ROGER TURNER, JOEL TICKNER, AND MOLLY JACOBS

How to Catalyze a Safer and More Sustainable Chemical Industry

The chemical industry's last century is a story of highs and lows—both provide lessons that can be used to design its future.

Over the past century, the chemical industry has become deeply embedded in all aspects of life, shaping how we eat, dress, stay warm and dry, inform and entertain ourselves, and produce the goods that surround us. Now the industry stands at a critical point: Recent scientific assessments warn that the pace at which global societies produce and release toxic chemicals is incompatible with long-term human safety. In response, both the United States and Europe have created policies to drive the industry toward sustainability.

In 2021, the US Congress passed the Sustainable Chemistry Research and Development Act, which established a whole-of-government, coordinated approach to advancing sustainable chemistry, including R&D, incentives, and workforce development. The European Union's recent Clean Industrial Deal establishes a plan to create a resilient and carbon-neutral chemical industry that makes products that are "safe and sustainable by design." Meanwhile, investors, brands, and retailers are calling on the industry to reduce toxicity as well as climate impact. Despite these pressures, the incumbency of the industry's foundational chemistries—which are optimized, capitalized, cost-effective, and integrated into global supply chains—creates almost insurmountable barriers to change.

There is an irony in the fact that an industry that was once an engine of innovation—taking fossilized carbon and turning it into the synthetics saturating today's world—has become a dinosaur at precisely the moment when it is needed to meet new climate and ecological goals. But does the industry's unique history also contain lessons for the future? In February 2025, the Science History Institute and the Lowell Center for Sustainable Production collaborated to convene the most recent T. T. Chao Symposium on Innovation, gathering historians, chemical engineers, business and investment professionals, government officials, and nonprofit advocates to examine how early twentieth-century government policy, private investment, and industrial strategy built the foundations of the modern chemical industry. This experience offered new insights for policymakers, investors, and others about how the chemical industry's sleeping dinosaur might be woken up for a new age.

The rapid expansion of the American chemical industry between the 1920s and 1950s, publicly subsidized and government-coordinated in key ways, offers useful lessons in catalyzing sector-wide change. Likewise, the decades thereafter, when numerous obstacles locked the industry in place, stifling the creativity it once had, also offer lessons—albeit of what to avoid. And the legal frameworks of the 1970s, which forced companies to start addressing the environmental costs of production, ended up creating a perverse incentive against innovation by placing higher regulatory burdens on new chemicals while assuming older, existing ones to be safe. Chemistry's last century is a story of highs and lows, both of which provide lessons that can be used to design its transformation in the future.

History not only demonstrates that change is possible; it gives specific insights into what sorts of approaches might get the industry where it needs to go in the next 20 to 30 years while untangling its current structure, which is rigid and unimaginative. More generally, if we want sustainable chemicals, we must shift from viewing sustainability as an environmental enforcement problem and instead see it as an innovation problem. Seen through this lens, the industry's next iteration will include toxicity and sustainability as a performance and innovation issue, incorporated into design and invention, rather than a regulatory problem dealt with once harm has been established.

Accelerated by war, maintained through patience

During the first two decades of the twentieth century, the US chemical industry was relatively small, manufacturing sufficient quantities of basic products to meet domestic needs. Complex chemistry had to be done elsewhere because US manufacturers lagged in organic synthesis. As a result, most synthetic dyes and fine chemicals like aspirin and Novocain were imported from Germany.

World War I disrupted German imports while it amplified demand—especially for the chemicals used in making gunpower and explosives. And newly developed airplanes required cellulose acetate to coat their wings. The US government established a War Industries Board that negotiated with industry leaders to set priorities, standardize products, and fix prices. The Alien Property Custodian, a federal agency, also expropriated German-held patents. Furthermore, a partial relaxation of antitrust enforcement allowed US firms to create associations such as the National Aniline & Chemical Company, which produced dyes and organic chemicals, while substantially reducing competition among firms. By sharing knowledge, coordinating production of precursor molecules, and dividing markets, the industry was able to transform itself between 1915 and 1918, when it employed more than 178,000 people and supplied the needs of the nation. The wartime boom led to huge profits, with DuPont's cash reserves, for instance, swelling to more than $90 million.

This wartime bounty meant there was plenty to invest in the next wave of the sector's evolution between the 1920s and 1950s. An important dimension of that evolution was what historians David Hounshell and John Kenly Smith call *chemicalization*: the rapid uptake of novel synthetic materials to supplement or replace natural ones. A classic example is nylon. DuPont did not set out to create the synthetic fiber. Instead, the company was researching polymers to replace celluloid, which was in demand for packaging and photographic film. After the laboratory of chemist Wallace Carothers serendipitously discovered the synthetic polymer that became the precursor to nylon, DuPont invested significant capital and chemical engineering expertise to develop scalable production processes. By 1940, nylon was turning a profit. The material was not only cheaper than silk, the natural fiber it largely displaced, but also more versatile. And it could be produced in large quantities from coal or emerging oil feedstocks. These advantages proved critical during World War II, when nylon was used extensively in parachutes and tire fabrics.

Federal investment in chemical research during World War II further accelerated the industry's breakneck growth. The federally directed synthetic rubber research program—dubbed the "chemical Manhattan Project"—drove collaborations between competitors and accelerated domestic production. Washington invested heavily in oil and gas infrastructure along the Texas Gulf Coast and in developing critical materials such as butadiene and styrene (components of synthetic rubber) and ammonia for munitions. A number of chemical innovations, from pesticides to polymers, were first deployed during the war. These included, for example, Teflon, which was discovered when a canister of tetrafluoroethylene gas, used in research on refrigerants, spontaneously polymerized. Teflon was initially used in the (actual) Manhattan Project to coat valves exposed to corrosive uranium hexafluoride.

The US government used a combination of loan and revenue guarantees that covered construction costs and purchasing contracts to rapidly build industrial capacity and the value chains underlying tires, explosives, aircraft, and more. These efforts reduced the financial risk for private sector investment and laid the foundation for postwar value chains and rapid growth. In the 1940s, plastic production grew by more than 300%, laying the foundation for chemicalization on a grand scale in the 1950s and 1960s.

History not only demonstrates that change is possible; it gives specific insights into what sorts of approaches might get the industry where it needs to go in the next 20 to 30 years.

The rise and fall of civilian chemistry

Thanks in part to the market the government fostered, the chemical industry was poised to make the transition from a critical wartime industry to a peacetime powerhouse. This transition was supported by the long-term mindset of investors who understood that scientific research could not provide immediate returns but rewarded sustained backing. Thus Willard Dow of Dow Chemical credited the development of styrene to the maintenance of "a prayerful attitude" and "plenty of so-called patient money." Companies, in turn, deployed strategies to reduce risk for their customers. For example, Union Carbide extended lines of credit to customers willing to adopt its new Vinylite resins, which ended up in Saran Wrap. Finally, public relations campaigns ensured that the growing postwar middle class viewed the industry's products as essential to everyday life. Soon, they were.

The 1950s and 1960s saw a marked shift from invention toward commoditization, including market creation and expansion. High capital costs inhibited new companies from entering the market, which meant that chemical firms were able to shift to selling their existing chemistries, including plastics, at the greatest possible scale and displacing traditional materials like wood, metal, and natural fibers. One factor driving this shift was antitrust policy, which often required patent holders to license intellectual property to others to ensure competitive markets. This policy resulted in actions that seem extraordinary in today's regulatory environment. For instance, in the late 1950s, DuPont built a nylon factory for its competitor Chemstrand.

Commoditization was also driven by the business patterns of chemical engineering firms, which often sold a single manufacturing plant design to multiple chemical producers. Manufacturing technologies similarly were licensed across the industry. For instance, widespread licensing of the Ziegler-Natta catalysis process led to the massive production of linear, high-density polyethylene and polypropylene in the 1950s. Because producers competed using essentially similar technology, success came from finding ways to drive costs down, increase scale, and stimulate new markets. Amidst these rapidly growing markets for existing products, chemical manufacturers had few reasons to develop new chemical inventions.

By the 1960s, commoditization's consequences became clear: Specific chemistries were locked in, while innovation in basic chemical production became a tedious process of generating incremental increases in yield and finding ways to turn waste into saleable products. (*Basic chemicals* refers to a few molecules, today derived from petroleum and natural gas, that underlie most chemical value chains and include ethylene, propylene, methanol, benzene, toluene, and xylene.) By 1961, *Fortune* magazine lamented the industry's increasing rigidity in an article titled "Chemicals: The Ball Is Over." By this time, Dow's ratio of R&D to sales, which was 7% in the 1930s, had fallen to just 3%. Still, intensifying competition did spur some major firms to renew their R&D efforts. Thus during the 1960s, DuPont invested $1.6 billion in 41 new products. But few paid off. Only one of the new DuPont materials—Lycra—reached its $50 million sales target by 1970. Even highly inventive polymers like Kevlar, which had remarkable properties, struggled to achieve commercial viability at scale.

Regulation reflecting changing public attitudes about chemicals between the 1950s and the early 1980s challenged the chemical industry in surprising ways. Public concern about the rising proportion of deaths from cancer led to the addition of the Delaney Clause to the Food, Drug, and Cosmetic Act in 1958. Although the clause was intended to restrict the presence of cancer-causing chemicals in food, it ended up affecting the production of persistent herbicides and pesticides, as advances in instrumentation made it possible to detect these chemical residues in food at quite low concentrations. Similarly, public concern about cancer helped the labor movement win passage of the Occupational Safety and Health Act of 1970.

Lawmakers intended the Toxic Substances Control Act of 1976 to be "a gap-filler for all the chemical products that did not fit into existing regulatory frameworks," especially toxic materials already in wide circulation like asbestos, polychlorinated biphenyls (PCBs), and vinyl chloride. Yet the law's most consequential effect was giving the Environmental Protection Agency authority to review all new chemicals introduced to the market. However, the law also "grandfathered in" all existing chemicals on the market—considering them safe until demonstrated harmful through a complex regulatory process. This provision created incentives to keep in use long-established chemicals that were unlikely to draw regulatory scrutiny. Major environmental regulations like

This transition was supported by the long-term mindset of investors who understood that scientific research could not provide immediate returns but rewarded sustained backing.

the Clean Air Act, the Clean Water Act, and the Superfund law constrained chemical manufacturing operations, forcing companies to internalize some of the costs of waste disposal and environmental pollution. The consequences of environmental pollution, as well as identification of the chemical industry with napalm and Agent Orange used in the Vietnam War, degraded the industry's public image. Chemists and industry leaders alike lamented that this shift in public perception made it harder to recruit outstanding talent into chemistry and chemical engineering.

If the US chemical industry seemed stuck by the early 1970s, the 1973 oil shock and changes in corporate finance introduced new rigidity, including a bifurcation in the industry. As the dramatic increase in oil prices reduced profitability, corporate leaders continued to redirect research toward "incremental perfecting of existing processes, rather than the development of new products," according to finance scholar Marco Da Rin. This precipitated a drop in R&D to below 3% of sales—among the lowest of major industrial sectors. Major players such as Monsanto, Dow, Union Carbide, and DuPont chose to focus on higher-value sectors that traditionally have higher R&D expenses, including specialty chemicals, pharmaceuticals, and advanced materials. They financed this transition by selling off assets used for commodity production of bulk chemicals to smaller companies like Huntsman and Cain Chemical. These smaller firms made profits by carefully managing costs, rather than by developing new products.

Meanwhile, the loosening of regulation over American capital markets, which made it easier to finance leveraged buyouts or hostile takeovers, also gave management powerful incentives to prioritize the immediate interests of shareholders. Fear of corporate takeovers led companies like American Cyanamid and Celanese to reward shareholders by buying back shares, again reducing money available for long-term growth driven by research and capital expenditures. Growing financialization through the 2000s has been recognized as a major barrier to innovation in the industry. The results of these changes in production, finance, and markets mean that the chemical industry—once defined by its vigorous innovation—has changed its basic processes very little over the last 50 years.

Reshaping the chemical industry

The story of the last century's problematic progress underscores the need to see sustainability in the chemical industry as an innovation problem, rather than an enforcement problem. The hazards associated with certain chemicals and manufacturing processes are intrinsic to their molecular structure and design. But with the right incentives and research expertise, these hazards are not inevitable.

This potential brings us back to the essential question of this article: How? How might safety and sustainability be addressed as an innovation problem? History provides several lessons that could be helpful. The first is that the most prominent drivers of innovation in the industry (in addition to regulation) have been crises. Wars, pandemics, and embargoes—indeed, protectionism broadly—all fuel fundamental change by forcing immediate public and private sector responses. Crises create urgency, concentrate resources, and unify what would otherwise be competitors or ideological adversaries around a shared goal. Yet waiting for a crisis is risky, often wasteful, and could work against the goal of sustainability. Crises prompt regulatory flexibility that would not be acceptable under normal conditions: Recall the boost to the First World War–era chemical industry from state-enabled violations of antitrust and intellectual property rights.

A second historical lesson can be found in the key role of "patient money," which could possibly drive sustainable innovation, but appears to be very much a thing of the past. Innovation requires a shared commitment to long-term investment among industry, shareholders, and government. Today the later stages of innovation such as demonstration, commercialization, and scaling often require more than a decade to mature, but there are no mechanisms to support this process. Secure government and private sector contracts, content mandates, procurement, subsidies, production tax incentives, and other market incentives for innovation in chemistry have mostly disappeared with few exceptions, such as those for sustainable aviation fuel.

Another lesson from the past is what not to do. Governments have tended to allow the social costs associated with chemical manufacturing to persist, with well-known detrimental effects often falling upon workers and communities located near factories. The history of PCBs, used in electrical transformers and hydraulic fluids, shows a striking example of this trade-off. As early as 1899, it was known that PCBs cause the onset of chloracne, a painful and chronic skin condition. However, that didn't stop Swann Chemical from establishing the first US production facility in Anniston, Alabama, in 1920. Manufacturing quickly ramped up, with more than 3,000 pounds of PCBs coming off the factory floor each day by the 1930s. After Monsanto acquired the Anniston facility in 1935, outside researchers reported evidence of liver damage and other health impacts among exposed workers. Nonetheless, Monsanto continued to market PCBs for decades, avoiding regulation and deploying public relations campaigns that promoted the versatility of these chemicals. It took until the late 1970s to significantly curtail the use of PCBs, but by then many ecosystems and human populations had been exposed. This legacy, along with the evolving legacy of per- and polyfluoroalkyl substances (PFAS), points out the need for government and industry to proactively address the harms associated with chemical production, rather than waiting for scientists and health professionals to figure them out forensically after products have entered markets and society.

A final, and related, lesson from the past is that the industry has advanced within the confines of the way it has been defined. When the chemical industry was called upon to assist with war efforts, it rose to the challenge. When markets shifted toward financialization, it rose to that challenge. But for all that it has changed American—and global—life, the industry has not pushed the boundaries of its own definition. As Barry Commoner observed in his 1971 book, *A Closing Circle*, the chemical industry's foundations were like a two-legged stool, built on physics and chemistry. Biology, however—the science of life, health, and ecosystems—was largely excluded. That omission has meant that the industry has concerned itself with what it can make rather than what its products do. As Commoner noted in a 1973 speech to the American Chemical Society, "The industry needs to be redesigned to fulfill the needs of society, rather than its own internal economic logic; and to accord with the imperatives of the ecosphere and of the enhancement of human welfare."

One takeaway from the last century of the chemical industry is that new opportunities might be unlocked by embracing biology—that is, the impacts of chemistry on health and ecosystems—as a route to sustainable chemistry. Added to the policy lens, biology could move the focus away from solving discrete problems such as energy use, product toxicity, and plastic waste toward a long-term vision for the industry as a whole.

The results of these changes in production, finance, and markets mean that the chemical industry—once defined by its vigorous innovation—has changed its basic processes very little over the last 50 years.

Driving industrial transformation

These lessons from history offer guidance to once again make innovation a central part of the chemical industry. The industry's rapid growth was never the result of a specific plan, but rather a set of circumstances that combined crisis-related innovation with patient money, market creation, and incentives. A rethink of the industry will need a plan that marries a reconceptualization of its societal goals with a combination of crisis-inspired sprint initiatives to solve immediate challenges (such as global contamination with PFAS or supply disruption for critical chemistries) and long-term industrial planning in combination with patient money. Both approaches come with benefits and challenges, but in combination their synergy could provide a blueprint for change.

The first element is the sprint. Sprints are the twins of crisis, but they are proactive rather than reactive, focusing on achieving a technical accomplishment within a defined time frame. Well-known examples include the Manhattan Project and the Apollo moonshot. In the context of the chemical industry, the synthetic rubber research program during World War II is an illustrative case, in which strategic government investment and coordination rapidly catalyzed development of a domestic industry. Such fast-paced, crisis-driven technological initiatives align public and private sector actors and demonstrate the feasibility of technology transformation. More recently, the sprint was exemplified by Operation Warp Speed, which successfully leveraged public and private sector innovation to deploy COVID-19 vaccines, therapeutics, and diagnostics nationally and globally. Emergency-use authorizations further expedited safety reviews and enabled the introduction of novel vaccines at unprecedented speed. The risk of sprint-style initiatives, however, is that removing regulatory and other barriers designed to mitigate harms may have unintended consequences.

A second element that can balance growth while limiting harms is long-term strategic planning, which has been proven in multiple high-tech sectors including nanotechnology, semiconductors, and renewable energy. It is particularly effective in industries that require large capital investment, extended R&D timelines, and coordination across sectors or the value chain. For example, the National Nanotechnology Initiative, launched in 2000, provided a coordinated, whole-of-government approach to R&D funding, incentives, and regulation that built confidence among private firms and venture capitalists, which went on to build a robust nanotechnology sector. Importantly, this framework incorporated the "Safe-by-Design" concept. The idea, which was not fully implemented in practice for nanotechnology, is that responsible technology designers can build public trust and foster sustainable innovation by proactively assessing risks to the environment and human health and by aligning global regulation. A number of additional government efforts, such as the Manufacturing USA initiative and, more recently, those envisioned under the Inflation Reduction Act and the CHIPS and Science Act, have recognized the need for more systematic planning approaches to grow industrial sectors nationally, including consideration of community and environmental impact. Among these are the Department of Energy's Clean Fuels & Products Shot, which set goals and established programs for moving toward chemicals based on renewable sources of carbon, the main building block for most chemistry.

Particularly important for the chemical industry, these long-term efforts can help overcome market failures in complex, capital-intensive industries. SEMATECH, short for Semiconductor Manufacturing Technology, exemplifies how the public and private sectors can work together to transform a flagging industry through long-term planning. Founded in the late 1980s, in response to stiff competition from the Japanese semiconductor industry, the SEMATECH partnership allowed companies to benefit from government seed funding and coordination around a shared technology roadmap that led to a reinvigorated and changed industry. The private companies were still in competition with each other, but the consortium helped to revive and reinvent an industry in which free market incentives were not fostering innovation. One of the limitations of long-term strategic planning in the United States, however, is that these efforts are subject to shifting political priorities and funding, which create uncertainty and can reduce firms' willingness to invest. Nonetheless, despite shifting US politics, most publicly traded companies have established (and retained) net-zero goals along with plans to reach them, demonstrating that industrial actions can occur organically after a certain inflection point.

Fostering sustainable chemical innovation

Smart policy to revive the chemical industry will include a combination of sprints and long-term strategic approaches. It will also require incentives to foster the supply of new chemicals as well as consumer demand. In contrast to earlier eras, however, a common goal of sustainability—biology as a third leg of the stool—can be used to drive collaborations that organize sectors and value chains and work to coordinate regulation and investment.

These planned initiatives can ensure that manufacturers have the time they need to test products and, when necessary, redesign them to avoid risks. With the right policy architecture in place, safer and more sustainable products can successfully compete with riskier incumbents by becoming cheaper, more valuable, or otherwise preferred.

Today's US political climate is, alas, not oriented to long-term vision. But history offers a hopeful lesson: The US chemical industry was already built once on the basis of a strategy for meeting the needs of a particular era. That industry, cocreated by the private sector and public officials, was hugely successful in pursuing its goals of innovating with utility in mind.

There is no reason, beyond political will, why the chemical industry's astounding history cannot repeat—but now with both utility and health in mind. A number of critical opportunities to develop a long-term vision for a sustainable chemical industry exist and should not be wasted. Supply chain security and resilience, especially in view of competition from China, are increasingly critical drivers for US policymakers to build domestic supplies of chemicals, as demonstrated by a recent report from the National Security Commission on Emerging Biotechnology. Importantly, the report notes the need for the United States to develop domestic supplies of biorenewable basic chemicals, in part due to the difficulty of competing with China on incumbent petrochemical-based chemistries.

A rethink of the industry will need a plan that marries a reconceptualization of its societal goals with a combination of crisis-inspired sprint initiatives and long-term industrial planning.

By the end of 2025, the European Commission will develop a Chemicals Industry Package to establish a sustainable and competitive chemical industry for the future in Europe. Investor groups are pushing for a decarbonized chemical sector to meet 2050 climate targets, while reducing toxicity. And although action to implement recommendations of the Federal Sustainable Chemistry Strategic Plan will likely slow during the Trump administration, with bold investment, smart policy, strategic risk reduction, and deep collaboration across sectors and value chains, the nation can act before the next crisis forces our hand.

***Roger Turner** is the curator of instruments and artifacts at the Science History Institute in Philadelphia, Pennsylvania. **Joel Tickner** is professor of public health at the University of Massachusetts Lowell, where he directs the Sustainable Chemistry Catalyst of the Lowell Center for Sustainable Production. **Molly Jacobs** is director of applied research for the Sustainable Chemistry Catalyst, a research program at the Lowell Center for Sustainable Production located at the University of Massachusetts Lowell.*