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Implications for Energy Innovation from the Chemical Industry

Ashish Arora and Alfonso Gambardella

Once a leader in industrial innovation, the chemical industry has changed countless aspects of modern life. From the plastic in the toothbrush we use in the morning, to the tires we drive to work on and the fuel that powers them, to the clothes that keep us warm, chemical innovations are so infused in our daily lives that we generally take them for granted.

It is difficult, therefore, to speak of *the* chemical industry, one that David Landes (1969, 269) has called the most "miscellaneous of industries" and which encompasses synthetic fibers, plastics, agricultural pesticides and fertilizers, food additives, health and beauty aids, and many other products and production components. Given this variety, attempting to summarize chemical innovation is difficult. Instead, we shall focus on industrial synthetic fibers and plastics and the inputs from which they are made. Their history offers useful lessons for how energy innovation and diffusion might be accelerated, in part because innovations in these chemical subsectors share common features with energy innovations.

Chemical innovation has been marked by the search for new inputs and the concomitant process innovations that allow the inputs to be produced and used. A prominent example of such a change is the shift from coal derived inputs for producing synthetic fibers and plastics to those from oil and natural gas. This change, which began before World War II in the United

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States, was accompanied by a flood of innovations, including advances in petroleum refining and new processes for the production of important synthetic fibers and plastics. Energy innovation, too, is likely to involve the development and large-scale deployment of new processes and new materials designed by chemists and chemical engineers.

Innovation in the chemical industry requires scaling-up laboratory discoveries into commercially viable products. This sort of scale-up is also common in the oil refining industry, and, indeed, chemical engineering has its roots in oil refining. The gigantic refineries that produce gasoline, kerosene, diesel, and a host of valuable inputs used in a wide range of commonly used materials embody numerous innovations in chemistry and chemical engineering. The biorefineries of the future will no doubt be different from the oil refineries of the present, but much of the expertise they require will come from chemists and chemical engineers.

There are more subtle connections as well. The successful commercial introduction of new materials has required careful attention to questions such as how downstream users would use them, whether existing processing machinery would have to be modified, and how the final product in which the new material was embodied would differ. All these considerations have effects that ripple through the value chain, which is typical of energy innovations as well.[1] For example, the introduction of a new automobile fuel may also require changes in how it is distributed and used, and a new form of rubber with different temperature-related properties may require new learning about best applications for its use. Chemical innovation, which has often consisted of new types of materials that are used to produce existing products, have long featured this type of adjustment.

Despite this complexity, for the most part, the chemical industry has relied upon markets to coordinate the required changes. This coordination is far from perfect. Many chemical processes have produced harmful by-products. However, the history of chemical innovation also reflects the search to mitigate or eliminate waste. For instance, chlorine produced as a by-product in producing caustic soda in the mid-nineteenth century was used to produce bleaching powder. Changes in the market place, especially growth in demand, have occasionally made what was hitherto waste more valuable and, therefore, worth capturing. Thus, in the nineteenth century in the United States, kerosene was the principal product produced from crude oil. Natural gas was routinely flared in oil pumps, and heavier components in crude oil, such as waxes, were simply tossed aside. Over time, in response to rising demand, techniques were developed to use these hitherto waste products. The implications for energy innovation, which centrally involves the problem of dealing with harmful by-products such as carbon dioxide, are obvious.

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[1] A “value chain” is a series of activities for which each step of the activity increases the value of the target product.

Major innovations in the recent history of the chemical industry have been the result of privately funded research carried out in the laboratories of large chemical and oil firms. In the 1870s, when the chemical industry revolved around synthetic dyes, firms believed that hiring chemists would help them discover new dyes, the way to commercial success. During the 1920s and years of the Great Depression, the spread of the automobile created demand for gasoline (and, hence, for new refining technologies), lacquers (as car paint), plastics, and materials for car tires. Later, World War II greatly boosted the demand for plastics, synthetic fibers such as nylon and polyester, high octane gasoline, and synthetic rubber. In each case, the payoffs for developing new materials, improving them, and developing techniques to reduce production costs and increase production volumes were significant and predictable. The post–World War II boom in the 1950s and 1960s further increased demand for synthetic fibers such as polyester and for new plastics such as polystyrene.

This commitment to investing in research, not simply in production, became ingrained in the industry. Hounshell and Smith (1988) argue that the commercial success of nylon, commercialized just as World War II started, may have been salient in shaping the thinking of the management of DuPont, and by extension, of other chemical firms as well. Hounshell and Smith describe in detail the largely fruitless attempts of DuPont management to search for blockbuster products that would be as successful as nylon. In the process, the company built substantial in-house capability for research and development (R&D), and for some time even operated an in-house "Polymer Institute." By contrast, most other technology-intensive sectors developed after World War II, by which time government support for research was more forthcoming and, in some cases, decisive in starting the industry.

Early in the history of the industry, when synthetic dyestuffs were based on advances in organic chemistry by German chemists, universities made formative contributions, and in the twentieth century, they have contributed indirectly (but importantly) by institutionalizing the learning being created by firms and by training students—creating the disciplines, as it were, of petroleum engineering, chemical engineering, polymer chemistry, polymer engineering, and so on. The federal government's role in supporting innovation in the industry has not, however, been limited to supporting universities and programs such as synfuels and the synthetic rubber program. It has also played a key role in facilitating the development of a "market for technology" in the industry, through both antitrust and intellectual property policy. But it has been in private research labs, and indeed through the research programs of a wide range of private firms including smaller players and specialized engineering firms, or SEFs, that most recent discoveries have taken place.

The development of new processes and materials alone does not make a significant contribution to economic growth; the new processes and materials have to be widely diffused. In the chemical industry, this diffusion was largely market based. Direct government subsidies were mostly unimportant. The rapid diffusion of synthetic fibers and plastics, such as nylon, polyester, and polystyrene was fostered by an extensive market for technology in which chemical technologies were widely licensed. Specialized engineering firms, which supplied technology and know-how, played a key role in this process. The emergence of these markets for technology appears to have been importantly due to antitrust policies, principally in the United States, and the enforcement of intellectual property rights.

In this chapter, we begin by laying out the early history of the chemical industry for an overview of the role innovation has played in its development. We then explore three noteworthy historical experiences. We describe the switch in coal-based raw materials to those derived from oil and gas and briefly analyze two government programs that have attempted to promote innovation: synthetic rubber and synfuels. We take a close look at the role that specialized engineering firms have played in the diffusion of important innovations, and we detail the effect that government policies have had on fostering innovation.

3.1 Early History

The modern chemical industry began with organic chemicals and, specifically, synthetic dyes. Beginning with William Perkin's accidental discovery of a mauve (purple) dye in 1856 while in Professor August Hofmann's lab, new synthetic dyes were rapidly and subsequently discovered in France and Germany. By the 1870s, German firms dominated the synthetic dye market. Although the initial discoveries were made in the labs of university professors—there were few chemical labs outside universities—private firms quickly began investing in their own labs: by the 1880s, the leading German firms had created in-house laboratories for discovering new synthetic dyes. Ten years later, the vast majority of synthetic dyes came from the R&D labs of German chemical companies.

University research remained important for opening up fields of inquiry and of suggesting fruitful areas of investigation. For instance, Friedrich August Kekulé's discovery of the benzene ring structure in 1866 was crucial for the discovery of dyes based on aniline by enabling researchers to predict what colors different reagents might produce. By the 1880s, university research was aimed at clarifying the structure of dyes discovered in corporate labs, and understanding their properties, rather than discovering new dyes as such (Murmann 2003).

The United States was a follower in scientific chemical research and also a net technology importer until World War I. During this time, American chemical firms focused on developing new ways of producing chemicals on a large scale, especially commodity chemicals like sulfuric acid (Arora and

Table 3.1 **Major polymer innovations: inventors and commercializers**

Polymer	Inventor	Organization of inventor	Commercializing firm	Year of commercialization
		Synthetic fibers		
Nylon	Carothers	DuPont	DuPont	1934
Polyester	Whinfield-Dickson	Calico Printers	ICI	1939
Acrylics	Various		Bayer; DuPont	1920–1930s
		Plastics		
Phenolic resins	Baekland; Edison and others		General Bakelite	1910
PVC	Fritz Klatte	Griesham Electron	Union Carbide; BF Goodrich and GE	1930s
Polystyrene	Various		IG Farben	1930
Low density polyethylene	Swallow, Perrin, Fawcett, Gibson	ICI	ICI	1939
Polypropylene	Ziegler-Natta; Hogan & Banks	Max-Planck Inst.; Montecatini; Phillips Petroleum	Various	1960s
Neoprene	Nieuwland, Collins	Notre Dame University; DuPont	DuPont	1936

Source: Arora (2002).

Rosenberg 1998). These innovations were based in experience, rather than scientific discovery—that is, the innovations arose from trial and error in the lab, rather than relying on recent scientific advances. Products such as fertilizers and gasoline also required large-scale production to reduce costs. As petroleum refining grew in importance, so did the demand for new refining processes.

The period from 1920 to 1960 probably marks the golden age of innovation in the chemical industry, at least as far as the United States is concerned. The major polymers—plastics and synthetic fibers—originated in corporate labs and were commercialized during this forty-year period (table 3.1).[2] This period also marks major developments in chemical engineering, with the commercialization of a number of important chemical processes. In many cases, fundamental scientific contributions came from researchers working for private firms, such as Wallace Carothers (DuPont), Frank Mayo (U.S. Rubber), and Giulio Natta (Montecatini). Paul Flory, later to receive the Nobel Prize in chemistry for his contributions to the area of polymer chemistry, worked for many years in the research departments of DuPont, Standard Oil, and other chemical firms before moving to academia.

[2] The two exceptions are the first synthetic rubber (neoprene), which was based on work by Julius Nieuwland at Notre Dame University, and the catalyst systems used to produce polypropylene and high density polyethylene, developed by Karl Ziegler at what is now part of the Max Planck Institutes.

Chemical engineering was a distinctly American achievement—more specifically, it was a testimony to America's very productive university-industry interface.[3] The signal contribution of universities was to train students and institutionalize the disciplines of chemical engineering, petroleum engineering, polymer chemistry, and polymer engineering (Rosenberg 1998). Many of the basic technological breakthroughs came from researchers trained in these new disciplines and moving on to corporate labs. For example, the first significant chemical process innovation, the Haber-Bosch process, was developed by BASF early in the twentieth century. The general-purpose nature of chemical engineering enabled university research and training to play an important role in applying engineering science to the practical problem of designing large-scale processes. A number of the major advances in catalytic refining techniques were developed by oil firms, notably Standard Oil of New Jersey (now ExxonMobil). University researchers were sometimes involved in these innovations, but typically in partnership with researchers from corporate labs. Notably, Warren Lewis and Edwin Gilliland from Massachusetts Institute of Technology (MIT) developed fluidized-bed catalytic cracking in close cooperation with the chemical engineers at Standard Oil (Spitz 1988).

Individuals and small engineering firms (which were typically entrepreneurial start-up firms) were another important source of chemical process innovation during the golden age. For instance, Scientific Design, a small firm founded in 1946, developed new fixed-bed catalytic processes for ethylene glycol, maleic anhydride, and, most important, for production of purified terephthalic acid, the basic building block of polyester. Similarly, National Hydrocarbon Company (now Universal Oil Products [UOP]), provided some of the fundamental advances in refining technology, including thermal catalytic cracking, reforming, and sulfur extraction. Universal Oil Products remains a leading source of refining technology to this day.

3.2 Case Studies in Chemical Innovation

New materials used by firms as inputs (rather than sold directly to consumers) typically take a long time to diffuse broadly. Not only are industrial firms inherently conservative in their adoption of new materials, diffusion also takes time because new materials often require complementary changes

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[3] See Landau and Rosenberg (1992) for a discussion of the role of MIT in the development of chemical engineering as a discipline. The large size of the market had introduced American firms to the problems involved in scaling-up production of basic products, such as chlorine, caustic soda, soda ash, and sulfuric acid as early as the beginning of the twentieth century. This focus on large-scale production had additional benefits when it turned out that the new petrochemical technologies had strong plant-level economies of scale. Because scaling-up output was not a simple matter—it involved considerable learning—early experience with process technologies gained American firms a head start when petrochemicals became the dominant feedstock after World War II.

in the physical infrastructure. This issue is likely to arise in the case of energy. Fuel cells for automobiles are a case in point. The concomitant changes needed in the physical infrastructure (such as fueling stations) are thought to involve large financial investments and coordination problems, greatly delaying the widespread adoption of fuel cells (see, for instance, Struben and Sterman 2008).

Another significant cause of delay is what Bresnahan and Greenstein (1996) dub "co-invention" by users—that is, the need for users of the new technology to become familiar with its use and in some cases to design complementary adaptations to facilitate its use. Bresnahan and Greenstein found that co-invention can pose significant costs in time and money to a company, as demonstrated by the resistance and delay in the switch from mainframes to client-servers in U.S. firms. David (1990) similarly argues that the diffusion of electrical power was slowed as manufacturers, used to steam power, had to learn how to exploit the full potential of this new energy source. In the case of the chemical industry, Hounshell (1988) shows that as new industrial materials were introduced, users had to learn about the properties of these new materials. For instance, when first introduced, rayon fiber was believed to be weaker than cotton fiber, and because rayon fibers were further weakened when wet, the material was assumed to be unsuitable for tire cord. However, it was discovered that hot rayon is 50 percent stronger than cotton. Rayon tire cord, however, did not take off until World War II, when circumstances forced the use of synthetic rubber for tires; synthetic rubber tires run hotter than natural rubber tires, and, therefore, rayon was a better cord material under those hotter conditions. This also illustrates the systemic interdependencies in chemical innovation.

However, in general, diffusion in the chemical industry has been surprisingly fast. The most notable is the swift and thorough switch from coal to petroleum as the dominant chemical feedstock after World War II.

3.2.1 Coal to Petroleum

At the end of World War I, coal was central to the chemical industry, not so much as an energy source but as a source of raw materials: coal-derived chemicals formed the basis of the chemical industry. For instance, coal tar provided a source for synthetic dyes, coal coking furnaces provided the nitrogen for fertilizers and explosives such as TNT, and coal provided the toluene for those explosives. Heating coal to make coke—a raw material in the manufacture of high-carbon steel—also produces a number of chemically useful gases and byproducts: coal tar, ammonia, and benzene. Indeed, firms such as Solvay, Koppers, and Allied Chemicals owned batteries of by-product coke ovens to produce these valuable chemicals. These joined a large complementary physical infrastructure of by-product coke ovens across the United States and around Europe, complementing a substantial accumulated learning about the use of coal by-products as chemical building blocks. As late as 1938, DuPont, the leading American chemical company, announced that it would create a synthetic fiber "from coal, air, and water" when starting its first commercial nylon plant in Seaford, Delaware.

Everything changed with the meteoric postwar popularity of the automobile, which greatly increased the demand for gasoline, leading refiners to improve oil-refining processes. Furthermore, the oil-refining process for automobile fuel used only a portion of the petroleum refined, leaving ample by-product with no clear use. During the 1940s, petroleum by-products from automobile oil refineries increasingly went into the production of basic materials, such as plastics, synthetic rubber, and synthetic fibers. Oil-based chemicals began to quickly outstrip the previously dominant coal-based chemicals.

The change had many dimensions. New extracting and refining technology for petroleum had to be developed. Further, there was a concomitant change in the technology from acetylene-based chemistry (triple bonds typical of coal by-products) to the ethylene-based chemistry (double bonds) of oil by-products. But, ultimately, the move from coal to oil was driven by the superiority of oil-based feedstocks and by falling costs of oil due to the progressive improvements in extraction and refining technologies.

The switch from coal to oil also is remarkable because of its rapid worldwide diffusion. That these processes were rapidly adopted in Europe is significant because Europe was abundantly supplied with coal (but little oil) and because Europe had pioneered the use of coal in synthetic dyes and plastics.

The switch to oil began in the United States, which had abundant domestic oil and natural gas reserves.[4] By 1950, half of the total U.S. production of organic chemicals was based on natural gas and oil; by 1960, the proportion was 88 percent. The switch came later, but as rapidly, in Western Europe. In the United Kingdom in 1949, for instance, 9 percent of total organic chemical production was based on oil and natural gas, and the proportion rose to 63 percent by 1962. In Germany, the first petrochemical plant was set up in the mid-1950s, and by 1973, German companies derived 90 percent of their chemical feedstocks from oil. In light of Germany's substantial endowment of coal and the fact that German firms had made large, irretrievable investments in coal-related technologies, the changeover of the German industry is especially remarkable (Stokes 1988). The swift diffusion of petrochemical technology in Europe ironically was aided by the World War II destruction of the German and French industrial capacity, which reduced switching costs. However, the ready availability of petrochemical technology from American firms, especially by specialized suppliers of technology and engineering services, was crucial. Equally important, if not more so, was the postwar availability of crude oil from the Middle East, with the supplies

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[4] The U.S. and European statistics detailed in this passage are from Chapman (1991).

guaranteed by Pax Americana.[5] In other words, markets in both goods and technology played a fundamental role in facilitating the switch from coal to petroleum in the United States and Western Europe.

The enormity of this shift may not be easily appreciated today, until we begin to consider an analogous energy innovation challenge, such as a possible increase in the use of biomass. At that point, a range of issues analogous to the coal-to-oil switch arise. For instances, can processes be developed that can handle variations in the composition of biomass sources? Can processes be developed to remove impurities from biomass that might interfere with their processing (such as poisoning the catalyst)? Can the likely undesirable by-products be removed after processing in a cost-effective and scalable manner? Can existing equipment be used? Similar questions were confronted and solved through innovation and diffusion during the coal-to-oil shift.

This shift is also remarkable because direct government intervention was not central to the shift. For the most part, advances in oil refining, advances in how new types of chemical raw material could be extracted from crude oil and natural gas, and the diffusion of these advances did not rely upon government subsidies or other types of government incentives. Instead, these were in responses to changes in the availability of different types of resources and fundamental advances in the underlying scientific and engineering knowledge about materials and large-scale chemical reactions. Further, as we discuss at greater length later, the diffusion of these new technologies was largely mediated by the market for technology, in which specialized engineering firms played an important role.

This episode also illustrates the power of demand in calling forth the development of new technologies. As oil became more widely available, and as advances in oil-refining increased the potential for extracting more useful raw materials from crude oil and natural gas, there were incentives to explore oil as the source of the basic building blocks for chemical products. These incentives were especially marked in countries that were relatively abundant in oil. Western Europe was abundant in coal, but oil was relatively scarce. America was generously endowed with both coal and oil but, relative to Europe, was relatively abundant in oil and, moreover, had less invested in producing chemicals from inputs derived from coal. Not surprisingly, America led the shift from coal to oil.

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[5] The discovery of oil in the Middle East was significant not only because it meant that more oil was available, but also because the additional reserves would be supplied through a global market, and, therefore, control over oil was unlikely to be used as an economic or military weapon. The U.S. guarantee of unhindered oil supply to Western Europe was also very important in this respect. We are grateful to David Mowery for bringing this to our attention.

3.2.2 The Synthetic Rubber Research Program

The Synthetic Rubber Research Program offers an interesting instance of a government-funded cooperative research program in the chemical industry.[6] This wartime program took place from 1939 to 1945, when the United States faced being cut off from nearly 90 percent of the world's natural rubber supplies located in Southeast Asia. As a response, the U.S. government formed a consortium of the leading rubber firms, some of the leading chemical firms, and selected university researchers to expand and improve the production of synthetic rubber. The program was later extended to 1956. Between 1942 and 1956, the U.S. government invested $56 million for R&D in this consortium. The program mandated free exchange of information among participants.[7]

The principal objectives of the program were threefold. The first was to expand greatly the scale of synthetic rubber production. The second was to improve the quality of the synthetic rubber and produce specialty rubbers, such as rubbers suitable for use at low temperatures. The third objective, less explicit and of lower priority, was to develop greater knowledge and understanding of polymers.

The first objective of the program was successfully met. By 1945, the United States produced nearly 850,000 tons of synthetic rubber (up from less than 10,000 tons in 1941), more than seven times the peak German production achieved in 1943. Virtually all of the ramped-up production went to the war effort; the U.S. government purchased all production from the program, and companies producing synthetic rubber did not have to worry about being able to sell it. Having a guaranteed market in the U.S. government was important because it released the companies from concerns that there would be insufficient demand for their efforts.

The tremendous increase in the production of synthetic rubber did not require radical technological advance. Although a variety of alternative monomers (building blocks) were tried out, it turned out that butadiene and styrene, used in the Buna-S rubber patented in Germany in 1921, were the most suitable.[8] Neither was the basic process fundamentally new. Even so, a variety of logistical and technological problems had to be solved, such as expanding the supply of butadiene, for which advances in chemical engineering and petroleum refining were critical. Butadiene could be produced from the by-products of oil refining or natural gas. It could also be produced from other sources, such as industrial alcohol (ethanol). Many different sources of ethanol were considered, including alcohol from grain

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[6] This section draws upon Arora (2002). In addition, see Herbert and Bisio (1985) and Morris (1989) for detailed accounts and assessments of the program.

[7] Eventually, thirty-six firms joined the consortium. In some cases, firms took special precautions to ensure that related internal projects were kept separate.

[8] Buna-S rubber was called GR-S rubber in the United States.

or molasses. In Europe, Chemische Werke Huls (a German specialty chemicals company) nearly built a tire plant with French red wine as an ethylene source; the United States actually imported beet ethanol for butadiene for the synthetic rubber program shortly after World War II. During the tenure of the Synthetic Rubber Program, Congress passed laws mandating use of grain ethanol for butadiene production. *Plus ca change, plus c'est la meme chose!* The vast bulk of butadiene, however, was ultimately produced from oil-refining by-products.

Styrene, the other key input, could also be obtained from coal by-products, but oil-based sources were more promising, particularly after new processes were developed that could produce benzene ring type molecules. Government coordination played an important role in styrene production as well. The Dow Chemical Company was asked to take charge of styrene production for the program and build large styrene plants in Torrance (California), Velasco (Texas), and Sarnia (Ontario) using Dow technology and to supervise construction of several other plants. Union Carbide Corporation was asked to build a large plant based on its technology, and Monsanto Company was asked to build an ethylbenzene-styrene plant using Dow and Monsanto technology, in partnership with Lummus Corporation. The Koppers Company was asked to build a plant using vapor phase alkylation process using technical contributions from UOP, Phillips Petroleum Company, and Koppers. U.S. production rose from less than 2 million pounds per month in 1941 to 20 million pounds per month by the end of 1943. By the end of 1944, production was 40 million pounds per month (Spitz 1988).

The program's second objective of improving the quality of synthetic rubber was complementary to the first objective. Once again, though not fundamental in terms of the science involved, a number of improvements to the polymerization process were critical in producing synthetic rubber of a higher and more consistent quality. These changes were especially important for "cold rubber," a new type of synthetic rubber also made from butadiene and styrene but of higher quality in some ways. Among other uses, cold rubber was better suited for automobile tires. By 1954, two thirds of all synthetic rubber produced in the United States was "cold." Especially noteworthy improvements involved better control over gel formation, improved modifiers and emulsifiers, and, in the case of cold rubber, a new catalyst as well.

After World War II, the Synthetic Rubber Program was no longer the only or even the principal source of innovation in synthetic rubber. For example, oil-extended rubber—cold rubber with added mineral oils, which was both cheaper and easier to process than cold rubber—was developed by Goodyear Tire & Rubber Company and, independently, by General Tire, which was not part of the research program.[9] New modifiers and carbon black (an

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[9] There were benefits, nonetheless, from Goodyear's discovery, because Goodyear, as a member of the cooperative research program, made its discovery available to all other members.

important rubber additive) came from Phillips Petroleum, not a member of the program until after those discoveries. Similarly, the next generation of synthetic rubbers (the so-called nitrile rubber) were privately developed by two firms, Goodrich and Goodyear, outside the synthetic rubber program.

Although the government's research program succeeded in its two main objectives, the program had significant design flaws that ultimately narrowed its effectiveness in encouraging more widespread innovation. Perhaps its greatest flaw was its inflexible insistence on a common "recipe" to be followed by all participating companies; this may have delayed the adoption of a number of improvements (Morris 1989). The justification for the common-recipe requirement was that it would facilitate cooperation among members and simplify processing. However, according to Morris (1989), the effect was to complicate testing and large-scale introduction of new recipes. The common-recipe requirement also pushed many consortium members to spin off or partition some of their internal research projects, thus protecting themselves from the restrictions of the government program.

The information-sharing mandate was both a benefit and a curse for the program. On the one hand, the mandate allowed a number of firms to enter the industry, particularly after the end of World War II. This greatly increased competition and contributed to the rapid growth of the industry. On the other hand, the mandate diluted the incentives of firms to develop innovations because they would have to share the information with their rivals, lowering their private returns. Consequently, some participating firms had research groups working in rubber and polymer technologies that were carefully kept apart from the research groups participating in the Synthetic Rubber Program. Many of the major advances in technology came from outside the research sponsored by the program during that time period.

The greatest failure of the government research program in promoting fundamental technical advance (as opposed to increasing the production of synthetic rubber for the war effort), in Morris's opinion, was in the case of synthetic natural rubber (i.e., a synthetic route to the production of natural rubber, as opposed to a synthetic material with properties like those of natural rubber). Although GR-S (Government Rubber Styrene, formerly Buna-S) rubber worked well for automobile tire track, natural rubber was much better for truck and airplane tires, where loads and temperatures are markedly higher. Many program participants, from both industry and academia, tried to develop a suitable synthetic rubber for trucks and planes. The solution turned out to be a process of synthesizing natural rubber itself by polymerizing isoprene. The pioneering research of the German chemist Karl Ziegler in 1950 (not the U.S. government research program), in the catalytic polymerization of polyethylene and related materials, was instrumental in synthesizing natural rubber. Morris (1989) suggests that the information sharing requirements imposed by the government program may have delayed the application of Ziegler's discoveries until 1955.

Thus, neither the basic process for producing synthetic rubber, namely, the butadiene-styrene process, nor some of the important postwar improvements in the process for synthetic rubber can be credited to the government-funded program. The government research program succeeded in its immediate wartime aims, but not in its longer-term peace time ones. However, the government funds at stake were small. Between 1943 and 1955, only $55 million were invested in R&D, a fraction of the nearly $700 million capital investment in synthetic rubber production in 1945 alone and less than 2 percent of the total value of the synthetic rubber produced over this period.

The government's synthetic rubber research program succeeded in increasing production because it quickly settled on a viable technology, standardized the inputs (for the most part), and coordinated the production. As well, it coordinated with the users of synthetic rubber and provided capital to construct the various production facilities. The program worked best where the technology required incremental improvements advancements, which, nonetheless, cumulatively had a large impact. The program was able to coordinate private parties on a given standard (e.g., the GR-S rubber standard), which was desirable because the standard itself was a good one. Getting to a good standard was more likely because the technology was relatively mature and progress required was incremental.

Conversely, the Synthetic Rubber Program did not facilitate development of radical breakthroughs or fundamental discoveries in polymer science (although it contributed to both). This undoubtedly had much to do with the priorities of the program, which imposed certain inflexibilities that hindered radical innovation. In some cases, the information-sharing mandate diluted the incentives of firms to develop innovations because they would have to share the information with their rivals. Further, the strong applied orientation of the program implied a reduced priority for the training of graduate students, resulting in a much smaller contribution to the growth of polymer science than might otherwise have been.

The program's history also highlights the diversity of the potential sources of innovation. In the rubber research program, important innovations came from unexpected sources outside the program. General Tire invented "cold rubber," and Philips Petroleum, a smaller oil company from Oklahoma, albeit one with a strong tradition of chemical research, made significant contributions to the development of carbon black and other modifiers. Therefore, an innovation environment that has left ample room for new players has also made greater room for success, rather than one placing large early bets on a handful of players.

A third lesson from the history of the Synthetic Rubber Program is that of the role of demand, or procurement. During the war, all production from the program was purchased by the government at guaranteed prices, and companies were, therefore, not concerned about being able to sell their product. After the war, the renewed availability of natural rubber raised doubts about the viability of synthetic rubber, but the greater versatility of different types of synthetic rubber eventually prevailed.

3.2.3 The Synfuel Program

As early as the 1920s, the U.S. government had experimented with liquefaction of coal and other substances for fuels, but it did not result in a significant program until the end of World War II.[10] The 1944 Synthetic Liquid Fuels Act led to a $30 million five-year Department of the Interior research program that attempted to alleviate shortfalls in the supply of oil during after immediately after the war. The basic technologies, coal liquefaction and coal gasification, already existed, but neither was commercially viable at prevailing prices. The objective of the program was to promote new processes, catalysts, and input sources that would lead to commercial viability. Through the program, a demonstration coal hydrogenation plant was constructed in 1949 that produced synthetic diesel and inspired great optimism for the prospect of synthetic fuel to replace fuel from crude oil, supplies of which at the time were limited and expensive. With a view of avoiding an "energy crisis" and dependence on "foreign oil" (a newly coined phrase at that point), Congress extended the program twice for an additional eleven years and increased funding to $87.6 million. However, the next plants built could not produce fuel at such low costs and high volume that had earlier excited so much optimism in the industry.

In the 1950s, a combination of lowered expectations for the synthetic fuels industry, the opening of Middle Eastern oil fields, new private forays into coal hydrogenation, and a political shift in both the executive and legislative branches of the U.S. government, led to Congress ending funding for synthetic fuel programs in 1953. Low-level research continued in "backburner" mode by the interior department, and later this research was transferred to the newly created Department of Energy in the 1970s.

The increases in crude oil prices in the 1970s revived the synthetic fuel efforts, with a mixture of motives consisting of reducing dependence on imported oil and promoting the use of coal, especially coal mined in the eastern part of the United States. The Energy Security Act of 1980 established the Synthetic Fuel Corporation (SFC), which was set up to promote the commercialization of these technologies. The corporation was a quasi-governmental entity comprising private industry partners and initially authorized for a maximum of twelve years and a maximum of $88 billion. The interest in synfuels heated up throughout the 1970s, and by the end of that decade, synfuels research was a major component of the nation's energy program. Spurred by instability in the Middle East, the high price of crude oil and fears that oil supplies were drying up, projected dramatic

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[10] This section relies upon Cohen and Noll's (1991) discussion of the program as well as http://fossil.energy.gov/aboutus/history/index.html and http://www.fas.org/sgp/crs/misc/RL33359.pdf.

increases in future oil costs, and concern that “market failures” were inhibiting private companies to invest in research, the synfuels program again regained popularity.

Under the program, some technical progress was made and large-scale processes were developed. Coal gasification appears to have been the most successful of the technological investments. One facility, the Cool Water Coal Gasification plant, which was provided price guarantees worth $115 million, succeeding in coming under budget and meeting the expected production and quality standards. However, Cool Water was a rare success for the SFC. Ultimately, low crude oil prices reduced the economic and strategic imperative to develop synthetic fuels from coal or other sources. The SFC was unable to lay the foundations for a commercially viable industry, in part because the technology failed to support reliable and large-scale production of affordable synthetic fuels. The broad consensus is that the government’s synfuel programs failed, though there is less agreement on the causes of the failure.

At the risk of oversimplifying the contrast, the Synthetic Rubber Program succeeded because there was an enormous growth in demand for synthetic rubber, whereas the synthetic fuel program largely operated in an era of abundant, though occasionally expensive, oil and gas. Although price signals and signals about the future growth in demand are not the only ones that matter, they surely were very important for the failure of the synfuels program.

3.3 Diffusion and the Critical Role of Specialized Engineering Firms

In 1999, the world’s then largest greenfield refinery and associated chemical plants, embodying the latest technology available with an estimated cost of around $6 billion, was commissioned in Jamnagar, India. The event passed by with little comment. In marked contrast, when an Indian company announced the development of a new car nearly a decade later, there was extensive publicity. And yet refining technology was developed only in the 1920s, whereas the internal combustion engine is nearly a century and a half old. One can infer that chemical technology has diffused so broadly that it is considered unremarkable for the latest technology to be used in a poor country. Put differently, there is no need for an Indian firm to try to design its own refineries and chemical plants because the required technology can be readily acquired at a reasonable price. The rapid diffusion of innovative techniques and processes is one of the striking features of the chemical industry. This is particularly true of chemical innovations since World War II, the diffusion of which were fostered by SEFs.[11]

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[11] This rapid diffusion greatly accelerated the maturation of the chemical industry and the consequent wide-ranging restructuring that the industry underwent in the United States in the 1980s, followed shortly by a similar restructuring in Europe (Arora and Gambardella 1998).

In a pioneering study, Freeman (1968, 30) noted that for the period 1960 to 1966, "nearly three quarters of the major new plants were 'engineered,' procured, and constructed by specialist plant contractors." Moreover, Freeman found that SEFs were an important source of process technologies; during 1960 to 1966, they accounted as a group for about 30 percent of all licenses of chemical processes. Freeman's findings are confirmed by more recent data analyzed in Arora and Gambardella (1998). These data show that for the period 1980 to 1990, almost three-fourths of all chemical plants in the world were engineered by SEFs. Although the share of SEFs varies across different types of chemical products, in practically all of them it is above 50 percent. Moreover, SEFs still account for about 35 percent of all licenses. However, SEFs in the 1980s were perhaps more important than this figure suggests because their very presence induced many downstream companies to license their processes. In essence, SEFs helped create a market for technology, making process technology into a commodity that could be bought and sold.

The first SEFs were formed in the early part of the twentieth century, and their clients were typically oil companies. However, SEFs also started operating in bulk chemicals such as sulfuric acid and ammonia. Later, most SEFs would design large-scale plants for refineries and petrochemical building blocks, such as ethylene. Companies such as Kellogg Engineering, Badger Engineering, Stone and Webster, and UOP are prominent examples of early SEFs.

In addition to diffusion, the SEFs also played a crucial role in the development of new and improved processes. However, with a few notable exceptions, SEFs did not develop radically new processes. The contributions of SEFs have been largely in two areas: catalytic processes and engineering design improvements.[12] For the most part, however, major process innovations came from the large oil and chemical companies (Mansfield et al. 1977). The SEFs were most effective at moving new processes down the learning curve. By acting as independent licensers, SEFs also induced chemical firms to license their technology (Arora and Gambardella 1998). The SEFs provide a vivid illustration of the economies of scale operating at the industry level, rather than at the plant or individual firm. By specializing in process design and engineering and by working for a number of clients, SEFs could learn and accumulate skills and expertise that no single chemical company could match.[13]

Adam Smith noted more than 200 years ago that specialization and divi-

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[12] A number of other SEFs have contributed to advances in engineering design. For instance, Kellogg made significant contributions to developing high-pressure processes for ammonia in the 1930s, while Badger is associated with fluidized-bed catalytic processes (in collaboration with Sohio). Similarly, the Danish SEF, Halder Topsoe, is the leading source of technology for ammonia plants. Lurgi, a German firm, licenses a number of technologies, including coal gasification.

[13] As independent developers of technology, SEFs are similar in some respects to today's biotech companies, allying with a number of chemical firms in developing new technologies.

sion of labor are more extensive in larger markets. As Bresnahan and Gambardella (1998) demonstrate, a large market is important for technology specialists, but this growth in market must be in the form of an increase in the breadth (more buyers) rather than merely depth (each buyer becomes larger). Indeed, SEFs account for a greater share of licenses to small firms and firms in developing countries, indicating the mutual dependence between specialist technology suppliers and firms that are not technically sophisticated (figure 3.2).

The challenge of innovation is more than the mere discovery and development of new technologies and feedstocks. The technology and processes for using these alternatives will have an impact on the environment only if they are broadly diffused and used. Technology diffusion has been faster when firms like SEFs have played a role in offering technology, sometimes bundled with engineering services. Rapid diffusion of innovation in the chemical industry has resulted when major innovations were not concentrated in the hands of a few firms, no matter how innovative. Instead, multiple sources of innovations appear to have been desirable.

3.4 Innovation Policies in the Chemical Industry

Two policy areas stand out with respect to their effect on innovation in the chemical sector. First, intellectual property rights protection, particularly patents, has stimulated innovation and the diffusion of innovations. Second, licensing and antitrust regulations have fostered wider competition and sped up diffusion of technologies.

3.4.1 Intellectual Property Rights

The chemical industry has seen extensive technology diffusion though it also enjoys strong patent protection. Although this may sound like a contradiction in terms, it is not. In chemicals, although patents are effective in deterring straight imitation, rivals were often able to develop competing variants of patented chemical processes. These processes differed in terms of operating conditions, starting materials, or in terms of yields, conversion rates, and properties of the final material. The ability to develop different processes resulted in a vigorous competition in the market for technology and a rapid diffusion of new technologies.

Despite the importance of technology specialists, the chemical industry has largely been spared the problems that some nonmanufacturing patent holders have created in several information technology sectors. Patents largely work well in the chemical industry in that they encourage the invention of new technologies and follow-on investment in commercializing those technologies (Cohen, Nelson, and Walsh 2000). They also encourage the widespread use of new technologies. Chemical patents work better because they are less “fuzzy.” They are less fuzzy because the object of discovery can be described clearly in terms of formulas, reaction pathways, operating conditions, and the like (Levin et al. 1987). But it is not merely that the object of discovery is more discrete in the sense of being a particular compound. Rather, it is the ability to relate the "essential" structure of the compound to its function. This allows a patent to include within its ambit inessential variations in structure, as in minor modifications in side chains of a pesticide.[14] In fact, chemical product patents frequently use Markush structures, which permit a succinct and compact description of the claims and allow the inventor to protect the invention for sets of related compounds without the expense (and tedium) of testing and listing the entire set.[15] The ability to explicate the underlying scientific basis of the innovation allows the scope of the patent to be delimited more clearly. The obvious extensions can be foreseen more easily and described more compactly.

Conversely, when innovations cannot be described in terms of universal and general categories, sensible patent law can only provide narrow patent protection. Failure to do so results in costly patent disputes, sometimes with devastating consequences for the economy, as an early epoch in the history of the chemical industry itself shows. During the 1860s, for example, when synthetic dyes first appeared, their structure was poorly understood. Broad patents led to litigation and, in some cases, unwarranted and harmful monopolies. In France, an excessively broad patent on *Fuchsine* (aniline red) was construed to include all processes for making the red aniline-based dye, even though the structure of aniline dyes was as yet unknown. There were also long and bitter disputes in England about the validity of the Medlock patent for *magenta* (another aniline dye); the dispute turned on the appropriate definition of "dry" arsenic acid (i.e., with or without water of crystallization). In the case of *aniline blue,* the dispute rested on whether the substitution of an organic acid for an inorganic acid in the production process was enough to avoid infringement (Travis 1993). The British courts interpreted patents narrowly, with the result that competition in the British organic dyestuffs industry remained vigorous until the industry itself was overwhelmed by its German rivals. By contrast, the *Fuchsine* monopoly in France devastated the local industry. It should be recalled that France at first rivaled Germany in organic chemistry, but the French synthetic dye industry greatly suffered from the *Fuchsine* dispute.

Until World War II, chemical producers did use patents to restrict entry and carve up markets. However, after the war, patents were used more frequently to facilitate technology licensing, particularly outside home mar-

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[14] In some instances, seemingly minor variations in side chains can have significant biological effects. Therefore, what is a "minor" variation is itself determined by the state of the current understanding of the relation between structure and function.

[15] A Markush structure is best understood as a language for specifying chemical structures of compounds, which allows generic representation for an entire set of related compounds. See Maynard and Peters (1991) for details.

kets. In a marked departure from their pre–World War II strategy of closely controlling their technology, a number of chemical and oil companies began to use licensing as an important (although not the only) means of profiting from innovation. Spitz (1988, 318) describes the licensing of the Hercules-Distillers phenol/acetone process "to any and all comers"; the process "was commercialized in 1953 and forever changed the way that phenol would be produced." This remarkable change in behavior appears to have been triggered in part by a newly vigorous antitrust policy in the United States, an issue that we discuss in some depth in the following.

One reason why patent protection promoted diffusion of technology was the greater competition after World War II in both product markets and especially in the market for technology. When multiple sources of technology exist, then even when the technology sources are not exact substitutes, they can provide effective competition. Arora and Fosfuri (2003) formally show that the presence of other technology holders, especially those that do not participate in the product market, encourages licensing, facilitating entry downstream.

It is also noteworthy that SEF licensing activities appear not to have been hindered by patenting. Indeed, in processes in which high rates of patenting occur, SEFs are more active than in processes with low rates of patenting (figure 3.1). Insofar as patenting rates are indicators of technological activity, this suggests that SEFs are active in diffusing technologies not simply in mature sectors, but also in sectors with high rates of technical advance.

An active technology market has also encouraged new entrants into the product market. Arora, Fosfuri, and Gambardella (2001) show that markets for technology encourage investment by chemical firms in developing countries, implying that technology suppliers lower entry barriers. Lieberman (1989) finds that licensing was less common in concentrated chemical products, and the limited licensing that did take place was by outsiders (nonproducers and foreign firms). Moreover, he finds that when licensing was restricted, there was less entry. In a related study of twenty-four chemical product markets, Lieberman (1987) reports that patenting by outsiders was associated with a faster decline of product price, once again suggesting that outside patenting encouraged entry in the product market. This is borne out by Arora and Fosfuri (2000), who show that the principle source of demand for technology licensed by SEFs are small firms in Western markets (North America, Japan, Western Europe) and firms in developing countries (figure 3.2).

3.4.2 Licensing and Antitrust Regulations

As we noted in the preceding, post–World War II, chemical firms have tended to license their technology, which has greatly contributed to technology diffusion. Ralph Landau observed in 1966 that the "the partial breakdown of secrecy barriers in the chemical industry is increasing . . .

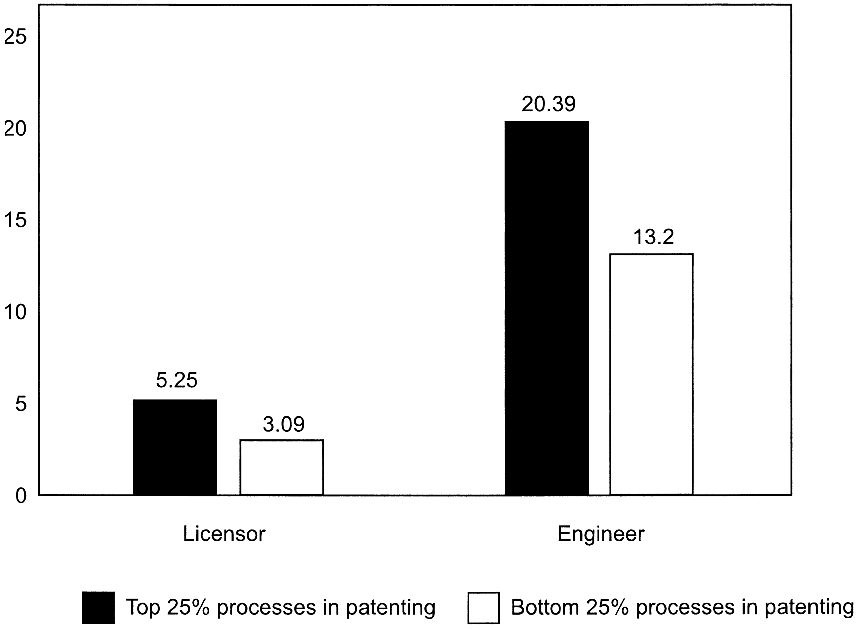

Fig. 3.1 Average number of specialized engineering firms by patent intensity in process, 139 process technologies (1980–1990)

Source: Our calculations, based on Chemical Age Project File (1991) data.

Note: The top 25 percent processes are in the top quartile in terms of the number of patents, and the bottom 25 percent of the processes are in the last quartile in terms of the number of patents filed.

the trend toward more licensing of processes" (Landau 1966, 4). Chemical firms have licensed heavily because they have faced competition in both the product and the technology markets. These two types of competition are interrelated. A competitive product market will encourage the entry of technology specialists (Bresnahan and Gambardella 1998). When Standard Oil, with its dominant position in the oil market, tried to restrict access to refining technology, the independent oil firms turned to specialized technology suppliers such as UOP. More generally, at crucial stages in the industry's history, antitrust rulings have directly increased competition in the product market and also reduced concentration of technology ownership, increasing competition in the market for technology.

The two firms prominently featured in the context of antitrust enforcement in the United States were Standard Oil and DuPont. William Burton, a scientist at Standard Oil developed the first commercially successful cracking process, a first major innovation in refining technology, in 1909 to 1910. However, Standard Oil was reluctant to invest in the process. As a result of an antitrust suit, the original Standard Oil was broken up into several firms

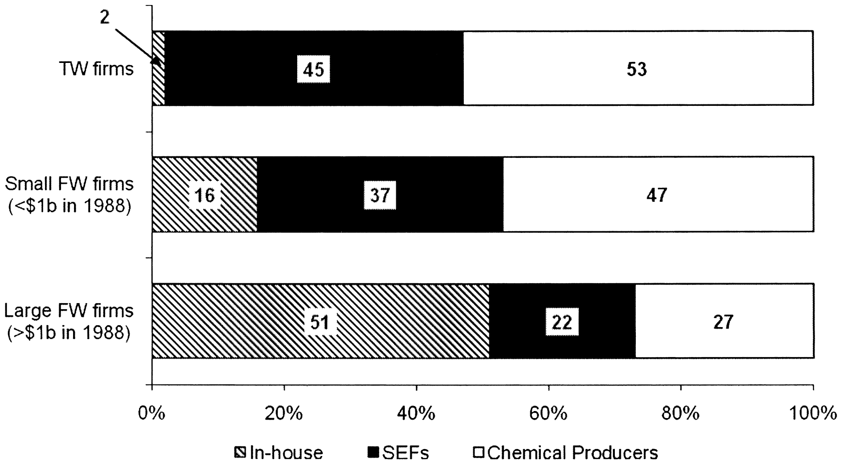

Fig. 3.2 Share of specialized engineering firms in technology licensing by type of buyer

Source: Arora and Fosfuri (2000).

Notes: TW = third world. Includes all countries except those in Western Europe, Japan, North America, Australia, and Eastern Europe (except Soviet Bloc). FW = first world. Comprises Western Europe, Japan, North America, and Australia. Large FW = first-world firms with turnover greater than $1 billion in 1988. Small FW = all other first-world firms.

in 1911, among which was Standard Oil of Indiana, where Burton worked, and which not only commercialized the process but also licensed it to a number of other oil refiners. The high royalty charged by Standard of Indiana led others to develop alternative processes, among which was UOP, which eventually developed into a leading supplier of technology to the petroleum refining industry.

The case of DuPont provides another important example of the role of antitrust policy. Founded as a maker of explosives powder, DuPont was split into three separate firms following a successful antitrust suit in 1913. The antitrust suit convinced the management of DuPont that the only path to future growth lay in entering new markets through innovation rather than acquisition of existing producers. In 1926, DuPont signed a comprehensive technology sharing agreement with Imperial Chemical Industries (ICI), which also involved market-sharing.[16] The agreement entitled DuPont to exclusive access in the United States to ICI technology, such as polyethylene. However, the fear of antitrust action pushed ICI to license polyethylene to other firms as well after World War II. Similarly, DuPont was nudged into licensing its nylon technology (and know-how) to a Monsanto joint venture, Chemstrand, in 1951. More recently, antitrust authorities in the United States and Europe intervened when Dow Chemical acquired Union Carbide.

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[16] The agreement would be dissolved in 1952.

The antitrust ruling attempted to try to maintain competition both in the polyethylene market as well as in the market for polyethylene technology.[17]

The more general point is that licensing flourished when firms faced competition from other technologically capable firms (whether at home or abroad) and licensing itself facilitated entry into the industry. The second tentative conclusion from the history of the chemical industry is that antitrust enforcement, including the occasional episodes of compulsory licensing, does not appear to have had a chilling effect on innovation. Part of the reason that innovation flourished is that in the United States, the industry has had multiple sources of innovation. No single firm, not even DuPont, has dominated the chemical industry, in the way I.G. Farben and ICI dominated their respective national industries between the two world wars.

3.5 Conclusions and Caveats

Three noteworthy aspects of innovation characterize the chemical industry.[18] First, chemical innovations are deeply rooted in science. However, despite a worldwide tradition of government support for scientific research, chemical R&D has been largely privately funded. In the United States, federal government support for chemical research, already at a relatively low level, has steadily declined over time. Second, other than early in the history of the industry when new dyes relied upon the scientific advances in organic chemistry led by German chemists, innovations have largely come from firms rather than universities. Universities, on the other hand, have played an important role in institutionalizing the learning, creating new disciplines (which have been crucial for sustaining innovations), and developing human capital. Third, the major phases of chemical innovation have been accompanied by large growth in demand.

These three aspects are closely related. The chemical industry rose to prominence when government support for research was uncommon, chemical innovations could capture large markets by substituting for a variety of materials used as industrial inputs, and the scientific understanding linking the structure of their materials to their properties could increase the productivity of attempts to discover new and useful materials. Thus, it made commercial sense for firms to invest not simply in applied research, but also in basic research—an area typically the domain of universities and government programs. Therefore, chemical innovation has relied more heavily than some other innovation-based industries upon private investments in research, development, and commercialization. Correspondingly,

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[17] Dow Chemical and British Petroleum (BP) Amoco were competing against Univation Technologies, a joint venture of ExxonMobil and Union Carbide. Dow and Exxon held the basic catalyst patents, and BP and Union Carbide supplied process technology for polyethylene. As a condition of the acquisition, Dow made its catalyst technology available to BP-Amoco.

[18] The beginning of this section draws upon Arora (2002).

government supported research, and university discoveries, have been less important.

However, although they feature centrally, established firms have not been the only actors in chemical innovations. Rather, they share the stage with a variety of other firms, including start-ups. If nylon and polyethylene were discovered in corporate labs (of DuPont and ICI, respectively), polyester, the most successful synthetic material used in everything from clothes to plastic bottles, was discovered by chemists working for the Calico Printers Association, a group mostly concerned with textile printing. The fundamental advances in catalysts for producing polyethylene and polypropylene came from the work of Karl Ziegler, a German chemist funded by the local coal industry association, and from a small oil company in Oklahoma, Phillips. If the first major refining technology, thermal cracking, originated from Standard Oil, the next one, catalytic cracking, was invented in 1936 by Eugene Houdry, a French engineer who moved to the United States to commercialize his invention. The technology was significantly improved by a group of firms led by Standard Oil of New Jersey. The implication is that innovation in the chemical industry has drawn upon a diverse range of sources, including corporate R&D labs and government programs, but also a variety of small firms and start-ups.

Large government initiatives have had mixed success. They have been successful in coordinating private decisions when innovation required complementary improvements in inputs and uses, as well as large investments in complementary infrastructure. They have been successful in coaxing incremental technical advances, which have cumulatively contributed significantly to productivity growth. The record of such initiatives in producing significant new technical advances in the chemical industry is poor, in part because these initiatives have had conflicting goals, such as increasing the efficiency of existing technology along with the development of new technologies.

The history of the chemical industry shows that technology has diffused effectively through markets for technology, without need for direct government subsidies. Markets for technology have also offered a prominent role for start-ups and other types of technology specialists, such as SEFs, which have been the engine of diffusion for chemical innovation as well as a frequent contributor. The chemical industry's history shows that indirect government policies that promote competition in the product market as well as in the market for technology can promote technical advance and productivity growth.

Competition in the technology market does not imply weakening intellectual property protection; rather, strong patent protection can facilitate competition by encouraging innovation by firms outside the industry, including start-ups. However, broad patent protection is effective when the underlying knowledge base is strong. For new bodies of knowledge, narrowly crafted patent protection works better at encouraging innovation and preventing logjams. In addition, from time to time, antitrust policy has prevented chemical technology ownership from being concentrated in a few hands, enhancing competition among technology holders.

History rarely repeats itself, and its lessons cannot be applied mechanically. However, it appears that as was the case of chemical innovation, energy innovation is more likely to be successful and effective when private R&D from diverse sources is stimulated and strong patents protection is combined with robust antitrust enforcement.

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