Research **Frontiers**

FOR THE CHEMICAL INDUSTRY

report on

The Second Annual SCI–CHF Innovation Day Warren G. Schlinger Symposium

7 SEPTEMBER 2005

CHEMICAL HERITAGE FOUNDATION

Chemical Heritage Foundation
Philadelphia, Pennsylvania

Printed in the United States of America

For information about CHF and its publications contact
Chemical Heritage Foundation
315 Chestnut Street
Philadelphia, PA 19106-2702, USA
(215) 925-2222
(215) 925-1954 (fax)
www.chemheritage.org

Cover design by Snyder Creative

Contents

Acknowledgments

The authors are grateful to speakers and participants at the second annual Innovation Day for identifying and exploring salient topics on the chemical research frontier. Sections of this report were initially drafted by participants in each of the breakout sessions; we especially wish to thank the following for their involvement: Ted Everson (Feedstocks of the Future and Nanomaterials), Christophe Lécuyer (Electronic Chemicals), Parry Norling (Feedstocks of the Future and Innovating for a Geographically Shifting Value Chain), Jody Roberts and Susan Saltzman (Environmental Chemistry and Chemistry of Energy Sources), and Jack Trumpbour (Innovating for a Geographically Shifting Value Chain).

Innovation Day 2005 and this report were made possible by the generous financial support of the Warren and Katharine Schlinger Foundation and the following institutions:

Air Products and Chemicals
Arch Chemicals
BASF Corporation
Celanese Chemicals
The Dow Chemical Company
Eastman Chemical
E.I. du Pont de Nemours and Company
Merck Research Laboratories
National Starch and Chemical Company
NOVA Chemicals
Rohm and Haas Company
Shell Chemicals
Sunoco

Finally, we are very grateful to the CHF events staff and publications team for their work to host a successful event and design, edit, and print invitations and reports.

Innovation Frontiers in Industrial Chemistry

A report on the Second Annual CHF–SCI Innovation Day 7 September 2005

SUMMARY

Squeezed on all sides—including from raw material costs (which are at unprecedented highs), narrowing access to feedstocks, and growing competition in commodity markets—chemical firms must create new high-value materials and services to survive and profit. This report summarizes the second annual CHF–SCI Innovation Day and suggests solutions for current challenges based on this annual forum in which scientists and technology managers gather to explore frontier areas for the chemical industry. The industry's future, we argue, lies in a strategic "wager" on disruptive technologies, balanced by incremental steps to develop new feedstocks and manufacturing processes that yield novel materials with less environmental impact.

INTRODUCTION

The chemical industry has rarely been in such a position of strength while facing such obdurate pressures. Between its founding in the late nineteenth century and the present, oracular pronouncements about what lies ahead for the chemical industry, including where companies should invest, what they should research, and who they should hire, have seldom had to accommodate such mixed auguries. Profits for 2004 and 2005 were very strong, signaling a sustained departure from the downturn of the late 1990s and early 2000s.[1] Yet predictions anchored on that strong economic base quickly collide with a raft of obstacles over the medium- and long-term horizon. Just as chemical companies pioneered the industrial research lab and other features of the modern corporation, they are now on the leading edge of the "flattening" of the world.[2] The rapid growth of economies in Asia means

---

[1] Marc S. Reisch and Alexander H. Tullo, "2005 Year in Review," *Chemical and Engineering News* 83:51 (2005), 24–32; Marc S. Reisch and Alexander H. Tullo, "2004 Year in Review," *Chemical and Engineering News* 82:51 (2004), 26–33.

[2] Thomas L. Friedman, *The World Is Flat: A Brief History of the Twenty-First Century* (New York: Farrar, Straus and Giroux, 2005), 339–367.

that chemical companies from China, India, and elsewhere (including well-established firms with extensive international networks) increasingly will compete on a globally even footing.[3] All companies must adjust to a much wider and more interconnected distribution of customers, raw materials, and even sources of innovation than ever before. Moreover, with globalized competition comes soaring demand for increasingly scarce raw materials. The strong profits of 2004 and 2005 must be viewed cautiously, given that significant increases in the price of feedstocks, especially natural gas, over that period suggest reduced margins for the future.

The past two years have also seen a series of hurricanes, earthquakes, and tsunamis that delivered first- and second-order shocks to the chemical industry. In the near term these disasters—particularly Hurricane Katrina—threatened the lives and livelihoods of firms' employees and stressed the United States' already overstretched chemical infrastructure. In the longer term, disasters will focus public and regulatory attention on the complex relationship among climate, environment, and chemical infrastructure. As several Innovation Day speakers pointed out, the industry must visibly contribute to solving, rather than exacerbating, problems of environmental degradation, climate change, and disaster relief. Whereas in the past successful new products were measured solely by market impact and new processes by reduced dollar cost and improved yield, innovation today must meet a bottom line combining economic, health, and social benefits. While these new performance metrics are often seen as a burden, they may, in fact, introduce new perspectives crucial to innovation. Professionals traditionally marginalized in chemical industry research, such as chemists in environmental and toxicology laboratories or process engineers dealing with waste streams, can now bring their expertise into the innovation process at an earlier, more effective stage.

In addition, several important predictive mechanisms for the chemical industry and its most important customers are nearing crucial turning points. In microelectronics, for instance, the *International Technology Roadmap for Semiconductors* has recently concluded that traditional semiconductor fabrication techniques (optical lithography of silicon) will no longer suffice if Moore's law is to extend beyond 2020.[4] Chemists will be key to manufacturing the new materials—carbon nanotubes, molecular transistors, and others—that will have to supplement silicon to maintain the exponential increases in processing speed, storage bit and transistor density, and number of transistors per dollar that the electronics industry has sustained for the past forty years. Similarly, concerns over the available oil supply for energy generation, transportation, and chemical manufacturing continue to intensify. Some even argue that the point of maximum oil production—Hubbert's peak—has recently been passed for the Middle East, as it was for the United States some thirty years ago.[5] New chemistries will be required both to solve the problems of alternative energy sources (fuel

[3] Patricia L. Short, "Global Top 50," *Chemical and Engineering News* 84:30 (2006), 13–16.
[4] John Markoff, "Chip Industry Sets a Plan for Life after Silicon," *New York Times*, sec. C, 29 Dec. 2005.
[5] Kenneth S. Deffeyes, *Beyond Oil: The View from Hubbert's Peak* (New York: Hill and Wang, 2005), 35–51; David Goodstein, *Out of Gas: The End of the Age of Oil* (New York: Norton, 2005), 223–240.

cells, wind turbines, solar, nuclear, or others) and to address the challenges of new chemical feedstocks obtained from bioremediation, biomass, or other sources.

The Pascalian Challenge

This combination of current profits and looming challenges offers a rare opportunity for chemical firms to define and implement new long-range plans. Specifically, we argue firms should make a "Pascalian wager" on long-term, potentially disruptive innovations.[6] Current business models are working well enough *for now* that companies can fund research into alternative materials, technologies, and processes that will be indispensable in the next fifteen to twenty years. Yet inventing and bringing to market those new materials will necessitate finding a new set of business models. In nanomaterials and specialty electronic chemicals, for instance, it is becoming obvious that firms must think in terms of inventing, manufacturing, and selling cubic centimeters, not tank cars, of product. Similar drastic rethinking of pricing and production will soon be necessary across many markets.

The challenge, then is to support enterprising researchers and managers who will explore the alternative technologies and materials needed down the road and also to encourage (and trust) those people to recognize when the current business models no longer work and when some alternative models must be chosen over others. Put differently, in an era when long-held rules of thumb about markets, raw materials, and manufacturing are reaching the end of their usefulness, innovators must be rewarded both for championing successful alternatives and for honestly assessing projects. Firms must terminate even seemingly successful initiatives if they do not promise to help the company cope with looming challenges. This approach will necessitate a change of culture, organization, and incentives in corporate chemical research. The industry must cultivate researchers and managers who are passionate but critical about long-range visions, and they must reorganize to give responsibilities to their most pragmatic dreamers.

Yet even while such long-range visions are necessary, they also present countervailing risks. Best known is the difficulty of matching high-level long-range plans to everyday work in the lab, at the plant, and with customers. Knowing what a company would like to be selling twenty years from now offers little information about what its employees should be doing on a day-to-day basis. Two related but increasingly important problems emerge from this difficulty.

First, because long-range forecasts are necessarily abstracted from the quotidian, concrete details of research and development, they can be too easy to generate and too rosy in outlook. There is no empirical check to prevent such visions from becoming grandiose. As a

---

[6] In his *Pensées* the seventeenth-century French polymath Blaise Pascal made a probabilistic argument for belief in God: if there were no deity, belief in such a being would still cost very little; if there were a deity, lack of belief would bring an infinite cost. The adjective *Pascalian* is now applied to any situation in which a low-cost investment has some (even if small) likelihood of return, but there is a nontrivial probability of an infinite cost to making no investment.

result futuristic schemes can feed hyperbolic expectations—hype—surrounding a new technology. As unchecked visionaries produce grander and grander claims, they gather more and more adherents with less and less practical output. At some point the bubble bursts. Because of such bubbles, investors, firms, and the general public have become skeptical of even well-planned visions. Partly this is a reaction to financial losses following the collapse of the telecommunications and dot.com booms in 2001 and the discovery of illegally over-hyped accounting at such firms as Enron. Such new sectors as nanomaterials are already learning the lessons of these collapses through a conscious attempt to roll back grandiose visions and prevent the emergence of a nano bubble.

Second, the public is now intimately familiar with what is usually left out of long-range visions, that is, the human health risks and environmental degradation that can affect individuals and communities for decades after the introduction of new technologies. Publics that were promised and came to demand cheap, abundant, and risk-free energy from nuclear power and oil; appealing and perfect foods through the use of pesticides and herbicides; and ever-cheaper and seemingly disposable electronics are now aware that those promises, when realized, can bring disruption as well as benefit. As a consequence the public and representatives from nongovernmental organizations increasingly assume all long-range visions contain unarticulated risks, even when an industry honestly believes no such risks exist.[7]

The good news on this front is that honest, innovative long-range planning may *increase* the chemical industry's credibility. Successful multidecade planning must take into account the benefits *and* disadvantages of new materials and technologies, must incorporate mechanisms for addressing public concerns, must not assume government or local communities will be willing to bear environmental or product-disposal costs, and must be cognizant of such looming obstacles to economic growth as climate change, water shortages in industrializing countries, diminishing easily extracted oil supplies, and a possible deceleration of Moore's law. In other words, the new approaches urgently required by the chemical industry need to be sustainable in a way that will help the industry overcome all challenges, rather than addressing one at the expense of others. A long-range vision that articulates and enacts a sustainable agenda will be less likely to meet public resistance (and more likely to recruit young talent) than one that makes large but dubious promises.

In the following analysis of six specific innovation areas we outline two general recommendations for matching long-term vision to current practice. First, the chemical industry needs to look to approaches that are currently marginal to its enterprise. For instance, we describe several ways that green chemistry can be brought in to make firms' practices more sustainable and marketable. Second, we highlight the current importance of

---

[7] Charles Perrow, *Normal Accidents: Living with High-Risk Technologies* (New York: Basic Books, 1984), 324–328; John D. Graham and John Wiener, "Confronting Risk Technologies," in *Risk versus Risk: Tradeoffs in Protecting Health and the Environment*, ed. J. D. Graham and J. D. Wiener (Cambridge, MA: Harvard University Press, 1995), 1–41.

what sociologists call "Pascalian funding."[8] Such funding is predicated on the logic of Pascal's wager: a small investment in a risky idea may bring some return, whereas no investment could result in near-infinite costs down the road. Thus, whether the bet succeeds or not, it makes sense to place it. Pascalian wagers have long been a feature of federal science funding, where smaller general-science agencies like the National Science Foundation (NSF) often have the will but not the capacity to fund such radical, long-range research. In contrast, mission-oriented agencies, including NASA, the Office of Naval Research, and the Defense Advanced Research Projects Agency, are committed almost exclusively to short-term, incremental progress. Yet their funding capacity is so great that they can "wager" on radical research with even very small percentages of their budgets, sometimes yielding large benefits.[9]

Analysis of the innovation areas described in greater depth on the pages that follow leads us to recommend that the chemical industry take advantage of current profits and enact its own regime of Pascalian funding. Clearly, research toward incremental short-term innovations must constitute the bulk of industry R&D spending. Yet the costs today to fund explorations of more radical approaches are relatively modest. As time passes, both the costs of investing and *not* investing in alternative materials and technologies will skyrocket. We also propose a paradoxical corollary: those firms that are most likely to see their markets and expertise superseded or undermined by new technologies must be the firms that fund and enable those new technologies. To take an especially salient current example, oil companies understand national energy needs and infrastructure much better than other firms. For now the bulk of their research will necessarily continue to focus on incremental improvements in finding and extracting oil and natural gas. But a small investment in alternative fuels and nonpetroleum energy sources today will give long-sighted companies a clear competitive advantage in terms of in-house knowledge, expertise, and experience when those alternatives become a reality. Investing in alternatives hastens oil companies' need to change their business model, but not investing now will make change impossible just when it is most urgently needed. The same is true for chemical firms operating in markets ranging from thin films for food packaging to advanced photoresists for semiconductor etching.

FRONTIER AREAS FOR INDUSTRIAL CHEMISTRY

The global economy is in transition, and many traditional materials and technologies show signs of giving way to new innovations. How will the current chemical industry, or some variant of it, devise innovations for the long term? As part of an ongoing search for answers to this question, the second annual Warren G. Schlinger Symposium in September 2005 explored six key areas for the industry: feedstocks of the future, electronic chemicals,

---

[8] For a deeper exploration of Pascalian funding, see Harry M. Collins, *Gravity's Shadow: The Search for Gravitational Waves* (Chicago: University of Chicago Press, 2004), 338–344.

[9] Some of the more far-out instances include Department of Defense funding for antigravity or parapsychology research. Some of the most notable Pascalian projects have come from industry—e.g., the discovery of high-temperature superconductors at IBM in 1986 and the invention of Unix at Bell Labs in 1969.

nanomaterials, environmental chemistry, chemistry of energy sources, and innovating for a geographically shifting value chain.

Feedstocks of the Future

Because feedstocks are the starting point for nearly all industrial chemistry, issues concerning their supply and cost encapsulate many of the long-range challenges facing the industry. While chemical firms were able to raise prices of many products in recent years, current profitability is being threatened by rises in the price of oil and natural gas, today's staple feedstocks. Some chemical firms are using this current profitability to fund research into alternative feedstocks, a model of innovation that offers important lessons across the industry.

In large part the history of the chemical industry is the history of successive feedstock regimes—from coal in the nineteenth century, to brine in the early twentieth century, to oil and natural gas at midcentury. The current era shows signs of ending, however. Rises in the price of oil and gas, combined with political volatility in most of the world's oil-producing nations, are not unique to the present. However, the recent spike is tied to new factors, including the rapid rise in demand from India and China, those countries' willingness to become more involved in the politics of oil production, and the increasing credibility of warnings about a finite oil supply. At the same time research across a variety of fields is making such alternative feedstocks as methane, clean coal, and converted biomass look more viable. At present the benefits and drawbacks of the alternatives are poorly characterized, and it is next to impossible to predict with accuracy which will emerge as a new standard for the industry. Analysts—including several speakers at Innovation Day—argue that the chemical industry should develop competencies to rely on a variety of feedstock materials geared to specific applications and produced around the world.

One way to make this leap from natural gas to alternatives would be to develop pathways from several different feedstocks to a single intermediary and then to develop new chemistries from that intermediary to industrial materials. One such proposed intermediary is syngas. A mixture of hydrogen and carbon monoxide, syngas could be used to produce hydrogen, methanol, and synthetic crude oil. These products would then become the ingredients for a wide variety of industrial pathways, including acetic acid, formaldehyde, dimethyl ether, ammonia, n-paraffins, fuels, and lubricants.

Natural gas reacted with steam offers an immediately available source for syngas. Development of natural gas feedstocks could be extraordinarily valuable in the globalization of chemical manufacturing and marketing (see also the section "Innovating for a Geographically Shifting Value Chain"). Another important source is bioremediation of coal, methane hydrate, and other minerals. Bioremediation, the use of microorganisms to convert materials from one form to another, has been used since ancient times for such foodstuffs as bread, beer, and cheese. Since the 1980s researchers at the U.S. Geological Survey and elsewhere have studied and advanced bioremediation of hazardous materials as a way to contain chemical spills, transform toxins into harmless substances, and purify drinking water. More recently researchers have begun examining ways to engineer microorganisms that transform coal or methane hydrate (found abundantly along the continental shelf) into methane. Feedstocks could be the "third wave" of biotechnology, following earlier medical and agricultural applications.

Unfortunately bioremediation for feedstocks may be just as vulnerable to public outcry as the first two waves of biotechnology. Releasing genetically engineered microbes into the environment in order to create the raw materials of industrial chemistry combines sensitive issues (environmental release, industrialization, and development at the expense of conservation) in ways that will stir protest. Moreover these long-standing issues may be most sensitive at the sites most likely to see implementation of bioremediation. For example, current proposals include using bioremediation to draw methane from abandoned mines where coal is too dispersed to unearth but is accessible to bacteria. Towns that have seen coal mines come and go may be too well-acquainted with the toxic mine tailings and economic dislocations left behind by past energy demands to accept corporate assurances that bioremediation is safe. The chemical industry must be particularly mindful of the lessons in risk assessment learned from past feedstocks when developing new ones.

Finally, it is unclear who can and should take the lead in this research: biotechnology, oceanography, coal mining, or other fields. Chemical firms have the opportunity to use this uncertainty to their advantage; only they understand the complex chemical pathways and industrial engineering necessary to make alternatives to oil viable. Moreover, as we argued in the 2005 *Research Frontiers for the Chemical Industry* report, if the chemical industry does not take the lead, other industries will, with potentially crippling results when these alternative feedstocks become indispensable.[10] The companies currently benefiting from high oil prices are the ones that must invest in Pascalian wagers to explore alternatives, even if over the medium term those alternatives are riskier than the status quo. Effective innovation will require choosing the best mix of alternatives rather than dependence on any one and rewarding scientists and technology managers who can move from theoretical and laboratory-scale research to the industrial scales necessitated by global markets.

Electronic Chemicals

If changes in feedstocks drive the chemical industry as *inputs,* electronic chemicals drive it as an extraordinarily profitable line of *outputs*. Currently the semiconductor industry is the "largest value-added sector in the U.S. economy" (and has been for some time).[11] Chemical firms make this possible by supplying the photoresists, acids, ion sources, and gases that

---

[10] Arthur Daemmrich and Cyrus Mody, *Research Frontiers for the Chemical Industry: Report on the First Annual SCI–CHF Innovation Day Warren G. Schlinger Symposium* (Philadelphia: Chemical Heritage Foundation, 2005), 6–8. The report can be downloaded at http://www.chemheritage.org/pubs/innov-frontiers.pdf.

[11] Erich Bloch and Ralph Cavin, *The Economy, Federal Research, and the Semiconductor Industry* (Cupertino, CA: Semiconductor Industry Association, 2000), 1.

allow circuits to be built on silicon wafers. As the electronics industry changes, chemicals firms will have to change as well, preferably by pushing innovation rather than reacting to it.

As with feedstocks, the challenge facing electronics is that dependence on a single material—here silicon rather than oil—is becoming less and less viable. Indeed, in some ways the silicon used in integrated circuits is no longer "silicon"; much more of the periodic table goes into a transistor today than even five years ago. High-volume testing procedures from the chemical industry have found their way into microelectronics as integrated circuit (IC) manufacturers try to discover exactly what delicate mix of exotic dopants will most enhance transistor performance. Yet these dopants can only take silicon so far. The 2005 *International Technology Roadmap for Semiconductors* mandates that supplements or alternatives to traditional silicon complementary metal oxide semiconductor (CMOS) transistors should be a routine part of IC manufacturing by 2019.[12]

Which alternatives will prevail is still an open question, however. A multitude of nanotechnology start-ups (most of which are spin-offs from academic research) has emerged in the past five years, each backing a different revolutionary approach to microelectronics. Larger companies with experience in manufacturing ICs have so far avoided picking any one approach, with some, such as IBM, leading the way in multiple directions at once, including spintronics, carbon nanotube transistors, and molecular electronics.

The evolving realities of the microelectronics industry will necessitate even greater collaboration between large and small firms. Even as products get cheaper (for example, in 2004 more transistors were sold worldwide, at lower unit cost, than grains of rice), the initial investment in their manufacture is becoming much larger.[13] The cost of a new chip fabrication facility is now approaching $3 billion. As a consequence, bringing new ideas to the manufacturing stage is becoming increasingly difficult. Small start-ups with the nimbleness to explore new alternatives quickly may be better equipped to secure intellectual property than large firms, yet that intellectual property is useless unless it is connected to the fabrication facilities needed to turn it into a product. Large firms must learn to cultivate partnerships with smaller ones. Such partnerships can, of course, be fraught with challenges in matching corporate cultures and scaling research and production, but with honesty about goals and assets on both sides, they may succeed.

One way to ameliorate the skyrocketing costs of fabrication would be to accelerate research in closely related but less capital-intensive product areas. One small sign of this, even among mainstream microelectronics companies, is the growing importance of research into and sales of new display technologies. Consumers no longer simply want faster electronics or more memory storage; as the iPod phenomenon has shown, they want a new *experience* of electronics, including displays that they can take anywhere, see in any light, and interact with

---

[12] Op. cit. note 4.

[13] Darrell Dunn, "PC for the Masses," *Information Week,* 29 May 2006, 47; Terril Yue Jones, "A Law of Continuing Returns," *Los Angeles Times*, sec. C, 17 April 2005.

in new ways. Already the most innovative display manufacturers are drawing upon novel chemistry, including field-emitting carbon nanotubes, to meet this demand. Such trial runs with carbon nanotubes may position firms like Samsung well for the possible day when nanotubes are also integral components of microprocessors.

Even more radical departures are in the offing. One call in the industry from such companies as Bell Labs is to move "from macro to micro and back." The miniaturizing trend of the past four decades has ignored the potential of technologies that are "electronic" but not "micro." Possibly the most important of these incorporate conducting polymer chemistry. It is now possible to print working electronic circuits onto ordinary overhead transparencies using an ordinary office printer, albeit with rather advanced "toner." In the future most conducting polymer circuits will probably not be manufactured at consumers' desks, although the approach suggests intriguing possibilities for how and where electronics are made. Even more intriguing are the possibilities for cheaply made, disposable electronics—small though not necessarily micro circuits made from conducting polymers and sewn into clothes or glued onto packages.

With their understanding of polymers and disposable consumer goods, chemical firms are even better placed to assist with this technology than with traditional semiconductor microelectronics. Selling their knowledge to both intermediate and end users, however, will be problematic. The chemical industry has a vast knowledge of properties of materials, yet that knowledge is useless if it is not made available to those who need it and in a way in which the chemical industry can earn ongoing returns. If makers of disposable radio-frequency tagging circuits do not know about the electronic inks or substrates they need when they begin their design process, their plans are almost sure to falter. The chemical industry, now more than ever, needs to devise new education and communication mechanisms that will allow information to flow out of their firms and into the hands of the customers who need it.

Nanomaterials

Feedstocks and electronic chemicals highlight the two fundamentals of Pascalian funding. Dependence on oil yields profits now, some percentage of which must go to finding alternatives to oil. Risky as it might seem, the companies best placed to look for such alternatives are those with the biggest stake in oil. Similarly, silicon is central to our economy now, yet firms must look to a future where silicon is no longer king. The companies best placed to push silicon off its throne are those that benefit most from its reign. Those most dependent on a dominant technology must be the ones to introduce its successor.

Yet we know innovation rarely works this way. Innovation often sweeps through an industry in the form of new start-up firms that force out adherents of an old technology and push forward new methods, materials, and applications. Large established firms that have pioneered one technology often find it difficult to innovate for a new framework. Worse yet, some crucial innovations do arise at large established firms but are only commercialized after they have migrated to smaller companies riding the next technological wave. Pascalian funding achieves nothing if the companies that make the research investment fail to capitalize on the innovations that investment creates.

Pascalian funding must be accompanied by good communication within a firm and good collaboration among competing companies. Few sectors exemplify this point more than nanomaterials. Because of its history and funding structure, nanotechnology is a microcosm of the fundamental problems facing the chemical industry as it plans for the long term: how do established firms know when to extricate themselves from a seemingly successful technology? How do they know when seemingly feasible alternatives are plagued by hype and overblown expectations? How do firms team up to make Pascalian funding more viable? And how do they "educate" each other about their products to make transformative connections possible?

Thus far the chemical industry has not known quite what to make of nanotechnology. Partly this is because chemistry has always been a nano science (molecules are necessarily nanometer scale), and hence the industry has a long history of manufacturing and marketing such nanoscale additives as carbon black. The question now is how and when to market products that explicitly bear the nano label—something that is already happening in the consumer goods sector with nano pants, golf balls, tennis balls, and sunscreen.

Despite this long history, in many ways nanotechnology is the first boom science of the twenty-first century. The growth of institutions, particularly federal and academic, around nanotechnology in the past five years has been dramatic. The growth of markets and profitable companies has been much slower, since many venture capitalists, established firms, and investors are leery of a nano bubble. Thus a mature strategy for nanomaterials could offer many lessons for how the industry can handle successive booms and potential bubbles and how to sort pragmatic vision from damaging hype.

If there is anything new about nanomaterials, it is that they allow chemists to envision materials as a complex of both molecular and supramolecular entities tailored for their chemical, physical, and mechanical properties. Chemists can pick from a menu of nanoflakes, -rods, -platelets, -shells, -cages, -sieves, and so on to engineer materials with novel, carefully controlled properties. Moreover, these nanocomponents can be employed in a variety of ways, ranging from applications in which nanomaterials are passive and dispersed in a bulk material to applications in which nanomaterials are "active" and arranged in an ordered pattern. For example, uses for carbon nanotubes span a spectrum from passive additives for making a stronger, more flexible tennis racket to precisely positioned active components laid down across electrodes to form a faster, more efficient transistor.

At the active, ordered end of that spectrum, nanotechnology could yield truly life-changing innovations: "smart" building materials, quantum computing, and interfaces between nerve cells and microelectronics. For now, most explicitly "nano" applications involve passive dispersions of simpler nanomaterials. In the short to medium term, nanomaterials will be most important in enhancing or upgrading pre-existing bulk materials, such as additives to make rubber bouncier, dyes more stain resistant, or zinc oxide sunscreen invisible. Few "killer apps" for which nanomaterials are the crucial ingredient will likely emerge over this period. However, if such disruptive applications do emerge, they will likely depend on materials and tools developed in the shorter term for more passive applications. Companies that generate the know-how to work with passive nanomaterials in the present will be well-positioned to supply more complex materials for much more sophisticated and profitable applications in the future.

The short- and long-range evolution of nanomaterials necessitates two forms of collaboration. In the near term, small companies may have the intellectual property for nanomaterials that could substitute for traditional additives, but they have neither the manufacturing capacity to commercialize their materials nor a network of industrial customers willing to transition from traditional additives to nanomaterials. Larger, more established firms specializing in additives have an opportunity to form short- to medium-term collaborations with these small nanomaterials firms, in effect trading manufacturing capacity and an industrial customer base for intellectual property. Over the longer term, though, nanomaterials companies must be wary of becoming too dependent on the additives business to recognize that their intellectual property also lends itself to more sophisticated applications. Yet in the short term nanomaterials firms risk overselling such long-range, sophisticated applications, creating disappointment and backlash when those promises do not come true. One solution to this delicate balancing act may be collaboration across multiple sectors. For example, a company that grows dendrimers must build collaborative relationships with commodity chemicals firms one day, biotechnology and pharmaceutical companies the next, and electronics manufacturers the day after that. This kind of multisector collaboration may have to proceed through multifirm cooperatives or industry organizations rather than from company to company.

As federal funding, particularly through the National Institutes of Health, is set to increase dramatically for medical applications of nanotechnology, nanomaterials firms will move quickly toward collaboration with the medical device and pharmaceutical industries. Indeed, highly profitable applications may emerge soon in diagnostics and sensors (e.g., single molecule-sensitive anthrax screens), drug delivery (e.g., dendrimers or buckyballs capable of taking pharmaceuticals past the blood-brain barrier), or noninvasive surgical measures (e.g. quantum dot–based thermal scalpels). Equally significant cooperation between nanomaterials firms and the microelectronics industry is already being forged at a high level. For instance, in 2004 the NSF's Nanoscale Science and Engineering program area signed a memorandum of agreement with the Semiconductor Research Corporation (a research-sponsoring industrial organization) to jointly fund research under the theme "Silicon Nanoelectronics and Beyond." Similarly, the Chemical Industry Vision2020 Technology Partnership has modeled itself on, and formed a collaboration with, the influential *International Technology Roadmap for Semiconductors*.[14]

For a variety of reasons, then, the nanomaterials sector can serve as a model for the pressing changes in funding strategy and business organization that will eventually face the entire chemical industry. First, largely because of federal nanotechnology funding, nanomaterials research is ahead of other parts of the industry in pioneering computer modeling for materials development. "Materials by design" is a mantra that can be heard loudly among nanotechnologists, but it will likely spread to other sectors, particularly pharmaceuticals and microelectronics. Intriguingly, *in silica* materials design may facilitate incorporation of such "downstream" considerations as environmental persistence and bioaccumulation much further upstream in the design process. This integration will necessitate new modes of communication between different arms of industrial research, development, manufacturing, and environmental health and safety. Since this issue confronts a broad spectrum of companies, it may best be addressed at the federal or industrial level through, for instance, a national center for nanochemical engineering.

Second, the ability of nanomaterials to enhance bulk characteristics through the addition of very small amounts of material will necessitate changes in business models that may spread through the chemical industry. Few nanomaterials are going to be manufactured and purchased on a large scale, meaning that the volume of product sold bears a complex relationship to profit. Companies producing nanomaterials will need to develop business models in which they earn revenue from very small amounts of chemicals that contain a large front-end intellectual property investment.

Finally, chemicals firms need to reorganize to take advantage of collaborations around nanomaterials. Because nanomaterials developed for one application may realize their greatest promise in another application, lucrative partnerships will be found in counterintuitive places. Chemical companies must encourage their researchers to network with a wide array of nanomaterials firms operating well outside the larger company's specialty. A chemist at a company that supplies the microelectronics industry may find a crucial nanocomponent in the products of a start-up currently partnering with pharmaceuticals firms. Researchers who can perceive novel applications for a nanomaterial and quickly form collaborations with the owners of that material's intellectual property will be well placed to commercialize disruptive, profitable innovations. At the same time chemical firms need researchers who can see past the bandwagon surrounding nanotechnology. Companies need to know whether the nanomaterials firms they wish to partner with are mere Potemkin villages with little more than a patent and a professor. Hype and overselling permeate nanotechnology and present pitfalls for chemical companies eager not to be left behind.

---

[14] Chemical Industry Vision2020 Technology Partnership and Energetics, Incorporated, *Chemical Industry R&D Roadmap for Nanomaterials by Design: From Fundamentals to Function, December 2003*, http://www.chemicalvision2020.org/pdfs/nano_roadmap.pdf (accessed 7 August 2006).

Discussants at the 2005 Schlinger Symposium's nanomaterials breakout session arrived at the provocative conclusion that the potential traps of partnerships in this area cannot be evaluated at the traditional peer-to-peer level. That is, companies cannot assume that all will be well if their own researchers have inspected a partner firm's intellectual property and their own managers have come to trust the partner firm's executives. A third party familiar with the working practices and innovation culture of both firms must evaluate whether the two companies can successfully work together and what changes are needed to make the collaboration productive. Likewise, someone with a view to the long-range career of a nanomaterial must evaluate how a long, unpredictably branching chain of customers will use products and potentially modify them for alternative applications.

Environmental Chemistry

Increasingly, nanomaterials are seen as both contributors to and solutions for environmental contamination. The two areas of nanomaterials and environmental chemistry are likely to be closely tied as chemicals firms devise long-range plans for achieving sustainable manufacturing and as the industry looks to invoke both economically beneficial innovation and environmentally responsible behavior as the basis for retaining public trust.

Indeed, the similarities between nanotechnology and green chemistry may spur specialists in each to learn from each other. In both cases firms, investors, and the public must be convinced that there is substance beyond the hype—that thinking in terms of "nano" helps solve real problems and that thinking "green" is motivated by a hybrid of profits and environmental performance and is not mere "greenwashing" for public relations. Neither nanotechnology nor green chemistry is its own industry; rather, both offer tools and methods that make it easier for chemical firms to innovate. Crucially, both combine interdisciplinarity with a comprehensive approach to design. Nanomaterials researchers use simulation and modeling to design molecules and supramolecular clusters for novel applications. Green chemistry uses these same tools to create catalysts that promote more efficient and less wasteful reactions, minimize or even do away with the most environmentally dangerous industrial solvents, and predict the toxicity of the chemicals used in or produced by a manufacturing process over the entire life cycle of their progress through the environment.

Currently regulators are unsure how to deal with nanomaterials, but it seems certain that regulations targeted to toxic effects from the size and chemical reactivity of particles will appear soon. Nanomaterials firms have a unique opportunity to preempt such regulations: by using molecular design software and approaches from green chemistry, they can tailor their nanomaterials to minimize environmental impact *now* rather than waiting to pay for cleanup later. The wider chemical industry has been slow to see the benefits of such preemption, but it may no longer have the luxury of choice. As speakers pointed out, there are now some 120 enforceable federal environmental laws on the books. Unfortunately, under present circumstances such laws usually bring hazardous materials to light long after firms have become dependent on them. Consequently the dollars spent to retool existing processes and to clean up spills is many times the amount spent to prevent running afoul of regulation in the first place.

Green chemistry may provide the technical tools to turn this situation around. Relatively small amounts of money spent on research into new separations and solvents, new software tools for predicting the toxicity of molecules, and borrowed techniques from biotechnology (e.g., "biomimicry" in manufacturing) may yield large savings in legal expenses and cleanup fees. Yet the technical side of green chemistry is wholly inadequate if not accompanied by changes in business culture and organization. Most important, green chemistry requires that companies plan for the long term with an eye to the forces shaping organizational survival other than the traditional economic metrics of profits and stock price.

Firms that have successfully implemented green chemistry programs have adopted a "triple bottom line" for sustainability that integrates growth and profitability, minimal environmental impact, and maximum social responsibility. Green manufacturing technologies can save money (economic sustainability), produce less waste (environmental sustainability), and, ideally, enhance the company's brand and attract young, environmentally committed talent (social sustainability). The latter can only happen, though, if the firm operates in a transparent manner, makes credible data about its processes and emissions available to the public, admits errors when they occur, and rewards employees for their integrity in admitting problems and ingenuity in promoting solutions that maximize the triple bottom line.

Achieving green chemistry on an industrial scale will require new kinds of cooperation between institutions. In particular, industry and government must develop a relationship that is neither antagonistic nor passive and that is oriented to the long term. To achieve economic, environmental, and social sustainability, the chemical industry must be out in front of regulation, continually demonstrating that it has thought about environmental issues and involved its own health and safety officers at every stage of research and manufacturing. Firms must also demonstrate that they are able to answer criticisms credibly and change their practices when criticisms are valid. At the same time the government needs to provide support for innovative green chemistry research and more actively foster technology transfer from academic centers to the industrial setting.

Once again we believe that this challenge calls for Pascalian funding. Small investments into green processes now can yield great returns later, and, crucially, those firms that are most dependent on unsustainable manufacturing processes must be the firms that champion research into alternatives to those processes. Yet as in other areas requiring this mode of funding, single firms may not be able to achieve the needed investment returns. Cooperation across the industry will likely be needed, and industrial organizations representing many firms may be required to interface with other sectors of society. For instance, federal and industry-wide funding for a national center for green manufacturing would be helpful in devising new catalysts and solvents that can be used by many firms. Universities can also play their part. For example, new curricula are needed to train graduate students in chemistry and chemical engineering to think in terms of more efficient and greener processes that save money and have safer life cycles. Firms should encourage business schools to train executives to think in terms of the triple bottom line and to teach a style of management that rewards employees who bring environmentally sustainable money-saving ideas into the innovation process.

Chemistry of Energy Sources

Research into new energy sources lies squarely at the intersection of the need to decrease global dependence on oil and to ameliorate environmental risk. Energy is becoming more expensive both because the oil supply is in doubt and because oil's environmental cost is becoming more apparent.

Of the six Schlinger Symposium topics alternative energy sources are caught in the deepest, most intractable tension between near-term and far-term action. Most mainstream economists, researchers, and executives agree that alternatives to fossil fuels will be needed someday. Within the chemical industry there is general agreement that the menu of alternatives includes bio-based fuels, fuel cells, wind and sea turbines, and solar and nuclear energy. There is even some consensus that such advances as engineered microbes for bio-based fuels, new membranes for fuel cells, conducting polymers for solar power, and fuel "pebbles" for nuclear plants are bringing those alternatives closer to reality. Yet there is little agreement on how to move forward to bridge today's advances with tomorrow's power sources.

The key to bridging this gap lies in understanding and improving the fit between the politics and the technology of energy. To say that energy, particularly oil, has a political dimension is nothing new. Yet the political dimension of energy is not just a matter of the internal struggles of oil-producing nations and the West's attempts to influence those struggles. Rather, political considerations and technological solutions go hand in hand. Is it a political or a scientific question whether wind turbines would help or harm the ecosystem of Massachusetts Bay or the Flint Hills in Kansas? Is it a political or an empirical question whether nuclear power has solved the safety problems that plagued it in the past? Is it a political or a technological question whether bio-based fuels, solar energy, or fuel cells can replace fossil fuels? There is no consensus on any of these questions, and there cannot be until the politics and the technology of energy converge.

Consider, for example, the question of how much energy to produce and where. Energy production is relatively centralized; large plants produce energy and connect to other large plants to form a grid that smooths the fit between production and consumption. Some alternative energy sources are being designed to fit squarely into this centralized plant-grid model. Hydroelectric energy, for example, travels long distances from Quebec to supplement a sizable portion of North America's power grid, and nuclear generators already sit side by side with those using fossil fuels at many larger plants. Currently little research is oriented to making hydroelectric or nuclear energy compatible with a less centralized system. Instead research into this class of energy sources is focused on tying consumers more efficiently and enthusiastically to national grids: developing new superconducting materials that allow loss-free transmission of energy over longer distances and advanced containment systems for new nuclear power–generation technologies that may lessen (or make the public more comfortable with) the risks that accompany radioactive materials.

In the short term these centralized energy sources are likely to predominate. Over the medium term, though, technologies that can be fitted to either centralized or dispersed energy-production models, particularly solar energy and wind turbine technology, show promise. Solar especially can be used to generate energy on-site to supplement electricity from the grid, or it can be generated at very large solar "farms" in lieu of a fossil fuel plant. Proponents of solar energy may wish to tailor the technology to make it viable for both models: success with solar-powered homes and office buildings may make it more politically and technologically feasible to create large solar plants. Much the same strategy will likely hold for energy sources that are geared exclusively to a decentralized model, such as fuel cells and miniaturized gas turbines. Fuel cells are usually talked about as replacements for the internal combustion engine in vehicles. Yet the early applications that will make the public comfortable with this technology and serve as a platform for technological improvement are most likely much smaller, simpler, or cheaper: for instance, improved batteries for laptop computers or backup generators for homes and businesses.

Moving from the current state of alternative energy technologies to a future in which a mix of many sources minimizes reliance on fossil fuels will be difficult. Chemical firms should be central to this transition since they have the expertise with needed materials: conducting polymers for solar power, ceramic superconductors for transmission lines, and ion-exchange membranes for fuel cells. Firms need to realize, though, that progress requires both technological and political developments. Industry should press for regulations and tax incentives that reward companies for researching alternative energy, and in return should engage with the local politics of energy in a spirit of compromise. Companies will need to understand and innovate in response to consumers' attitudes toward different energy sources. If, for instance, aesthetic or environmental worries create resistance to nuclear power or wind turbines, these concerns should not be dismissed as the objections of Luddites. Firms that address these concerns by, for example, introducing new turbine designs that have less visual and environmental impact or new fissionable materials with clearly developed long-term disposal plans will be rewarded with significant market opportunities and broad stakeholder support.

Innovating for a Geographically Shifting Value Chain

The rapid development of Asian economies and other changes to markets and international trade arising from globalization underscore the need to shift to the Pascalian model. Many sectors within the chemical industry are transitioning away from stable but declining material platforms such as fossil fuels, petroleum feedstocks, and silicon photolithography of CMOS transistors; similarly, the industry as a whole is moving away from a stable but declining research paradigm. Traditionally firms have pictured innovation as a centralized activity, with flagship research labs almost always located near corporate headquarters. In an industry dominated by firms in Europe and North America, innovations traditionally emerged in those regions and only spread to other parts of the world after they were commercialized and "black-boxed" into transferable units.

As the economies and educational infrastructures of China, India, and other developing nations grow, however, it is increasingly obvious that both competitive firms and important innovations will increasingly arise outside Western Europe, Japan, and North America. At the same time globalization means that firms can find a winning combination of educated workforce, access to local raw materials, and industrial infrastructure in an increasing number of places around the world. Firms can elect to locate their research labs internationally to draw on different talent pools and to keep research closely aligned to increasingly globalized manufacturing. Moreover, if they do not support research labs around the globe they risk neglecting opportunities from innovations that will come out of China, India, and other countries.

For the chemical industry, globalization is vital not because it allows access to a uniform, homogenized "globe" but because it allows firms to weave together a larger set of very local patches of the globe. Firms should approach globalization neither in the spirit of simply exporting technology, knowledge, and business models to newly opened markets that operate just like markets everywhere nor as an opportunity to strip-mine new locales of ideas, people, and materials that can be taken anywhere. Instead globalization challenges firms to adapt to local conditions. By doing so, they can take advantage of innovations stimulated by the challenges of these conditions, which requires taking a long-term view and making a Pascalian wager on unproven research. In many cases adapting to local conditions will be difficult, costly, and time-consuming; it would be easier to ship in materials, talent, and business models from headquarters. But by investing to adapt to these local difficulties now, firms will better position themselves for a day when they may have no choice but to adapt.

The globalization of chemical industry research is a matter of making it *possible* but not necessarily *easy* for different parts of the globe to interact. Preserving regional independence and idiosyncrasy may paradoxically be the best way to make innovation truly global. Speakers at the Schlinger Symposium offered gas-to-liquid technology as an instructive example of how local necessity generates globally useful innovation. This technology relies on a set of reactions in which natural gas, coal, or another feedstock is first converted into syngas, after which the syngas is fed into a Fischer-Tropsch reactor and converted into a paraffin wax. The paraffin then can be upgraded for fuel use, particularly in diesel engines. The Fischer-Tropsch (F-T) process was developed in Germany in the 1920s as a way for that coal-rich and oil-poor country to achieve autarky and avoid dependence on oil imports. During World War II the F-T process fueled the German war machine. After the war it found few applications in Europe, where most countries switched to oil and natural gas for energy supplies and chemical feedstocks.[15]

The F-T process was next adopted on a large scale in apartheid-era South Africa, which like Nazi Germany was rich in coal, poor in oil, and sufficiently estranged from world trade that it needed oil substitutes. Sasol, the South African energy conglomerate, adapted and perfected the F-T process. Today under South Africa's prospering post-apartheid economy, Sasol has found numerous international partners for its gas-to-liquid technology. The F-T process will now help energy firms meet the needs of other regions that are poor in oil but rich in other resources that may be converted to fuel.

Our focus here is not on the ethics of conducting research on behalf of immoral regimes. Rather, the history of the F-T process highlights the truth of the adage "necessity is the mother of invention." Few things spur innovation of alternatives more efficiently than a paucity of resources. Globalization has abolished many developing nations' dreams of total autarky, but autarky of a kind may be useful in guiding the innovation process. This can be ethically and economically risky territory: we do not recommend that firms deliberately deprive their international research and production centers of the resources they need. But guidelines that encourage reliance on homegrown talent, ideas, and resources may turn up innovations that would not be discovered if headquarters were seamlessly connected to their global subsidiaries. Firms need to be willing to sacrifice some oversight and allow some local variation at their global research and production facilities. Encouraging local self-reliance will stimulate innovation and cultivate trust between headquarters and its subsidiaries that will allow profitable innovations to be communicated throughout the company.

The history of the F-T process shows one way to leverage local variation on behalf of sustainable globalization. The F-T process was originally used to convert syngas from coal into paraffin, yet, as we have seen, natural gas and bio-based feedstocks could also be transformed into syngas. Locally available feedstock resources, whether oil, coal, natural gas, methyl hydrate, or agricultural by-products could be turned into syngas, which, through the F-T process, can be turned into more complex organic molecules that serve as the precursors for an astonishing variety of materials. Multiple possible inputs go through a single process and produce multiple outputs; the same technology allows whatever is locally available to be turned into whatever is locally needed.

FINAL REMARKS

Throughout this report we have advocated a Pascalian funding model for R&D in the chemical industry: plowing current profits into research so that small investments in long-term alternative technologies will be amplified as those alternatives become more viable. Such investment in alternatives must come from firms that are most heavily dependent on the technologies that those alternatives will supplant. Not to invest would cripple those firms

---

[15] Raymond G. Stokes, *Opting for Oil: The Political Economy of Technological Change in the West Germany Industry, 1945–1961* (Cambridge: Cambridge University Press, 2006), 217–231.

when there is no choice but to switch to alternatives. We recognize that it is difficult for firms to depart from technologies in which they have heavily invested their personnel, infrastructure, and corporate identity. One solution we recommend is to continue the trend of collaborations between large firms and smaller single-technology ventures.

Ever since the accidental laboratory synthesis of mauveine by William Henry Perkin in 1856 and his subsequent launch of a small dye firm, the chemical industry has seen major waves of disruptive technology. No single change on the scale of Bakelite or nylon looms in the near term, but the coalescing of feedstock shortages, high energy costs, deepening environmental concerns, and emerging global competition suggest reasons to turn to research with a more distant time horizon. Business analysts frequently argue that existing firms are trapped by current manufacturing technology and cannot redefine themselves. Yet each of the areas described here offers chemical firms the opportunity to draw on their current expertise, take chances, and support the pragmatic dreamers who will create tomorrow's industry.

SCHEDULE OF EVENTS

Warren G. Schlinger Symposium
7 September 2005

9:00 A.M. **Opening Plenary: "Chemical Research in the 21st Century"**
Anthony Cheetham, University of California, Santa Barbara

10:00 A.M. **Breakout Sessions**

Feedstocks of the Future
Moderator: Rich Myers, The Dow Chemical Company
Speakers: Ron Sills, BP America
Mark Finkelstein, Luca Technologies

Nanomaterials
Moderator: Steven Freilich, DuPont Central R&D
Speakers: Jack Solomon, Praxair
Alan Rae, NanoDynamics

Electronic Chemicals
Moderator: Gary Calabrese, Rohm and Haas Company
Speakers: Elsa Reichmanis, Lucent Technologies
Marie Angelopoulos, IBM

Chemistry of Energy Sources
Moderator: Paul Clark, NOVA Chemicals
Speakers: Judith Stein, GE Global Research
Horst-Tore Land, PEMEAS

Environmental Chemistry
Moderator: Miles Drake, Air Products and Chemicals
Speakers: Paul Anastas, ACS Green Chemistry Institute
Cecil Chappelow, Air Products and Chemicals

Innovating for a Geographically Shifting Value Chain
Moderator: Jim Alder, Celanese
Speakers: Mike Silverman, KBR
Jennifer Holmgren, UOP

11:45 A.M. **Luncheon and Gordon E. Moore Medal Ceremony**
Lecture by Jeffrey John Hale, recipient of the 2005 Moore Medal

2:00 P.M. **Breakout Sessions (see above)**

4:00 P.M. **Closing Plenary**
Moderator: Arthur Daemmrich, Chemical Heritage Foundation
Speakers: Jay Ihlenfeld, 3M Research and Development
Michael Schrage, MIT Media Lab
Alfred Hackenberger, BASF