Why did chemical engineering emerge in America instead of Germany?

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As a scientific productive activity, engineering associates closely with natural science on the one hand and industry on the other. The America's industrial structures and academic institutions influenced the emergence of chemical engineering. The science-oriented characteristic of chemical engineering in turn affected the development of industrial structures, especially the rapid rise of a competitive petrochemical industry.

Chemical engineering and its beginning

Chemical engineering is quite peculiar among the many branches of engineering. Other branches – civil, mechanical, electrical, aerospace – are mainly applied physics. Chemical engineering is unique in integrating chemistry with physics to investigate systematically industrial processes of chemical production. Biochemistry is, alongside genetics, a major strand of molecular biology. Molecules, the transformation of which is the fort of chemistry, are ideal building blocks on the nanometer scale. Chemical engineering occupies a strategic position in the Big Things of the twenty-first century: biotechnology and nanotechnology. It is well prepared for the challenges, partly because from its inception it has adopted the open spirit of science, developed principles susceptible to modified generalization and ready to jump on new knowledge to make it productive. (Its ranks boast the highest percentage of PhDs than any other branch of engineering in the United States).

Historians generally agree that chemical engineering was developed by the Americans in the beginning of the twentieth century. By that time, organic chemistry was almost a century old, and inorganic chemistry, counting from Antoine Lavoisier's pioneering work in the 1780s, even older. Industries for inorganic chemicals were widespread. Organic chemicals were more complicated, but industries using them to make dyestuffs, pharmaceuticals, and other products were quite advanced. Why did chemical engineering come so late?

The lucrative organic chemicals industry was dominated by Germany. Its dyestuffs firms, the first to realize the importance of maintaining a technological edge, established the world's first industrial research laboratories. Industrial researchers cooperated closely with staffs of graduate schools, another institution pioneered by the Germans. Together they made Germany the world leader in research, chemistry, and chemical industry, attracting students and professionals from many other countries. The three American who founded chemical engineering, William Walker, Warren Lewis, and Arthur D. Little, had all studied in Germany.

When, back home, the Americans were struggling to development the contents for this new branch of engineering, the Germans invented and industrialized the Haber-Bosch process to synthesize ammonia and produce synthetic fertilizer commercially. The Haber-Bosch process, winner of two Nobel Prizes, is even today acknowledged as one of the crowning achievements in chemical engineering. Yet it was not the work of chemical engineers; Fritz Haber was a chemist, Carl Bosch a mechanical engineer. Cooperation between chemists and mechanical engineers was the standard practice in Germany. Its prowess was proved by thriving industries.

Why didn't the Germans develop chemical engineering? They surely had the brains. What did the Americans find wanting in prevailing practices? What advantages did chemical engineering bring? What new technologies did it bring? To try to answer these questions we have to examine the industrial structures in the two counties as well as the technical contents of chemical engineering itself.

Products and processes of production

What purposes does chemical engineering serve? To understand its functions, we must distinguish between a product and the process of its production. An automobile is a product, mass production a process. Consumers, who come into contact with products only, seldom think about production processes. Without efficient processes, however, they would not be offered such great varieties of products at such affordable prices.

Product and process both require engineering, but different kinds of engineering. In chemistry it may be confusing, because chemical reactions are usually called processes. We will not use this term and reserve "process" for production process on the industrial scale.

Students in chemistry classes shake a test tube or stir a beaker over a flame to speed up a chemical reaction. Industrial plants cannot simply shake or stir a thousand-liter tank over a furnace, not because it is too heavy but because it is too dangerous. Heat transportation and distribution is much more difficult in large containers because of their relatively small surface-to-volume ratios, and uneven distribution in a tank of chemical reactants can end in a deadly explosion.

To scale up a chemical reaction from test-tube to industrial level requires a lot of knowledge and effort. This is apparent in the Haber-Bosch process. Haber's method for synthesizing ammonia required temperatures up to 500°C and pressures up to 1000 atmospheres. Because such high pressure and temperature were enormously difficult to attain on the industrial scale, his invention might have remained a laboratory curiosity. Fortunately, BASF, armed with the world's first industrial R&D facility, invested heavily in developing processes for high volume production. The complexity of scale-up was acknowledge by the Nobel Prize awarded Bosch, who headed the scaling-up project, (Haber had got his already).

In production processes chemical engineering found its niche. But the question remains: Why did the Germans left it to the Americans? To answer this question, let us take a look at the structures of chemical industry in the two countries.

Chemical industries and engineering

Germany	USA
● economy of scope	● economy of scale
● fine chemicals: dyestuffs, drugs 137,000s in thousands of dyes	● heavy chemicals: soda, petroleum 2,250,000 tones of sulfuric acid
● advanced science, small volume	● capital intensive, high volume
● product innovation → chemistry	● production process → engineering
● chemist & mechanical engineer	● chemical engineer
● industrial R&D → proprietary	● university R&D → open science

1827	Liebig's Lab. at Giessen	1861	MIT
1860s	Technische Hochschule Höchst, Bayer, BASF	1888	Chemical engineering course
		1908	Am. Inst. of Chemical Engineers
1877	BASF's Main Laboratory	1915	Little: unit operations
1880s	physical chemistry	1923	Walker & Lewis: *Principles of Ch.E.*
1899	Doktor-Ingenieure	1929	Ch.E. research group in DuPont
1908	Haber: ammonia synthesis	1920-	petroleum refining
1911	Bosch: ammonia production	1940-	petrochemical

Sophisticated products and scientific research

Chemicals come in great varieties, even without counting plastics and synthetic fibers, which did not exist at the historical time at issue. Most chemical do not reach consumers but are used up in manufacturing processes, such as bleaching agents in the textile and paper industries. They roughly fall into two classes. Heavy chemicals such as acid or soda are consumed by industry in enormous volume. Fine chemicals such as dyes and drugs are greater in variety and more complicated in structures, but are consumed in smaller amounts.

The German industry mainly specialized in fine chemicals. These high-tech, high-value products required sophisticated chemistry to design and technical personnel to market. To synthesize novel dyes required advanced chemistry and ample scientific research. The dyes firms were keen on product design, on making dyes for all colors of the rainbow. They were also keen to develop novel marketing techniques that helped their customers to use these sophisticated dyes on fashionable fabrics. However, they were not too keen to improve the efficiency of production processes. They produced thousands of different dyes, but the amount of each dye was small, typically a hundred tons or so. For such small volumes, scaling up was rather easy and could readily be handled by teams of chemists and mechanical engineers. If the production processes they designed were less than maximally efficient, the little waste was easily absorbed in the fat profit margin of high-value products.

When they saw opportunities for novel products with high-volume demands, the Germans could mobilize their technical capacity in special projects to develop production processes, which they kept proprietary. This they did for the Haber-Bosch process for synthetic ammonia and fertilizer. But these were singular cases. For their core business of fine chemicals, they did not see the need for developing a discipline dedicated to efficient production processes.

High volume productions and scientific engineering

The American industry was mainly for heavy chemicals. These low-tech, low-value commodities required little if any science to design. But they were produced in huge volumes. America produced more than two million tons of sulphuric acid alone in 1913. High volumes implied large plants with demanding scaling up. Furthermore, the razor-thin profit margins of these commodities made the smallest waste painful. These industrial characteristics called for efficient production processes, not merely for this or that plant or product, but industry wide. The call was heeded not by industrialists but by academics: Walker and Lewis of MIT and their consultant friend, Little. Their answer was superior engineering based on scientific approaches.

The heavy chemicals industry already existed for over a century, during which industrial processes were developed mainly by cut and try. By trial and error, industrial chemists had developed many chemical processes and built many plants. Industrial chemistry constituted a distinctive branch of chemistry. Its textbooks were like cookbooks that offered catalogs of recipes. They described the techniques and listed the equipment for each process separately, treating the procedures for one process as special to it and not applicable to other processes. Tedious and repetitive, they showed the trees but gave no hint about the forest. Lack of general principles hindered adaptation of procedures. Knowledge acquired in industrial practices was locked into specific processes and not accumulated. New processes were developed by time-consuming cut and try. As the wheel was invented anew for each process, technology progressed but slowly.

Not content with a catalog of industrial processes, Walker, Lewis, and Little proceeded like natural scientists, only their phenomenon, chemical processing, is manmade. They examined many existing chemical processes and abstract their general form. At the heart of industrial chemical processing are chemical reactions, but they alone are not sufficient. They are accompanied by physical mechanisms such as thermodynamic and fluid dynamics, which distribute heat and bring ingredients into proper contact to ensure smooth reaction. Chemical and physical mechanisms interact in intricate ways, but ways that exhibit certain patterns, which the pioneering chemical engineers set themselves to extract.

A generic process involves preparation of raw materials, chemical reaction under controlled conditions, separation of products, recycle byproducts, and disposal of wastes. Each stage engages certain basic building blocks called “unit operations,” for instance emulsification, filtration, distillation. And the same unit operations occur in many processes. The chemical engineers introduce a general conceptual framework for thinking about chemical processes, delineated the general operations, very much like natural scientists do to natural phenomena.

The result is a new science, chemical engineering science. As the science developed over the decades, chemical engineers go deeper into the underlying mechanisms. They developed mathematical theories, so that they can calculate and predict the performance of processing plants without expensive experimentation.

Scientific engineering confers great economic advantages. Plants and raw materials account for a much higher percentage of costs in chemical industries than in other manufacturing, where labor costs are higher. Capital costs, much of it lies in financing, are especially high for high volume productions, where they can consume up to one half of product revenues. Tinkering and modifying expensive plants, which delay operation and boost financial costs, are doubly unwelcome. High capital costs put a premium on the ability to understand operating principles in the planning and design stage, which is a goal of chemical engineering.

Let us pause to ask: Why not the British? We have been comparing the American and German industries, but the British industry was similar to the American. Britain was among the first to establish a heavy chemicals industry, and after an initial success, lost the competition on fine chemicals. In fact, chemical engineering was first envisioned by the British George Davis, whose pioneering ideas the Americans acknowledged. As an industrial consultant and inspector, he visited a great variety of chemical processing plants, perceived certain common factors, and tried to spell them out. His effort frizzled in Britain but his dream was eventually fulfilled in America. Why?

Such questions are best left to historians. I can only guess that academic and government attitudes played a role. To develop a discipline emphasizing general principles was more suited to universities than commercial firms, which would be happier to develop specific processes that could be patented. The major British universities, disdainful of “ungentlemanly” pursuits, were less than enthusiastic to provide technical education. This was often cited as a reason for Britain’s relative technological and economical decline since the mid nineteenth century. By comparison, the atmosphere in America was more open-minded and pragmatic. If its colonial universities had shared the British snobbishness, they were put to competitive pressure in 1862 by the Morrill Land Grant College Act, which gave government lands to colleges that offered courses in “agricultural and the mechanic arts.” Among the universities the Act helped was Massachusetts Institute of Technology, the nursery of chemical engineering.

To answer a question raised, it may be well to compare chemical engineering with another American innovation, industrial engineering that facilitated mass production of mainly mechanical products such as cars. Fabrication and assembly of mechanical products are labor intensive. Shortage of labor, especially skilled labor, in America forced Americans to automate manufacturing processes and develop assembly of interchangeable parts from early days. Trying to substitute human workers by machines, industrial engineering focused on worker-machine interfaces, such as the time-motion study well known to historians. In contrast to the mechanical industries, the chemical industry is more capital intensive than labor intensive, and chemical engineering addressed only physical processes. Furthermore, the materials handled in chemical processing are mostly fluids, which are more susceptible to mathematical representation and generalization than mechanical pieces that come in infinite varieties of specific shapes. The style of chemical engineering is quite different from that of industrial engineering. However, the differences seem to be determined more by the technical characteristics of the industrial works at hand than by local cultural fashions.

From engineering science to new industries

Reciprocal relations exist among the structure of knowledge in an engineering discipline, the structure of natural phenomena it understands and utilizes, and the structure of industrial and social needs it serves. German engineering has always been formidable. Mechanical engineers such as Bosch were trained on the job in the chemical industry. Their expertise was not systematically articulated but was locked in their persons. The technology they developed remained mostly a corporate property. It is “localized” knowledge not suitable for globalization. In America, chemical engineering was developed by university professors keen on education. Their knowledge was systematically represented for students who could go out to work anywhere. It is a science open to generalization and adaptation.

Armed with scientific understanding, American chemical engineers were able to develop processes for new chemical reactions rapidly. A triumph was the war-time production of penicillin, in which processes were extended from chemistry to biochemistry. Another was the development of fluidized bed for Houndry catalytic cracking in petroleum refinery. MIT collaborated closely with Standard Oil of New Jersey to develop the process, educated students on industrial sites, and advanced chemical engineering principles simultaneously as they built the pilot plant.

The story continues. The hydrocarbons contained in crude oil are raw material for many organic chemicals. Today, most plastics, resins, synthetic fibers, ammonia, methanol, and organic chemicals are manufactured with oil or natural gas as feedstock. They are called petrochemicals, and there are thousands of them. Manufacturing of each requires a different process, and the availability of chemical engineering science played a crucial role in the almost overnight mushrooming of the petrochemical industry after World War II.

Specific chemical processes can be kept proprietary, general principles cannot. Engineers formed consultant firms, many of which performed their own R&D. These firms assumed the burden of design, development, construction, and even personnel training. They delivered turn-key plants designed to the specification of clients, thus reduced the technological barrier of entry. This was a novel industrial structure, resulting in a highly open and competitive petrochemical industry. The practice was copied worldwide

Second part of a talk presented at *Eidgenossische Technische Hochschule*,
Zurich, January 21, 2003.

First part: Local and global knowledge in science and engineering.
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