The End of the Chemical Century? Organizational Capabilities and Industry Evolution

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The latter decades of the twentieth century have revealed a dynamic version of industrial capitalism that represents a marked departure from the more stable variety that dominated the first three-quarters of the century. Unfortunately, most of our concepts for understanding economic phenomena are based on equilibrium models that can only account for incremental changes from optimal conditions. In business history, Alfred D. Chandler, Jr. [9] has developed concepts that explain the relative stability of industrial capitalism, but can his model also account for instability and change? At an abstract level, Chandler's analysis posits that large firms exist because they have *organizational capabilities*; that is abilities and knowledge that are peculiar to their institutions. Some of these abilities are organizational: ways to gather, process, and act upon pertinent information. Some of these abilities are know-how--ways of doing things. When combined with economies of scale and scope in production and distribution, organizational capabilities allowed large firms to enjoy long periods of growth and profitability.

This paper explores the evolution of organizational capabilities in the chemical industry, one of the great "Chandler" industries of the past 150 years. The industry was very stable until recent decades when numerous mergers, asset sales and swaps, and, demerging--firms dividing themselves into separate companies--have reshaped it. Recently, Union Carbide spun off its industrial gas business as Praxair; ICI America split itself into two companies creating Zeneca, a biology-oriented entity; and Eastman Kodak announced plans to separate itself from Eastman Chemicals [1; 5; 7; 11; 17; 20; 22; 25]. How can one account for all this churning in an industry that was one of the most stable and profitable for most of this century? Is this a response to the development of the market for corporate control? The demerger of ICI might have been inspired by a takeover attempt by Hanson [17]. To pay for the acquisition, Hanson probably would have sold or split-off ICI's profitable pharmaceutical and agricultural chemical businesses to pay off the investors. The new entity, Zeneca, is less likely to be undervalued by the stock market, which would close the door on would-be corporate raiders.

This analysis does not answer the question as to why a traditional diversified chemical company was undervalued in the first place. The chemical industry has been labelled "mature" since at least the beginning of the 1960s [30]. Maturity can be defined by a set of symptoms including slowing growth,

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lower profit margins, and falling product prices. The causes of maturity are more obscure and are often attributed to too much competition. If this is the case, how did too many competitors overcome the barriers of economies of scale and scope and organizational capabilities that had kept competition gentlemanly for decades?

Are there deeper structural reasons for the transition of the chemical industry? My answer is yes, because the organizational capabilities of chemical firms have largely become generic; that is, anyone can acquire the capability to manufacture chemicals without having to buy out DuPont or Dow. Also, changes in chemical technology led a convergence that largely eliminated firm specific organizational capabilities. When the industry's organizational capabilities became obsolete, sometime between 1955 and 1965, a flood of new entrants and companies entering new markets led to chronic overcapacity [27]. In an attempt to win the battle of market share, companies bet on economies of scale that insured that large total capacity increases flooded already crowded markets. After decades of cut-throat competition, it now appears that a new round of consolidation will put the industry on a more profitable basis, except in basic petrochemicals where government investment in developing countries continues to bring onstream additional unneeded capacity [10]. In the past decade United States chemical companies have shut down 25% of their basic petrochemical capacity [7]. In most other sectors, the chemical companies are still betting on economies of scale to maintain market share and profitability in a narrower range of product lines [8].

The chemical industry has gone through periods of consolidation in the past, especially between the wars. What makes this current period different is that in the past consolidation in older products was accompanied by dramatic expansion in new products based on organizational capabilities that were specific to particular firms and the industry generally [27]. Today the industry has no dynamic strategy and constantly shifting structures. Following a more general industrial trend, it has adopted the dubious tactic of personnel reduction in an industry where labor costs are a small fraction of total costs [18]. The other major thrust is to increase market share in large existing businesses. In terms of structure, companies are experimenting with different ways of organizing their businesses [6; 8]. In general, the trend appears to be toward profit centers. Dow has recently reorganized its businesses into 32 profit centers [12]. DuPont created a new vertically integrated organization to run its nylon business [13].

In highly competitive product lines in which one company has little advantage over any other, centralization makes sense. Nevertheless, it is a very difficult transition for an industry that has experienced high growth and profits from a host of revolutionary new products for most of this century.

The chemical industry was so successful for so long because it developed the ability to apply chemistry and chemical engineering to the manufacture of new compounds and materials. This was not a case of simply exploiting science for technological purposes. In fact most important technological innovations are initially not very well understood scientifically [2]. This is almost a necessary condition for a radical innovation. If it were a straightforward application of existing science, then the innovation would be obvious to many investigators. After a laboratory breakthrough has been made, the scaling up of the process for large scale production requires another set of skills. These two critical organizational capabilities were necessary for establishment of the chemical industry in the nineteenth century.

The chemical industry was an entirely new industry that found a niche for itself between suppliers and processors of natural or raw materials and down stream producers of consumer goods. The chemical industry fit into this niche because the traditional companies, usually but not always, did not integrate either forward or backward. An important reason for this lack of movement was the difficulty in understanding and controlling chemical reactions to make products at a reasonable cost. There were difficulties at two levels. First, there was the basic chemistry of chemical reactions, which was beyond the purview of science until the latter half of the nineteenth century. Of course, entrepreneurs do not have to know what they are doing to be successful, but they do have to be able to produce repeatable results. Even if a chemist could make a reaction go the way he wanted in the laboratory, the scaling up to a large process involved numerous technical problems that had to be solved empirically. Linking the chemical reaction and the large scale plant is the catalyst, a substance that makes the reaction proceed in the proper direction and the appropriate speed. Catalysis is a nonintuitive concept that still lies on the periphery of science. The technology of these essential materials evolved slowly during the nineteenth century; understanding of them remained minimal.

By the late nineteenth century there emerged a clearly articulated vision for the "chemicalization" of industry generally. Arthur D. Little, who was an expert on the new chemical process to make paper, was one of the major visionaries [27]. Chemicalization consisted of three prinicples. First, the application of basic chemical principles, such as the law of conservation of matter and basic chemical techniques such as analysis would lead to significant improvements in virtually all processing industries. Second, the natural chemicals that were used in processing industries could be made synthetically or replaced entirely by new synthetic ones. Third, basic *materials* could also be replaced by new or synthetic ones [15].

The overall mission of chemicalization led to a fraternal relationship between chemical companies. The opportunities for growth appeared to be so immense that there was little reason to compete for bits of turf. There was a whole world of industry to be chemicalized. Another reason for cooperation was a technical one. The number of potential industrial chemicals rises exponentially with the number that are already available. Therefore it did not make sense for a company to invest in the same chemicals that others made. Instead, each company tended to specialize around certain technologies, which represented the accumulated chemical and engineering knowledge that existed in each firm and could not be easily duplicated by rival firms. Thus, there were unique organizational capabilities in each firm. Chemical companies were each others' best customers. This interdependency promoted cooperative rather than competitive behavoir [27].

During this era of success and prosperity, a transformation of the chemical industry was beginning. Progressive elements within industry and academia were aware that chemical technology had run far ahead of science and that the gap was getting wider. It was not that academic chemists were not working on important problems in chemistry; it was just that the problems they selected were not relevant to the work of industry. So some companies began to do more academic-style research on subjects of industrial significance. There was also a growing realization in academe that the resources of the chemical industry were enormous and could be tapped to support industrially relevant research [16; 27].

When an industrial technology becomes a big business, academic researchers are attracted to it because the new technology usually poses interesting scientific questions and there is potential for support. Corporations have supported university researchers working to put a firmer scientific foundation under their technologies. What corporations did not fully realize is that academic research creates a large amount of generic knowledge that makes entré into a particular technology much easier [23]. Therefore, the progressive industrial patronage of academic research helped to undermine the organizational capabilites of the donor firms.

One important rapproachment between the chemical industry and academia occurred in the chemical engineering department of MIT. Led by Warren K. Lewis, MIT chemical engineers created a research agenda to establish a more generalized, systematic (scientific) underpinning to their art. The MIT creed soon spread to other colleges and universities through Lewis's pioneering textbook, *The Principles of Chemical Engineering* [29]. The long term importance of this agenda was to make the generic component of chemical engineering grow at the expense of specific practice. In other words, when designing a chemical plant, chemical engineers now had a set of generalized principles that applied to all chemical processing. Thus, the amount of specific knowledge needed to build a particular plant decreased. As the modern academic profession of chemical engineering grew and prospered, the university emerged as a center of generalized knowledge and matriculated chemical engineers spread the gospel to a host of processing industries. Chemical engineering capabilities were becoming relatively more common and inexpensive to acquire.

In chemical research, a few large companies, DuPont and I.G. Farben especially, also began to initiate programs to improve the scientific understanding of their own products and processes. The most dramatic example was polymers or long chain molecules. One of the most important materials used in the chemical industry was cellulose derived from wood. After processing, it was sold as rayon fibers, cellophane film, celluloid plastics, movie film, and fast-drying lacquers. DuPont during the 1920s had become primarily a cellulose processing company selling all the above products. Inspite of its importance, cellulose remained a mysterious molecule. This was also the case for the increasingly numerous synthetic resins, such as commercially successful Bakelite [16; 27; 29].

To remedy this situation in polymers and other important areas of chemical technology, DuPont central laboratory research director Charles M.A. Stine, in 1926, proposed that the company hire prominent academic chemists and put them to work on industrially relevant topics. When it proved impossible to attract established academics into industry, Stine settled for younger Ph.D.s. In two areas, polymers and chemical engineering, Stine succeeded in hiring outstanding young researchers. It was in the just emerging discipline of polymer chemistry that DuPont struck gold--or more precisely, nylon. To work on polymers Stine hired Wallace H. Carothers, an assistant professor of organic chemistry at Harvard. In his research at DuPont, Carothers elegantly and convincingly demonstrated that polymers were not mysterious entities but just longer versions of ordinary organic molecules. To prove this assertion Carothers developed techniques for making polymers out of ordinary organic molecules. From the technological perspective, these techniques could be used to make innumerable new materials that might have commercially useful properties. Two such products, neoprene synthetic rubber, (1930), and nylon, (1934), were discovered serendipitously during experiments designed for purely scientific purposes [16].

Once the chemists had shown that neoprene and nylon had some potentially useful properties, the chemical engineers had to figure out how to manufacture these materials on a commercial scale. The intermediate chemicals used to make the polymers were laboratory curiosities and methods for controlled large scale polymerization did not exist. Led by MIT trained chemical engineer Crawford Greenewalt, DuPont overcame the technological barriers confronting nylon; at the same time, neoprene was developed by an equally competent chemical engineer. The neoprene and nylon experiences gave DuPont a tremendous new organizational capability that it would exploit for decades [16].

The uniqueness of this capability began to erode at the same time that it was being established. One aspect of the scientific research program at DuPont was publishing, which kept chemists happy and created good will in academia. But Carothers' published papers taught other chemists how to make polymers and directly led to the discovery of a different type of nylon and polyester by other researchers. In general during the 1930s many polymers with potentially useful properties were discovered but the commercialization was very risky in terms of both technology and markets [16].

The diffusion of polymer science and technology was greatly abetted by World War II. The United States government invested heavily in polymer products to replace scarce or unavailable materials. The most dramatic example was synthetic rubber. When the Japanese attacked Pearl Harbor the United States depended on natural rubber from Southeast Asia. During the war, an industry-government-university effort established a giant synthetic rubber industry which produced two million tons of rubber for the war effort. In adddition to creating a new industry, the synthetic rubber project and other similar ones acted to accelerate the development of polymer science and the diffusion of polymer engineering. After the war many American chemical, oil, and rubber companies had organizational capabilities to manufacture, fabricate, and market polymer products [27].

Entering the post war era, the chemical and allied industries manufactured a wide range of polymers which replaced other materials in a vast array of uses from toys to packaging and structural uses. Polymers would be the major growth area of the chemical industry throughout the 1940s, 1950s, and 1960s. Although the development of new polymeric materials became commonplace, companies did maintain significant organizational capabilities through relationships with downstream fabrication. DuPont's knowledge of textile fibers and close relationships with textile companies gave it the dominant position in the development of the synthetic fiber industry generally. During the 1950s these organizational capabilities eroded and new competitors entered most segments of polymer markets. By the 1960s however the development of polymer science and technology had led to a flood of new products which increasingly competed with other polymers for market niches. Everyone jumped on the polymer bandwagon and soon it began to sag from the weight of all the riders. Although polymers were clearly the most important new sector of the chemical industry, there were other important growth areas [16; 27; 29].

World War II unleashed three other technological trajectories that would carry the industry for decades: petrochemicals, pesticides, and pharmacueticals. As synthetic rubber had done for polymers, other war projects acted as prototypes for subsequent developments. The chemistry and engineering behind these fields was still in an embryonic stage, so they offered the possibility for firms to develop unique organizational capabilities.

Petrochemicals resulted from the technological capability to break up crude oil molecules and recombine them into specific compounds [10; 29]. The core of these technologies were catalysts and integrated plant chemical engineering. The latter consists of the ability to optimize the performance of a complex plant consisting of many processing units producing many different products. Before the war the oil companies had lagged in developing capabilities in these areas, an oversight that created opportunities for individuals such as Eugene Houdry and J. Ogden Armour. Both developed processes for "cracking oil" into smaller molecules. Armour's Universal Oil Products Company (UOP), before being bought by a consortium of oil companies (to avoid paying royalties) in 1931, began to do research on catalytic petrochemical processes. During World War II, UOP made important contributions the development of fluidized bed catalytic cracking of crude oil for gasoline production--the technology still used today. After the war the oil companies spun off UOP to avoid antitrust problems. The new independent company soon stunned the oil industry with its new catalytic process, Platforming, that dramatically improved the octane rating of gasoline. It also led to the production of important aromatic hydrocarbons such as those used to make nylon and polyester [29]. Previously these chemicals had been extracted from coal. UOP had developed expertise in the key capabilities in these industries, catalysis and integrated plant design chemical engineering, ahead of most of the oil companies. To build plants they teamed up with oil companies or construction companies. Thus, UOP developed critical organizational capabilities for the petrochemical industry without building a large organization.

Other entrepreneurs, usually chemical engineers, realized after World War II that the manufacture of chemicals from petroleum would be a major growth area and that neither the traditional chemical companies nor the oil companies had fully acquired the needed skills. One of the most successful of these entrepreneurs was Ralph Landau who founded Scientific Design Company in 1946. Like UOP, Scientific Design developed in-house capabilities in catalyst research and integrated plant design chemical engineering [29]. Because these capabilities would have been expensive to acquire, the oil and chemical companies often licensed Scientific Design's processes. By working with numerous companies and by licensing their processes, the engineering companies accelerated the technical development of the petrochemical industry. They also allowed other companies and countries to enter the petrochemical industry through turnkey plant acquisitions. Not surprisingly, in the 1950s and 1960s the industry was invaded by many newcomers, including a shipping company and a retail drug firm [7; 27; 29]. The petrochemical-polymer team accounted for about half of the industry's sales by the 1960s [27].

The second major growth area--pesticides--offered chemical companies the opportunity to develop significant organizational capabilities, primarily in research [3]. The first modern pesticide, DDT was discovered by Paul Mueller in 1939 after twenty years of searching for a chemical to protect wool from moths. His experimental technique consisted of getting samples of chemicals and testing them on moths. After the war chemical companies developed an elaborate set of animal, insect, and plant screens to determine the physiological activity of compounds. There was considerable art to designing screens and interpreting the results. During the 1950s and 1960s chemical companies discovered dozens of chemicals that exhibited useful insecticidal, herbicidal, and fungicidal properties. Just when the polymer-petrochemical complex showed signs of maturity, agricultural chemicals gave the industry a boost in the 1960s and 1970s. In recent years, however, innovation and sales growth have declined. In addition, the high cost and unpredictability of research in this area, the problems of regulation and liability (for example, DuPont's catastrophic experience with its Benlate fungicide), the saturation of markets, and the lack of growth in farming have combined to take the lustre off agricultural chemicals [4].

The third wartime development, the mass production of penicillin, sparked the transformation of the pharmacuetical industry from a primarily chemical-based industry to one centered more on biological science and biochemical engineering. Most of the companies that made this transition were already in the pharmaceutical and/or fine chemical business. For chemical companies the entré into this business was by acquisition, which was a diversification into a new business with different organizational capabilities. The discovery of new drugs is a difficult research process that depends on an elaborate system of screens or the discovery of new metabolic pathways. In recent years, innovation in the pharmaceutical industry has slowed dramatically, the primary reason appearing to be the exhaustion of current research trajectories [26]. Until one or more breakthroughs occur, possibly from genetic engineering, the pharmaceutical industry will become increasingly competitive and not a major field for diversification for chemical companies.

As early as 1960, some chemical company executives saw that the post war growth fields were becoming increasingly competitive signalling that future major developments in these fields were becoming increasingly unlikely. DuPont, which believed that its real organizational capabilities were organizational and managerial, explored diversifying into aircraft construction and amusement parks. When these steps proved to be too radical for a family dominated, tradition bound company, DuPont tried to repeat the past. The company revitalized its Development Department, which had orchestrated the first round of diversification in the 1910s and 1920s [16]. This appears to me to be creating a structure to take the place of a strategy, or creating structures to discover strategies. When a company is exploiting a successful strategy, there is little need to articulate it because everyone implicitly knows what it is. For DuPont that strategy had long been the replacement of natural substances with sophisticated synthetic ones made from relatively inexpensive raw materials. DuPont tenaciously held to the middle ground between raw materials and final processors.

Without a new strategy, the 1960s innovation initiative at DuPont failed to establish new trajectories or traditions. Everybody worked within the older regimes and the results were predictable--a host of high performance polymers that cost a fortune to commercialize and had difficulty finding profitable market niches [16]. Recently Dow has repeated the DuPont experience. Dow had for a long time thrived as a low cost producer of commodity petrochemicals. Dow had been the first chemcial company to move to the Gulf Coast, had pioneered in modern petrochemical plant construction, and had moved aggressively into Europe after World War II. In the mid-1980s the company realized that it no longer had any specific organizational capabilities in these areas. Like many other chemical companies it jumped on the bandwagon of specialty chemicals. However, this field is relatively small and already has many competent firms in it. Another Dow move was to purchase a pharmaceutical company, Merrill Labs which makes the blockbusters Seldane anithistamine and Cardizem heart drug. These drugs, however, are facing difficulties and like other pharmaceutical companies, Merrill does not have major new drugs in the pipeline to replace them. Repeating DuPont's history, Dow recently created a corporate level organization to orchestrate the company's movement into new product lines [7; 8; 12]. Again, I believe, a structure in search of a strategy.

In general in the 1970s and early 1980s the chemical industry hunkered down and tried to survive, environmental regulation, oil shocks, and recessions. When no new major initiatives were forthcoming during the Reagan Prosperity, the financial sharks began to move in. The Bhopal disaster in 1984 opened the flood gates for wholesale "restructuring" [7; 29]. The chemical industry is still big and powerful. Rather than be at the mercy of the financial market for corporate control, the chemical industry has attempted to restructure itself, if only to increase the value of its stock [7; 8]. Generally, this restructuring has been based on the assumption of future industry stability. Industry leaders expect that there will be moderate but unexciting growth in the market for most chemicals and that the products that are currently manufactured will not be threatened by major innovations. The industry is thinning down and cutting costs to fight to the death over market share in core product lines. Chemical companies are realigning resources to best serve today's customers.

What of the R&D goose that once laid the golden eggs? Research might still be the area in which organization capabilities are important. The relationship between the structure and properties of chemical compounds has not fully become a science. Chemists have become very clever at making new molecules but the process of determining efficacious uses of those molecules still requires an unusual degree of insight. The history of chemical research is rich with tales of serendipity because of this fact. The stories are somewhat misleading because they emphasize the creation of a new chemical compound instead of the *recognition that the new compound has a combination of unusual properties that might find commercial applications.* Of course, the more knowledge there is within a corporation of the uses of chemicals in the outside world, the more likely a match will be made between a compound and a use. Information continually flows into the corporation from the ongoing contacts with customers. The odds of making a match between novel compound and profitable niche are increased dramatically with the breadth of exposure. With the streamlining of chemical companies and the redistribution of research resources into narrow profit centers, I wonder if future potential innovations will be overlooked.

Research alone is not enough to reinvigorate an industry. The science of chemistry has continued to progress and industry continues to produce marvelously sophisticated new products. These products have not become major market successes because they are competing in already crowded market niches with other reasonably good products [21]. To restore its youthful vigor the chemical industry will have to develop new organizational capabilities. The task today is more difficult than it was in the past because the world-wide scientific and technological infrastructure is so well established. In terms of materials, composites appear to very promising but the research field is already crowded. In order to gain important new capabilities the chemical industry might have to integrate forward. In order to get industry to use composites, the chemical industry might have to do the fabricating of final products. The automobile industry might be a good customer for composite automobile body parts. Another example, is the chemical industry's attempts to develop a new wave of agricultural chemicals based on seed-pesticide combinations. The seeds are genetically altered to build in resistance to the company's particular herbicide [4]. This could lead to a forward integration of chemical producers into the seed business. It is still entirely possible that a new wave of innovation based on new technological trajectories into new markets is possible but it does seem clear that the the industry will have to develop new organizational capabilities to make this transformation occur [14; 32].

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