of using up the surplus chlorine that industry executives wanted to get rid of, chlorine generated by the chlor-alkali process that produced one of the basic industrial chemicals on which the industry was built.[31] Coinciding, or lagging slightly, “demand” for pesticides and other organic chemical products escalated.

Also slowing the emergence of green chemistry is the market milieu. More than perhaps any other science, chemistry has been captive to industry, although geology comes close. Industrial “needs” determine chemistry curricula to a far greater extent than is true, say, of physics curricula. Likewise, the American Chemical Society has had a closer connection with the chemical industry than biologists have had with medicine, though the rise of biotechnology is changing this. Asked why there has been relatively little change in chemical engineering curricula in the face of environmental pressures, one department chair I interviewed actually dragged out the old cliché, “There just isn’t room in the curriculum.” A further indicator of the backwardness: Whereas about half of PhD-granting chemistry departments in the U.S. still require students to pass a test in a foreign language, none requires an equivalent test in toxicology, according to green chemist John Warner of UMass-Boston.

Moreover, professional licensing tests for chemical engineers showed very little change between 1980 and 2000 in terms of requiring environmental competence as part of being a certified chemical engineer. Professional licensing in the U.S. is conducted under auspices of the American Institute of Chemical Engineers, and rather than drawing in young turks with state-of-the-art knowledge, AIChE relies primarily on retired chemical engineers to devise the tests. There is an irony in this: Credible estimates suggest that greener processes may actually cut in half the development time to produce new polymers, partly by simplifying manufacturing requirements and partly by reducing environmental compliance transactions.[32] Hence, it could be said that industry actually needs university researchers to point the way, but the captive relationship undercuts this leadership potential, a point worth reflecting on in the context of Owen-Smith’s analysis of the “dual hybrid” university in chapter three.

More generally, government officials in the EU, Japan, and the U.S. alike have little concept of how green chemistry might be used to modify traditional approaches to environmental regulation. The top levels at EPA are not very knowledgeable about forefront science, perhaps any science, and the general reputation of the executive office of the president among environmental scientists is pretty low. Several European nations do better on both counts, with Sweden generally regarded as being in the forefront via their Chemical Inspectorate’s planned phase out of the most dangerous chemicals. But this move is timid compared with the bold possibilities foreseen by a handful of green chemistry visionaries who argue that it is technically and economically feasible to eliminate virtually all chlorinated chemicals.[33] Social scientists need not take sides among the technical disputants in order to recognize that except for a brief period in the mid 1990s, there has been little public dispute regarding the possibility of a broad phaseout of brown chemicals.[34] Even major environmental interest groups have hardly any PhD chemists on staff, which may be part of the reason many continue to focus on land preservation, endangered species, and other obviously worthy issues, but fail to call attention to the potential malleability of the chemical universe to attack toxics problems at the source by moving toward a vision of benign by design.

On the other hand, green chemistry is becoming institutionalized within the research community, as indicated by the annual Gordon Conference on Green Chemistry; the OECD has been organizing periodic workshops on Sustainable Chemistry; the International Union for Pure and Applied Chemistry likewise; and meetings of the American Chemical Society and equivalent organizations now include panels on green chemistry. *Chemical and Engineering News* has begun to feature articles on the subject. The so-called “Reinventing Government” initiative of the Clinton-Gore Administration created an annual Green Chemistry award competition starting in 1995, and the National Academy of Engineering in conjunction with the EPA office of research and development in 2005 launched a program for 50 teams of college students who will “research, develop and design sustainable solutions to environmental challenges.”[35] A Green Chemistry Institute within the American Chemical Society has several dozen affiliate organizations throughout the world, and ACS staff and volunteers have undertaken significant efforts to revise chemistry textbooks and pre-collegiate curricula to include green chemistry.[36] The Royal Society of Chemistry has launched the journal *Green Chemistry*. Finally, the U.S. House of Representatives Committee on Science originated HR 3970, the 2004 Green Chemistry Research and Development Act in March 2004, which easily passed in the House despite opposition by the Bush Administration; but the measure died in the Senate.

Government, Business, and Science

What makes one research area so compelling while other areas are ignored? Why the belated push on supercritical fluids and solvent replacement, yet almost no movement on the use of medicinal chemistry principles for industrial chemicals? Why nano-bio, nano computing, and many other facets of nanoscale inquiry, yet very little support for what seems like the most important potential, molecular manufacturing? I do not presently have answers to these questions that are as good as I would like, partly because of the shortage of social science and historical scholarship together with the absence of a perspective on contemporary events that time eventually will lend. Some of the story is pretty hard to miss, however.

The commercial possibilities for nanotechnology seem uppermost in the minds of government officials,. This appears to be a manifestation of “an almost religious belief…in the powers of science-based technology…. (O)nly scientific and technological supremacy over the rest of the world will allow the country to prosper economically.”[37] The 21st Century Act mandates ongoing reporting and priority setting on what needs to be done to keep the U.S. “competitive” in nanotechnology commerce. As a first approximation, I believe that major technoscientific initiatives fostering the interests of political-economic elites are more likely to succeed than those which do not. As Hess puts it in chapter five, understanding “where two research fields…have developed radically different levels of credibility and research funding requires a sociology of knowledge that is attendant to industrial priorities, regulatory policies, and social movement politics” (or the lack thereof). The solicitous attention from elected officials comes about partly because of the privileged position that the business sector enjoys in what are known as market-oriented societies, but that might equally well be termed “elite-interest” societies.

Business executives occupy a role unlike that of any other social interest, in part because they are structurally located to make key economic decisions including creating jobs, choosing industrial plant and equipment, and deciding which new products to develop and market. Many direct and indirect supports, interferences, and other partly reciprocal connections between science and business of course arise during this process. Sometimes referred to incorrectly as the "private sector," business actually performs many tasks that are public in the sense that they matter greatly to almost everyone. Even if no business executive or lobbyist ever interacted in any way with government officials, business would be highly political in the sense of exercising influence over key public choices. However, business of course also is privileged in a second sense, in that executives have unrivaled funds, access, organization, and expertise to deploy in efforts to influence government officials.[38]

Although the connection with business and government in a system of political-economic power is crucial to understanding the new political sociology of science, just as Hess finds the story of cancer research and treatment more complex than the standard interests perspective alone can handle, so it is with nanoscience and green chemistry. Government officials' willingness to splurge on nano is due in part to the fact that the five myths of science analyzed by Dan Sarewitz are pretty much alive and well in the halls of Congress and in government corridors throughout the world. These include "The myth of infinite benefit: More science and more technology will lead to more public good," "The myth of accountability: Peer review, reproducibility of results, and other controls on the quality of scientific research embody the principal ethical responsibilities of the research system," and "The myth of the endless frontier: New knowledge generated at the frontiers of science is autonomous from its moral and practical consequences in society."[39]

There has been considerable analysis of changes in university-industry relations in recent decades, including a number of chapters in this volume, with talk of triple helixes and new forms of intellectual property and so forth.[40] Sufficient for present purposes, however, is an utterly obvious and simple fact underlying the sophisticated analyses: More chemists work with and for industry than for any other social institution, and the same is true, or soon will be true, of nanoscientists and technologists. Both the great successes and the horrible failings of the past century's chemistry can be traced in part to the close relationship between science and business, and the same probably will prove true of nano capacities. A higher percentage of chemistry majors work for industry than is true of any other science major. Many are direct employees whose pay and career literally depend on the continuing good will of their bosses, but even researchers in universities bend curricula to perceived corporate "needs," earn extra money by consulting, and seek grants and contracts from businesses. Moreover, NSF and other government programs explicitly tout the economic payoff.[41]

Thus, the starting point for understanding science as part of a system of power is to acknowledge that those with authority in business and government make use of scientists to the extent they find it convenient, profitable, or otherwise in line with their own aspirations. Sometimes this takes a straightforward route, with "members of a relatively small, like-minded elite…justifying their power over important scientific and technological choices by referring to the need for an efficient response to both commercial and military threats."[42] Getting a jump on foreign competition is surely in the minds of some legislators voting to support nanoscience, and hesitancy on green chemistry has something to do with excess capacity in the world chemical industry, enormous sunk costs in plant and equipment, and declining fortunes of the U.S. chemical industry (due partly to domestic prices for the main feedstock, natural gas, that are higher than most competitors pay in other nations). Conversely, there is no question but that brown chemistry was extremely useful to businesses, and those deploying the chemicals had little motivation to worry about long-term health and ecosystem effects.

Although a full replay of the 20th-century cowboy economy is unlikely given heightened environmental awareness, businesses exploring nanoscale manufacturing or new products utilizing nanoscience are likely to find that near- and middle-term profits may be compatible with longer-term problems for society. For example, diagnosis of ill health made possible by tiny, ingestible sensors may increase medical costs and rates of iatrogenic illness by inducing physicians and patients to intervene where they previously would not, but this need not impact profitability of the company manufacturing the new sensor. If nanoscale surveillance makes privacy even less protected than is now the case, the problem will be borne largely by persons other than executives of the relevant companies. Hence, the emerging technical potentials can be useful to business and government even if in some larger, longer-term sense they cause more problems than they solve (a cost-benefit calculation with results no one can know in advance).

The Privileged Position of Science

That the myths concerning science are widely shared is part of the basis for a privileged position for science that grants forefront researchers considerable autonomy, and that calls on social scientists to produce a nuanced understanding of science and social power. Science is not as directly central to daily life as is business, of course, and scientists lack the monetary inducements deployed by business executives; nevertheless, there are some interesting and important parallels with the privileged position of business. Thus, just as public well being depends on what is called a "healthy" business sector, so has technological civilization come to rely on scientists, engineers, and other technical specialists to conduct inquiries into matters beyond most people's competence, train future generations of technical specialists, and perform functions at the interface between scientific knowledge and technological innovation. As scientists link with business, they obtain certain privileges.

The linkages with business and government obviously magnify the influence of scientists on the social construction of everyday life, but it would be a serious mistake to suppose that the scientists are merely the handmaidens in this relationship. Many technoscientific researchers originate and undertake their inquiry to a far greater extent than that inquiry is foisted upon them: It was not consumers or workers or business executives or government officials who chose not to pursue green chemistry – none of them had an inkling of how molecules are put together. If anyone chose, it was the chemists – although unpacking their "choice" could occupy a good number of historians, sociologists, philosophers, and others, and I doubt whether "choosing" is the best term to describe the sociotechnical processes that led to brown chemistry or any other complex technological trajectory.

The same goes for nanotechnology: "There's plenty of room at the bottom," Eisenhower said in his farewell speech in 1961? No, of course it was Richard Feynman, the Nobel-winning physicist, who first suggested that there might be a future in working at the atomic level with non-radioactive materials.[43] And every other contributor to the discussion likewise has been a trained scientist or engineer, except for public figures touting and voting to fund the new initiatives (which virtually none of them much understand). As mentioned above, mainstream nanotechnology leaders at NSF and elsewhere have worked to downplay the potential for the more radical innovations associated with molecular self-assembly. Thus, a semifinal draft of the

21st Century Nanotechnology Act called for the National Research Council to submit to Congress in 2005 a review of the technical feasibility of molecular self-assembly for the manufacture of materials and devices at the molecular scale, and to assess the need for standards and strategies for ensuring “responsible development” of self-replicating nanoscale devices. However, this was substantially watered down in the final version of the bill, and Christine Peterson of the Foresight Institute blamed the deletion on “entrenched interests." "That's sad, Peterson said; “immense payoffs for medicine, the environment and national security are being delayed by politics."[44] The politics to which she refers is occurring largely within the technoscientific community.

Nobel-prize winner Richard Smalley dismisses both the promises and the problems associated with molecular manufacturing: "My advice is, don't worry about self-replication nanobots. . . It's not real now and will never be in the future."[45] Smalley, developer of carbon nanotubes and a major force in the U.S. National Nanotechnology Initiative, says the necessary chemistry simply will never be available. His argument, presented in a number of highly visible publications including a cover story of *Chemical and Engineering News*, holds that there is no way to place atoms or molecules sufficiently precisely. Disagreeing with him point by point in a series of published letters is Drexler, a dominant force within the Foresight Institute, which aims to help prepare humanity for the nanotechnology era he believes is coming.[46]

Those that count within the nanoscience community tend to side with Smalley in dismissing Drexler’s view. U.S. nanotechnology czar Mihail Roco might have reason to downplay the more radical potentials, for fear of provoking the kind of resistance that agricultural biotechnology has encountered in Europe. Although Congress ultimately defeated a requirement to set aside for ethical, legal, and social issues five percent of the $3.6 billion nanotechnology authorization, the House Science Committee inserted a requirement for public consultation in the 2003 nanotechnology legislation precisely to try to head off a GMO-like fate.[47] An Undersecretary for Technology at the U.S. Commerce Department explicitly noted that rationale at a NSF-sponsored symposium on societal implications of nanotechnology in December, 2003. More generally, government funding and industry interest both depend in part on public quiescence, on treating nano capacities as ordinary, boring science and technology, rather than as an issue similar to GMOs or nuclear power perhaps deserving intense, widespread scrutiny.

However, it is not as clear why so many others are willing to go along in dismissing molecular manufacturing, with even Greenpeace issuing a pretty tame report on nanotechnology as a public issue.[48] ETC Group, the NGO that did a great deal to bring the GMO issue onto public agendas, is calling for a moratorium on certain nanotechnology research and diffusion, but they are more worried about the environmental and health effects of potentially ingestible nanoparticles such as carbon nanotubes.[49] And the ETC proposal so far has not won much of a following. Within the NSF sphere, Roco and his allies as of this writing were managing to keep the controversy over molecular manufacturing entirely off the table in public meetings sponsored by the NNI. Not only presenters but even audience members asking questions at such meetings somehow get the quiet message that retaining one's credibility requires not discussing molecular manufacturing. I have asked participants and other observers how that message is telegraphed, and the answers are not very illuminating. Everyone "just knows" not to talk about it.[50]

As a decision theorist, I have no professional opinion about which of the technoscientists is correct. I do notice that the anti-Drexlerian arguments shift quite a bit over time as if earlier arguments were found wanting. And I notice that Smalley, Whitehead, and Roco utilize assertion and flamboyant language, in a way that reminds me of other realms of politics. When they do mount an argument, metaphors such as "slippery fingers" play a larger role than equations. That may be unavoidable in debating futuristic potentials, one must acknowledge; still, there is a somewhat eerie resonance with many previous arguments about what technical innovation cannot do – from flying across the Atlantic to open heart surgery. Hence, it may be premature to dismiss the possibility of molecular manufacturing, for good and/or ill.

Whoever may be winning in the scientific community's internal battles, if scientists are exerting broader social power in the nanoscience and brown/green chemistry cases, what is the nature of the influence? I do not refer to ordinary interpersonal relations in the laboratory or battles for influence within subfields, of course, but to the world-shaping influence exercised by the development and deployment of new knowledge – or the failure to develop and deploy it.[51]

Influence of this sort does not normally take the form: A has power over B when B does what A chooses. Such a formulation probably is too simple for understanding influence relations in any complex social situation, but is especially questionable when it comes to the "cascading series of unintended consequences" that followed in part from chemists' inquiries into organic chemistry, and that may follow from nanoscientists' current enthusiasms.[52] Social scientists need an approach to scientific influence that is consonant with the bull-in-the-china-shop or sorcerer's-apprentice character of the havoc that science-based practices sometimes wreak. This also must allow room for the nearly magical and extremely useful outcomes sometimes catalyzed by scientific knowledge, as well as for the fact that a high percentage of scientific work reaches and benefits/harms no one at all outside of a few researchers in a subfield.

Suppose we were to suspend certain assumptions about the inevitability and rightness and naturalness of science as now conducted, backing far enough away to look afresh at the whole set-up. Isn't there a sense in which it's a bit weird to have quietly allowed 20th-century chemists and chemical engineers to go along their merry ways synthesizing tens of thousands of new substances that the world had never before experienced, and helping produce and distribute billions of tons of substances that from some points of view can be characterized as poisons or even chemical weapons? From our present vantage point, knowing what we do about the potentials of green chemistry, isn't it somewhat strange that chemists (more than anyone else) chose not to activate these potentials earlier – a lot earlier?

With respect to nanoscience and technology, the dangers awaiting may or may not rival endocrine disruption and environmental cancer and species extinctions and the other effects of synthetic organic chemicals. However, it is pretty difficult to miss the fact that the nanologists are busy creating nontrivial threats, some of which could be unprecedented: As Bill McKibben puts it, looking not just at nanotechnology but also at human biotechnology and related technologies, "a central question facing humanity in this century is whether by the end of it we still will be human."[53] So far, the nanoscientists are about as free of external restraint as were the brown chemists of the previous century. For the new political sociology of science, then, stepping outside the assumption that it is natural for scientists to pursue science makes it evident that something peculiar is going on, not unlike children playing with matches while the grownups are away – except, in this case, it is not clear who the grownups are.

Again, however, where is power in this story? Like a child who is not himself powerful can obtain a parent's gun and shoot up a school, scientists are not powerful in the ordinary sense of the word, yet they collectively have very substantial effects. A conventional way of thinking about the hazards created by technoscientists is in terms of unintended consequences, especially secondary and tertiary consequences. Social observers long have assumed such consequences to be a ubiquitous fact of social life, and it seems clear that complex new technoscientific endeavors are bound to entail outcomes that cannot be entirely foreseen. The dominant perspective acknowledges the predicament, but treats it as just something to be regretted. That approach has plausibility, but it also steps over an interesting and important question: What is the nature of the power relationships around unintended consequences? Who can be construed as making the decisions?

Normally, the implicit answer is: No one; vector outcomes emerge. However, as Winner says, unintended consequences are not not intended.[54] Someone is at least implicitly deciding to go ahead even though going ahead entails unintended consequences -- some of which are likely to be negative, and perhaps quite potent. Whoever is participating in that choice can be said to be exercising authority over others, inasmuch as those ultimately suffering (or enjoying) the unforeseen results would not be doing so without those making the original choice having decided to proceed.

Many scientists and others with influence over unintended consequences would claim to be operating within a legitimate political-economic order, and would claim that they have the consent required to proceed. Under contemporary law, that is correct. In every other way, however, the argument is pretty silly, inasmuch as many of the future victims/beneficiaries are not yet born, live in countries other than the ones catalyzing the R&D, are utterly ignorant of the whole business, are outvoted by those who want relatively unfettered technoscience, have been led to suppose the activities entirely safe, or otherwise cannot meaningfully be said to have given consent. My purpose here is not moral blame or philosophical inquiry; it is merely to point out that enormous authority is being exercised in choosing to proceed with potent new technoscientific capacities given the likelihood of unintended consequences. Political sociologists of science need to come to grips with this exercise of authority, not assume it away as do most technoscientists, their allies, and even their opponents.[55]

A closely related exercise of power is that which goes into shaping agendas and shaping the governing mentalities via which both influentials and non-influentials think about issues.[56] This is one of the most important ways that power manifests, frequently leading to non-decisions rather than manifest controversies. Little noted to date in the literature on this “third face” of power, as Lukes termed it, is the fact that technoscience excels at shaping human thought and the agendas based partly on it.[57] Thus, chlorine chemistry helped set the agenda for environmental problems: PCBs in the Hudson River are polychlorinated biphenols; DDT, dieldrin, and aldrin are chlorinated pesticides; CFCs that deplete the ozone layer are chlorofluorocarbons. Industry actually manufactured the chemicals, of course, and millions purchased them, so chemists did not act alone; but they certainly created the potential that set the agenda.

In doing so, they inadvertently helped teach humanity (including future chemists) that unintended consequences are a normal part of technological innovation, part of what is termed the price of progress. As soon as a new capacity is developed, many people come to consider it unthinkable to “go back” to an earlier state – whether that is to a chemical state prior to organo-chlorines, or to not manipulating matter at the nanoscale. More subtly, in the 20th century, the potentials of brown chemistry and chemical engineering were so technically sweet and so agriculturally useful in “combating pests” that it was unthinkable to require that chemicals be proven safe prior to introducing megatons into the ecosystem. Creating unthinkability of these kinds arguably is the most subtle and most potent form of technoscientific power.

One of the main reasons that technoscientists can do this time after time, while maintaining their privileged position, is that they have considerable legitimacy and credibility in the eyes of most persons. Scientists in films sometimes are socially awkward and preoccupied with matters far from most people’s everyday realities, but with the exception of renegades such as the dinosaur-cloner in “Jurassic Park,” scientists normally are depicted as innocuous or as proceeding within acceptable norms. Except for aberrant situations such as the Tuskegee syphilis experiments, almost no one questions that scientists have a right to pursue the research they do -- even if, on reflection, one might be hard-pressed to explain exactly from whence that “right” emanates. Similarly, although many people experience skepticism or impatience when expert opposes expert in testimony at a trial or other public venue, in the absence of such conflict most of us are disposed to assume that technoscientific experts pretty much know what they are doing within their fields of endeavor.

Restating that seemingly sensible and harmless assumption darkens its implications: university chemical and nanotechnology researchers going about their normal business are not questioned closely by outsiders, and hence are not very accountable for their research or teaching (except, to a degree, to other members of their subfields). This helps insulate them from undue external influence – except perhaps from those awarding grants and contracts– but it also partially insulates them from appropriate external influence. Which verbs to use for describing the influence relationships?: Have the scientists seized authority, or been delegated it? Are they imposing outcomes, or suggesting trajectories? Do they decide, or do they negotiate? My own sense is that many different influence-oriented verbs apply at various times to various facets of technoscientific choices and outcomes, and that the influence relationships are ineffably messy. What can be said with clarity is that some technoscientists have considerable latitude in their actions, that some of the actions interact so as to produce outcomes that sometimes have considerable impact on the world outside of science, and that technological civilization may lack both the discursive and institutional resources for holding the influentials accountable.

Discussion

Although those wielding scientific knowledge clearly exert enormous influence, the nanotechnology and green chemistry cases provide little or no evidence that scientists as individuals or as identifiable groups have the power to defeat other elites when there is manifest conflict. Military, industry, and government elites often give technoscientists quite a bit, of course; when there is overt bending to be done, however, it tends to be the researchers who do it. They want government or industry funding, because they lack the resources to evade or fight new government regulations, because universities cannot operate without business and governmental largesse, or because as employees the scientists and engineers are simply following the boss's orders.

Further reducing any power in the conventional sense that might be imputed to scientists is the fact that to a substantial degree they are creatures of the cultural assumptions of their societies. They think and act the ways they do partly because they are cognitive victims of their cultures: They simply have not gotten much help in revisioning what chemistry could be, nor in recognizing that rapid R&D and scale-up usually prove problematic, nor in thinking through the manifestly undemocratic implications of the privileged position of science.[58] If the mass media focus on conventional problems such as endangered species and chemical spills, rather than on restructuring molecules, scientists and engineers are among those whose mental landscapes become dominated by a focus on symptoms, who become unable to rethink the underlying causalities. If emerging or speculative gee-whiz capacities predominate in stories about technological futures, it is not only the attentive public whose thinking is thereby misshapen; technoscientists' thinking likewise is stunted.

For example, as of this writing, to my knowledge no mass media source or semi-popular science publication has ever pointed to the obvious similarity between nanoscience and green chemistry: both are about rearranging atoms and molecules to supposedly better serve (some) humans' purposes. Although chemists ought to be able to figure that out for themselves, in most respects they are just ordinary people operating according to standard procedures and cognitive schemas. Neither the cadre of chemistry-ignorant journalists nor the rest of technological civilization has given chemists much assistance in breaking out of those molds.

Another indicator of that lack was the failure in 2001 of environmental groups to contact a congressional committee considering tax credits to assist mom and pop dry cleaners in switching over to supercritical carbon dioxide in place perchloroethylene, the dangerous solvent now widely employed. Dow Chemical, in contrast, stimulated an active letter-writing campaign by conventional (i.e., brown) dry cleaners, and the tax stimulus for chemical greening died in committee. The relatively toothless 2004 Green Chemistry R&D Act likewise expired in the Senate after passing the House, partly because it received modest endorsements from mainstream groups but no real push from environmentalists. More generally, even the major environmental NGOs have few chemists on staff, devote their energies primarily to endangered species and end-of-pipeline cleanup, and with the partial exception of groups focusing on clean industrial production are pretty much caught up in opposing various uses of brown chemistry rather than pushing for a green chemical industry.

It may seem a bit weird to say that chemists need to be informed by non-chemists, but it is a fact: As a vice president of Shaw Carpets, a business executive without an advanced degree, expressed the point at a recent congressional hearing: "I am the guy whose job it is to tell the chemists and chemical engineers that they can make carpets using environmentally friendly processes, because they come to the job from universities where they have not learned about it."[59] That kind of insistence has been altogether missing in the contexts in which most chemical R&D personnel have worked for the past century; the equivalent cuing is missing in the contexts now populated by nanologists.

That said, it nevertheless is worth reiterating that both technoscientists' failures to actively pursue green chemistry and their possibly misguided rush toward the nanoscale are occurring without the knowledge or consent of the vast majority of those potentially affected. Some people and organizations are exercising discretion on behalf of, or against, others, and hardly anyone seems troubled by the fact. Again, however, scientists have not gotten much help in noticing that this is true. They are content to proceed without consent partly because it often is in their interests, but also because they have not learned to do otherwise -- the social order has not arranged to teach them. Green chemistry leader Professor Terry Collins of Carnegie Mellon insists on chemistry ethics being central to the curriculum. I doubt whether that is nearly enough, because not only do business-oriented incentive systems give strong motivation for setting ethics aside, but longstanding, elite-dominated traditions more subtly impair just about everyone's capacities for thinking straight about emerging technoscience. One learns to accept that "private" businesses have a right to do whatever will sell profitably, learns to accept scientific research as the equivalent of free speech rather than just another social activity subject to periodic renegotiation, learns to believe that unlimited technological innovation is both inevitable and highly desirable, and learns to assume that unintended consequences are just a regrettable fact of life rather than a task to be mastered. These assumptions or myths align in ways that accede legitimacy and accord capacity to technoscientists and their allies, and they impair technoscientists' thinking and practice along with that of everyone else.[60]

In applying the above insights more specifically to the blocking of green chemistry and the acceleration of nanoscience, we can maintain symmetry by thinking in terms of a combination of technological, economic, and cognitive momentum. Brown chemists and their industrial allies and consumers of chemicals could be foregrounded, but it might be more accurate to de-individuate by saying that green chemistry has been marginalized by brown chemistry. Literally, in the sense that textbooks brimming with brown-chemical formulas make it difficult for green chemical ideas to find a place in the curriculum or laboratory. But also in the more socially complex sense that industry engineers have been trained in brown chemistry, the industry has huge sunk costs in brown chemical plant and equipment, and the assumptions that go along with that momentum themselves obscure the possibility or even the desirability of an alternative. Moreover, government regulatory procedures and laws are set up negatively -- to limit the damage of brown chemicals -- instead of positively and actively seeking the reconstruction of chemicals to be benign by design. Similar social processes are likely to interfere with sensible governance of nanoscience's emerging potentials.

The blending of structural position, quiescent public, and habits of thought that I have woven together fits with the general spirit of the more complex interpretations of power offered by third-wave feminists and by other recent observers of social life.[61] It fits as well with the multidimensional stories told by other contributors to this volume, especially that of Hess in chapter five. The nuances are unfortunate, in a way, robbing us of a simple, black-and-white story that is easy to transport cognitively. A simplified but not simplistic condensed story of brown/green chemistry and nanotechnology might run along these lines: Some technologists glimpse new capacities and begin to develop them; political-economic elites come to believe that these may serve their purposes, and make additional funding available; other technoscientists move into the emerging fields, partly in order to obtain the new funds; the relevant scientific communities proceed to develop new capacities that then are scaled up by industry and government far too fast to allow the relatively slow learning from experience that humans and their organizations know how to do. There is no way that journalists, interest groups, government regulators, and the public can learn enough fast enough about the new capacities to institute precisely targeted protective measures in time. And, in fact, many of them actually have no disposition to “interfere.”

Some STS scholars have attempted to depict the dicey relationship in terms of what they call “principal-agent theory.”[62] The principals (e.g., government officials) who provide funds lack the requisite knowledge and other resources to prevent opportunism and shirking by the scientist-agents, so special controls need to be established, such as intermediary research institutions and research programs that can serve boundary functions in intermediating between researchers and those paying the bills.[63] Whether the putative “principals” are in any meaningful sense in control of the scientific enterprise is called into question by the nanoscience and green chemistry cases, among others. [64] More importantly, I doubt that government officials normally should be seen as the principals, inasmuch as they are in another sense supposedly agents of the general public, in a relationship that is deeply troubled. Government officials also have a proven willingness to invest heavily in dubious technoscientific projects coupled with an inability to catalyze meritorious R&D such as green chemistry.

Whether or not anything comes of the principal-agent approach, the green chemistry and nanotechnology cases offer an opportunity to reflect regarding which decisions appropriately can be left to scientists, which to industry and markets, and which really deserve broader scrutiny and deliberation by media, public interest groups, independent scholars, government officials, and the public. How can scrutiny come early enough, how can it be sufficiently informed and thoughtful, and by what institutional mechanisms? Considering how profoundly scientific understanding, and lack of it, has affected everyday life in the case of synthetic organic chemistry, and probably will do so in the case of nanoscience, it seems to me that social thinkers may need to think harder about the "constitution" of technological civilization. For scientific knowledge and technical know-how are not mere tools; they actually help constitute and reconstitute social structures and behaviors.[65] Because decisions about technoscience have transformed everyday life at least as profoundly as what governments do, the new political sociology of science perhaps ought to avoid emphasizing nation-state decision making, as some contributors to this volume appear to be doing. Ought we not also – and perhaps more importantly -- be on the lookout for authority relations embedded <u>in</u> the R&D system, innovations that lead to fundamental changes in the ways people spend their time, money, and attention. As Winner puts it, technology actually is a form of legislation, inasmuch as "Innovations are similar to legislative acts or political foundings that establish a framework for public order that will endure over many generations."[66]

In "deciding" that our built and natural environment would be shaped by plastics and other chemical products, governments were involved, certainly, but chemists and chemical engineers in conjunction with business executives arguably were the primary "policy makers."[67] Decision making, or non-decision making, of that sort now is shaping the future of nanofabrication and other emerging nanoscience. If experts are to participate more helpfully in the future in nongovernmental (as well as governmental) policy making, nontrivial revisions in the social relations of expertise almost certainly would be required.[68]

At present, scientists work according to agendas that are at least partly illegitimate -- shaped without sufficiently broad negotiation, oriented substantially toward purposes many people would find indefensible if they understood them, and shaped without sufficient attention to the requisites for acting prudently in the face of high uncertainty. It is impossible to say how much of the power rests with scientists, how much with political-economic elites, and how much with systemic forces (if such actually can be separated out from those in the powerful roles), because the forces, vectors, and sectors influence one another in ways too complex to parse. What we can say with some assurance, as David Dickson expressed the point two decades ago, is that science is “a powerful tool that can help us understand the natural universe in potentially useful ways, but at the same time carries the seeds of human exploitation. How to tap the one without falling victim to the other is the key challenge….(A) properly democratic science policy will be achieved only by a political program that directly challenges the current distribution of wealth and power.”[69]

It seems to me that the brown/green chemistry and nanoscience cases offer opportunities to reinvigorate older, interest-based understandings of science and power by integration with the more recent constructivist tradition. A new, reconstructivist understanding potentially awaits – one nuanced enough to appreciate micro-local realities within scientific laboratories and fields, and yet one that aims to reduce elite appropriation of knowledge and to direct technical capacities for more justifiable public purposes.[70]

Endnotes

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46. The Drexler-Smalley exchange is published as “Point-Counterpoint: Nanotechnology: Drexler and Smalley Make the Case for and Against ‘Molecular Assemblers,” Chemical and Engineering News 81 No. 48 (December 1, 2003): 37-42.

47. 21st Century Nanotechnology Research and Development Act, Public Law 108-153, December 3, 2003. For commentary on the law’s passage, see Small Times, “Signed, Sealed, Delivered.

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48. Alexander Huw Arnall, Future Technologies, Today's Choices: Nanotechnology, Artificial Intelligence and Robotics; A Technical, Political and Institutional Map of Emerging Technologies (London: Greenpeace Environmental Trust, July 2003).

49. ETC Group, "Size Matters! The Case for a Global Moratorium" (April 2003), www.etcgroup.org; ETC Group, "Nano's Troubled Waters: Latest Toxic Warning Shows Nanoparticles Cause Brain Damage in Aquatic Species and Highlights Need for a Moratorium on the Release of New Nanomaterials" (April 1, 2004), www.etcgroup.org.

50. For further discussion, see E. J. Woodhouse, "Special Issue: Social Aspects of Nanotechnology," IEEE Technology and Society Magazine 23 (Winter 2004).

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60. On impairment generally, see Charles E. Lindblom, Inquiry and Change: The Troubled Attempt to Understand and Shape Society (New Haven, CT: Yale University Press, 1990). For analysis of myths around technoscience in particular, see Sarewitz, Frontiers of Illusion .

61. See, for example, Fraser, Justice Interruptus, and Campbell, Using Women.

62. This is one version of the much-maligned but also widely heralded rational choice approach. An overview of the principal-agent approach in the context of social choice more generally is James S. Coleman, Foundations of Social Theory (Cambridge, MA: Harvard University Press, 1990).

63. David H. Guston, "Principal-Agent Theory and the Structure of Science Policy," Science and Public Policy 23 (August 1996): 229-240.

64. For a skeptical view of principal-agent theory based on analysis of several European research programs, see Elizabeth Shove, "Principals, Agents and Research Programmes," Science and Public Policy 30 (October 2003): 371-381.

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65. Sclove, Democracy and Technology.

66. Langdon Winner, The Whale and the Reactor: The Search for Limits in an Age of High Technology (Chicago: University of Chicago Press, 1986), 29.

67. Frank N. Laird, “Technocracy Revisited: Knowledge, Power, and the Crisis of Energy Decision Making,” Industrial Crisis Quarterly 4 (1990): 49-61; Frank N. Laird, “Participatory Analysis, Democracy, and Technological Decision Making,” Science, Technology, & Human Values 18 (1993): 341-361.

68. Dean Nieusma, Social Relations of Expertise: The Case of the Sri Lankan Renewable Energy Sector, PhD dissertation, Rensselaer Polytechnic Institute, Department of Science & Technology Studies, 2004.

69. Dickson, New Politics of Science, 336.

70. On reconstructivism, see Woodhouse et al., “Science Studies and Activism,” and E. J. Woodhouse, “Taking Constructivism Even More Seriously: Reconstructivism,” *Social Epistemology* 14 (2005 forthcoming).

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