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Engineering Knowledge

by

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Introduction

Our main purpose is to examine how engineering knowledge was exploited in the United States to propel the nation from its 'catching up' or latecomer status during much of the 19th century to that of a leading nation among those advancing the frontier of both knowledge and application during the first decades of the 20th century. In historical context, the description 'useful knowledge' was often employed to distinguish knowledge of immediate relevance to the needs of a growing nation. We aim to illustrate how universities came to play central roles, not only in pushing forward the frontier of useful knowledge by expanding its range and depth, but also in pioneering new means for diffusing and exploiting this knowledge. These roles are particularly evident in those disciplines that explicitly welcomed and focused on the possibility of application. Hence, "useful knowledge" can be taken to be knowledge that is eventually embedded either in final products or in the manufacturing technology that produces these final products.[1]

The historical nature of our investigation also serves to highlight the nature of engineering knowledge and how it may be distinguished from scientific knowledge, not only in terms of the immediacy of application, but also in how such knowledge is generated and its nature. Although we will make observations about developments in several sectors, our main focus of attention is on science and engineering in the aeronautical and chemical industries where the specific character of the engineering knowledge that was needed and developed was influenced by the absence of predictive scientific theory and the significance of experimentation. To establish the historical context, we briefly review the precursors to developments in aeronautics and chemicals

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[1] See Kline (1995) for a very useful history of the evolution of terminology in American usage initially involving distinctions between pure and applied science from which the distinctions between science and technology emerged.

that occurred during the 19th century in agriculture and the mechanical arts, areas that in that era (and often today) share some of the same features of engineering knowledge that we find in aeronautical and chemical engineering during the first half of the 20th century.

The American Experience in Generating Useful Knowledge in Agriculture and the Mechanical Arts

During the 19th century, popular interest in the improvement of American skills in agriculture and the mechanical arts led to the formation of many societies, associations and institutes.[2] Private and public initiatives operated in parallel during that age and in our own and then, as now, involved an ongoing discussion of the role of government support (at both state and Federal levels) for higher education. The Morrill Act of 1862[3], which is sometimes viewed as the precipitating event for the introduction of technological knowledge into US higher education, was a culmination of prior efforts by agricultural and mechanics societies to win recognition and public support. These efforts had already led to the establishment of many state colleges and institutes.[4] Although often associated with agriculture, the dominant industry of the age, the Act itself simply established priority, allowing a state to benefit from the grant so long as it would support:

> …at least one college where the leading object shall be, without excluding other scientific and classical studies and including military tactics, to teach such branches of learning as are related to agriculture and the mechanic arts, in such manner as the legislatures of the States may respectively prescribe, in order to promote the liberal and practical education of the industrial classes in the several pursuits and professions in life.[5]

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[2] For an overview of the contributions of the public sector in a 'developmental state' framework with detailed history see Ferleger and Lazonick (1993). For surveys of such US agricultural societies see True (1928) and for the UK, whose mechanics institutes were influential in the formation of industrial institutes such as the Franklin Institute, see Sinclair (1974), Shapin and Barnes (1977) and Hole (1853).

[3] The Act was entitled, 'An Act donating Public Lands to the several States and Territories which may provide Colleges for the Benefit of Agriculture and the Mechanic Arts.'

[4] Although supported by some southern Senators including Jefferson Davis and James Mason, President Buchanan vetoed the legislation that was to become the Morrill Act noting concern that the bill 'would be likely to interfere with existing colleges in the several States and have an injurious effect.' VerBurg and Vlasin (2006:22). While only narrowly supported in the 36th Congress, it was overwhelmingly passed in the 37th Congress and quickly signed into laws, perhaps in part because its statement of purpose provided for training in 'military tactic' and it initially excluded those states in insurrection against the US government (the second of these provisions was removed following the Civil War).

[5] 37th US Congress, 2nd Session, Statutes at Large, Chapter 130, Section 4.

The Morrill Act can be seen as a milepost in the negotiations between private and public initiatives aimed at the professionalization of those fields concerned with technology and their introduction into higher education.

The significance of the co-evolution of private and public initiative as well as the singular importance of public support was indicated in the observations of a distinguished academic of the time, Daniel Coit Gilman:

> …Under […] different forms there may have been, when the Congressional Endowment Bill [Morrill Act] was passed, twenty institutions which could be grouped under the general title of scientific schools. They were variously termed, in popular or official phraseology, scientific schools, polytechnic schools, technological schools, agricultural schools and they differed as much in worth and in influence as they did in name. In one respect they were alike: they were all imperfectly endowed. Most of them were also on an experimental basis, -- no person being able to say exactly what they might, could or should be. Still they were very significant indications of the spirit of the age. They showed a desire for an advanced education on some other basis than the literature of Greece and Rome. They showed the willingness of rich men to give to scientific colleges. They showed the popular craving for what was vaguely termed, for want of a better word, a *practical* education.[6]

The Land Grant colleges stimulated further investments at the state level since the Morrill Act explicitly excluded the use of funds derived from the Federal grants for the construction of buildings. Considerable experimentation was to follow as ideas of practical education in agriculture led to various debates about implementation such as whether the establishment of 'model farms' as laboratories for agricultural education would be expected to financially contribute to state-supported institutions and, if they did, whether this would represent unfair competition with private farms or whether the entire enterprise of university education of farmers would create a privileged class.[7]

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[6] Emphasis is in the original, Gilman (1867). Daniel Coit Gilman, (1831-1908), who founded the Sheffield Scientific School at Yale, was one of the earliest presidents of the University of California, the first president of Johns Hopkins University, and the founding president of the Carnegie Institution.

[7] For example, among the several objections of one Michigan farmer commenting in 1852 on proposals to establish the Michigan Agricultural College, "The … proposed institution [would be] exclusive and aristocratic…It opens peculiar and exclusive privileges to one class of the community, at an expense which all must contribute to pay" VerBurg and Vlasin (2006:9).

Although the Land Grant colleges attempted to address the mechanical arts, it was private initiative that led the way during the latter half of the 19th century. In the East, pre-existing schools of mechanical arts included Rensselaer Polytechnic Institute, the Lawrence Scientific School of Harvard and the Sheffield School Yale.[8] However, as Kargon and Knowles (2002) note, it was in the then 'West', e.g. Pittsburgh, Cleveland and Chicago, where private initiatives by Carnegie, Case, and Armour produced a new generation of engineering schools to address the challenges of rapid industrialization. Although courses in the mechanical arts were begun at several of the land grant institutions, including the Massachusetts Institute of Technology (MIT), these efforts were somewhat fitful, and in MIT's case, did not initially contribute to institutional success.[9] The competition between engineering in the land grant institutions and privately supported institutions continued in the opening decades of the 20th century, with the growth of further new institutions such as the California Institute of Technology, founded in 1891.[10]

The other important elements in the historical development of technology in universities were the role of laboratories and 'extension', the latter referring in the first instance to agriculture, but later involving all sorts of efforts to extend the experimental and learning features of the university into practice. A common feature of the development of private technology-oriented universities was the establishment of specific laboratories, often with direct links to industrial applications. Hence, even at the science-led California Institute of Technology, where Robert A. Millikan sought to establish a high voltage laboratory 'to probe the secrets of the atom and its nucleus by high voltage discharges.'[11], funding from Southern California Edison Company's was sought for the laboratory because it would create an advancing understanding of electrical insulation and long distance power transmission.[12] Nor was Millikan reticent in stating the reasons for seeking *private* support:

> One of the most dangerous tendencies which confronts America today is the apparently growing tendency of her people to get into the habit of calling upon the state to meet all

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[8] Kargon and Knowles (2002:2) note that the first of these was 'reformed by B. Franklin Greene in the late 1840s along the lines of the École Centrale des Arts et Manufactures of Paris.'

[9] MIT, founded in 1861, struggled in the depression of the 1870s and did not begin its ascent until the 1880s,aided importantly by an effort to build 'relationships with practicing engineers and industrial corporations.' see Lecuyer 1995:43)

[10] Kargon (1977)

[11] Kargon (1977:15)

[12] Kargon (1977:14,24)

> their wants. The genius of the Anglo-Saxon race has in the past lain in the development of the individual initiative, and if we lose that we shall lose our most priceless heritage.[13]

The construction of this laboratory, named the Norman Bridge Laboratory of Physics, was an important juncture in the development of American laboratories of the 19th century at technical colleges and institutes. These were often aimed, like the 'model farm' at providing a laboratory for engineering practice while the later, post World War II laboratories, were often predicated on a much higher level of public support, where the fundamental purpose was the pursuit of purely scientific (i.e. without direct regard to prospects for application) rather than technological knowledge. Whether at private or land grant institutions, these earlier laboratories were often aimed at providing direct experience with tools and techniques Seely (1993). They were, however, occasionally being used for the generation of new engineering knowledge. An example is W.F.M. Goss's locomotive laboratory at the land grant Purdue University where, among other contributions, the practical value of multiple smokestacks in steam locomotives was discovered and demonstrated.[14] In the 19th century, the university laboratory was more likely to be about demonstration and, hence, diffusion of knowledge than it was the generation of new knowledge. This was, in part, because of a continuing process of exchange with the universities of Europe, a process that involved trial and adaptation of knowledge for practical purposes of American agricultural and industrial growth.

Diffusing Useful Knowledge in Agriculture

The demand for useful knowledge was further addressed by the Hatch Act of 1887 which provided Federal support for a network of agricultural experiment stations which were meant to '1) acquire and spread practical information on subjects connected with agriculture, and 2) perform original science-based research.'[15] The further expansion of the public science system was again controversial and another instance of the contest between public and private initiative. One example was Federal activities in the distribution of seed varieties acquired from Europe and other areas of the world, first run by the Patent Office and then by the US Department of Agriculture (established 1862).[16] As Kloppenburg Jr. (1988:65) observes, this program led to

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[13] Millikan (1922:330-1) as cited by Kargon (1977:15)

[14] Seely (1993:347). In Goss' laboratory a full-sized locomotive was mounted on rollers whose brakes could be adjusted to exert variable force up to the full pulling capacity of the engine, allowing accurate performance measurements and design experimentation Goss (1891).

[15] Huffman and Evenson (1993:22)

[16] Kloppenburg Jr. (1988:63-4) examines this program in the context of the tension between the politically popular distribution of seeds to constituents by their Congressional representatives which peaked in 1897 with the free distribution of over 1 billion seed packets.

the Federal government ‘constraining private capital accumulation’ in the seed business. For their part, the agricultural experiment stations conducted research aimed at improving the productivity of all types of agriculture enterprise and attempting to solve problems of plant and animal disease.[17] The experiment stations also engaged in an ambitious program of information dissemination, using the Hatch Act’s provision of free postage, to disseminate millions of the pamphlets and circulars to individual farmers.[18]

Public support for agricultural research and its dissemination benefitted from the large political constituency of the US rural population at the beginning of the 20th century and the diversity of climates, soils, and agricultural activities which might benefit from research.[19] By contrast, industrial interests and constituencies were more diverse and more divided about the value or efficacy of public research support. This is well illustrated by the modest growth and success of ‘engineering experiment stations,’ the first of which was established at University of Illinois in 1903, followed shortly by University of Iowa. By 1931, forty such stations existed, although (Seely 1993:350) concludes that they were often ‘poorly supported,’ noting that only the University of Illinois had an annual budget over $10,000. In the absence of large public programs, private initiatives focusing on specific industries were established at a number of universities, including those discussed above.

Transformations from the Past to Present

Between the first two decades of the 20th century and the present, there has been a remarkable transformation in the role of the university engineering research. In 2009, academic engineering research expenditures amounted to $7.9 billion and comprised 17.5% of total academic research expenditures. In assaying the continued pursuit of the engineering knowledge we describe here, it would also be appropriate to include significant shares of the research conducted in medicine and some portion of the research in biological and physical sciences, the three other largest areas of academic research.[20] The division between private and public research continues to the present and only crude surmises may be made of their relative contributions to the advance of immediately useful knowledge – i.e. concerning technological advance. We know that the size

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[17] True (1928)

[18] True (1937:164) notes that by 1909, publications were being sent to 750,000 addresses in the system as a whole.

[19] In the 1900 census, 60% of the US population was classified as living in rural areas compared to about 15% today,

[20] Reported expenditures are in 2005 constant dollars. In 2009, the shares of medical, biological and physical sciences were, respectively, 33.6, 20.9 and 10.3%, National Science Board (2012:Figure 5-4)

of technology development expenditures far outweighs those for the commonly employed categories of 'basic' and 'applied' research and that universities perform just over one half of 'basic' research and about one third of the total of basic and applied research. However, as has now come to be widely accepted, though these categories are well-defined for posing queries about the prospects for application and generating indicators, they are nonetheless underpinned by a 'linear model' which characterizes technology as applied science. It is now better appreciated that the entirety of the scientific and technological enterprise is interactive and interdependent.[21]

What is clear in historical retrospect is that engineering research has traversed a path from the peripheral position in the academy it occupied at the beginning of the 20th century to a central position. In doing so, important inroads have been made by predictive scientific theories and models. The extent to which this is perceived to be the case, however, may also reflect changes in fashion for the appropriate clothing by which to dress academic research proposals and programs. Much as the 'war on cancer' was headlined in research proposals aimed at understanding cell physiology.[22] Engineering research may be best cast as advancing 'engineering science,' even when it involves inductive experimentation and problem solving activities where predictive scientific theory and models offer only rudimentary guidance.

The division between public and private support for this research continues, but the balance has shifted so that today, two thirds of academic research funding is received from Federal (59%) and state and local (7%) governments, while one fifth is received from private industry. These aggregates are often depicted as a natural progression towards the broader recognition of the public good features of research. They are, however, the consequence of many individual stories of the tension between private and public initiative in individual sectors of activity. They also reflect a transformation from the US position in the late 19th century as a country engaged in catching up to one of being a world leader in most areas of technological endeavor. Perhaps most importantly, they reflect very different conditions shaping the accumulation of useful knowledge and, indeed, the nature of this knowledge. Whether it is knowledge imported and adapted from more abstract understanding or distant places, derived and systematized from the specific experience arising from practice, or arising from the efforts to solve specific problems for which no theoretical template is immediately available are influences that shape not only the

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[21] Kline and Rosenberg (1986)

[22] Fujimura (1987)

balance between public and private initiative, but also the appropriate institutional forms for supporting the creation and dissemination of this knowledge.

In examining this history, one of our primary concerns is the ease with which American universities have institutionalized new disciplines in the academic world, even when those disciplines, or the fundamental sciences underlying those disciplines, had been developed elsewhere. For in some respects, it can be argued that the economic impact of new, useful knowledge is determined not so much by the creators of that knowledge as it is by those who first develop the capacity to disseminate and to exploit that knowledge in various sectors of the economy (These last concerns, of course, go far beyond the university community and include a range of commercial skills and economic incentives in the private sectors of the economy).

We have deliberately used the word "sectors" rather than "sector" because of the need to examine the 20th century transformation of engineering research at a disaggregated level. If one considers the sectors that are ordinarily regarded as "high-tech," it appears that the roles played by the universities are distinctly different from one sector to another. The computer sector has had a very different interface than semiconductors; in fact, **within** the computer sector the university interface with computer hardware has been very different from that of computer software; medical devices, in turn, have been very different from both computer hardware and software; and the biotech sector has been totally different from **any** other industrial sector in a variety of ways, but especially in the extent to which academic researchers have come to play the additional role of business decision makers and entrepreneurs.

In the case of the engineering disciplines of chemical and aeronautical engineering, the underlying sciences of chemistry and aerodynamics had certainly been developed first in Europe, indeed, in both cases primarily in Germany, but the associated engineering disciplines first entered the university curriculum in the US. There was, of course, more than one explanation for such apparent anomalies, not the least of which were (1) the two most devastating wars of the 20th century and their very differing effects upon Europe and the US, and (2) differences in natural resource endowments between the US and Europe that had an especially important influence on the rate and direction of research in chemical engineering.[23]

But another part of the explanation is much more subtle, involving as it does the nature of the often complex relationship between a science and the engineering discipline that is commonly

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[23] On this last issue, see Rosenberg (1998).

associated with it. We “unpack” some of these issues in the sections which follow, and their relevance to the role played by American universities in the economic performance of certain key sectors of the economy.

Aeronautical Engineering

Aircraft design became a subject of great importance in the second decade of the 20th century. Germany completely dominated the underlying science, the theory of aerodynamics, under the towering leadership of Ludwig Prandtl at Gottingen University. Prandtl was a professor at Gottingen from 1904 until his death in 1953. His articulation of the boundary-layer hypothesis in 1904, a hypothesis that had emerged out of his earlier interest in the flow of liquids, was to become the most fundamental concept of aerodynamic theory, a theory that was further elaborated primarily in Germany in the interwar years.

As von Karman was later to describe Prandtl's major achievement in aerodynamics:

> "He ingeniously assumed that the total effect of friction on any part of the airplane can be estimated by the trick of restricting the investigation of the forces to a thin sheet of air close to the surface, which he called the 'boundary layer.' The rest of the surrounding atmosphere was not affected by friction of the moving plane, and its motion could still be explained by the air circulation theory. Prandtl's simple concept of the boundary layer marked one of the most important advances...in the theory of flight."[24]

The modern study of aerodynamics has dealt primarily with the determinants of lift and drag on a flying object. This field of research was totally dominated by German aerodynamicists in the first 30 years of the 20th century. Nevertheless, in the interwar period it was the Americans, and not the Germans, who excelled in aeronautical engineering as an academic discipline and its application to aircraft design. These developments are summarized by Anderson:

> ...(A)erodynamics is a branch of the more general subject of fluid dynamics, which encompasses the flows of fluids and gases in general, not just air. Although aerodynamics is sometimes viewed as a modern science, in many respects it is inseparable from the older science of fluid mechanics.[25]
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> Following World War I, the snail's pace at which the U.S. aeronautical-engineering community was able to absorb, appreciate, and apply the aerodynamic theory developed by Prandtl and his students was to be expected, given the differences in educational philosophy between Gottingen and the typical engineering college in the United States at that time. Gottingen was a research university with major emphasis on the sciences;

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[24] von Karman (1967:61)

[25] Anderson Jr. (1997:5)

> Prandtl's research group was the first major collection of engineering scientists to work in aeronautics. In contrast, U.S. engineering colleges produced engineers, who were taught to focus on the empirical methods required to build something. It is no wonder that the early NACA engineers were slow to understand and embrace the new aerodynamics theory...[26]

Research in aeronautical engineering in the United States, especially at California Institute of Technology, MIT and Stanford, all drew heavily upon Prandtl's fundamental research. But much more knowledge was required in the successful design of aircraft, knowledge that was **not deducible from the science of aerodynamics**. Consider the propeller tests conducted at Stanford University by W.F. Durand and E.P. Lesley from 1916 to 1926. These protracted experimental tests were necessary because there was no way in which the body of scientific knowledge would permit a more direct determination of the optimal design of a propeller, given the fact that "The propeller operates in combination with both engine and airframe...and it must be compatible with the power-output characteristics of the former and the flight requirements of the latter."[27]

Thus, designing a propeller is not independent of the design of the entire airplane, and the ten-year search project not only expanded the understanding of airplane design but also increased confidence in the reliability of certain techniques utilized in aircraft design - a far from trivial consideration in the case of aircraft. An important consequence of the experiments, which relied heavily upon wind tunnel testing, was not so much the ability to improve the design of propellers as to improve the ability of the designer to achieve an **appropriate match** between the propeller, the engine and the airframe.

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[26] Emphasis as in original, Anderson Jr. (1997:293). American backwardness in aerodynamic research persisted well into the realm of supersonics. For an extensive treatment of this subject, see (Constant 1980), Chapters 4-6. Constant has argued that American backwardness in aerodynamics, especially in turbo-compressor phenomena, handicapped the U.S in making the transition to the turbojet. Constant states: "An examination of the central theoretical innovations in high-speed aerodynamics described in Chapter 5 will reveal that American scientists, with the exception of the special case of Theodore von Karman, made no such contributions. Before 1940, none of the major theoretical developments in transonic or supersonic aerodynamics were the product of American science. Instead, such advances were the work of Germans or of scientists with German training (Ackeret, von Karman). Some important work on supersonics was done in Britain, but it did not approach the quality of the German investigations…The purpose of American high-speed research was empirical engineering development data for normal technology, not theoretical progress in aerodynamic science." Constant (1980:152-3).

[27] Vincenti (1990:141). We are greatly indebted to Walter Vincenti for insights on the specific issues discussed here as well as many other issues.

It is worth observing also that Durand and Lesley began their propeller experiments by first designing and constructing the necessary wind tunnel equipment, since American capabilities even with respect to wind tunnels were well behind European capabilities at the time. Three years earlier, in 1913, when MIT began its program in aeronautical engineering, it brought Jerome Hunsaker, at the time an Assistant Naval Constructor at the Boston Navy Yard, to MIT in order to offer a special series of courses in aerodynamics for naval officers. As evidence of America's distance from the research frontier at the time, Stuart Leslie reports that "Hunsaker spent the summer catching up with the latest advances in Britain, France, and Germany, then designed and built a wind tunnel for MIT modeled after one he had studied at Britain's National Physical Laboratory." [28]

America's continued backwardness in theoretical aerodynamics is thoroughly documented in (Hanle 1982), a book that describes the growing concern with which a small number of Americans monitored European aerodynamic research in the 1920s. The book also documents the central role of a private philanthropic organization, the Daniel Guggenheim Fund for the Promotion of Aeronautics, in achieving the transatlantic transfer of aerodynamics, a field of research in which they considered America to be far behind Europe in that decade. In the second half of the 1920s the Guggenheim Fund provided endowments to the aeronautical departments of 7 universities: New York University, California Institute of Technology, Stanford University, University of Michigan, MIT, University of Washington, and Georgia School (later Institute) of Technology. The Fund's decision to support aerodynamics at Cal Tech in southern California was influenced, at least in part, by the fact that that area had already become a center for the manufacture of aircraft. It was also concerned with the regional distribution of the universities that received its support but, as Hanle also points out, "All save Caltech were geared to produce working engineers more than scientists" (Hanle 1982:4).

As was eventually realized, what was essential to the successful design of aircraft was not just the requisite scientific knowledge or the experimental equipment. Indeed, the central point with respect to aircraft is precisely the extreme difficulty of the process of aircraft design because of the absence of an adequate body of scientific knowledge. The method of experimental parameter variation was necessary because a useful quantitative theory simply did not exist.[29]

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[28] Leslie (1993:78)

[29] Vincenti credits the eighteenth century engineer, John Smeaton, with originating the method of systematic parameter variation. "The engineering methodology appears clearly – the first prominent example – in the work of John Smeaton early in the Industrial Revolution in Britain. His influential study of the performance of waterwheels and windmills, presented before the Royal Society in 1759, contained the two main methodological components: a systematic method of experiment and the use of working scale models" Vincenti (1990:138). Mokyr (2002:68-76)

Durand and Lesley's experiments at Stanford University led to a better understanding of how to approach the whole problem of aircraft design. In this sense, a critical output of these experiments was a form of generic technological knowledge that lies at the heart of the modern discipline of aeronautical engineering. As Vincenti has astutely observed:

> In formulating the concept of propulsive efficiency, Durand and Lesley were learning how to think about the use of propeller data in airplane design. This development of ways of thinking is evident throughout the Stanford work; for example, in the improvement of data presentation to facilitate the work of the designer and in the discussion of the solution of design problems. Though less tangible than design data, such understanding of how to think about a problem also constitutes engineering knowledge. This knowledge was communicated both explicitly and implicitly by the Durand-Lesley reports."[30]

A further observation of general significance to aeronautical engineering research needs to be made. As Vincenti points out, what the Stanford experiments eventually accomplished was something more than just data collection and, at the same time, something other than science. It represented, rather, the development of a specialized methodology that could not be directly deduced from scientific principles, although it was obviously not inconsistent with those principles. One cannot therefore adequately characterize these experiments as applied science:

> "...(T)o say that work like that of Durand and Lesley goes beyond empirical data gathering does not mean that it should be subsumed under applied science...(I)t includes elements peculiarly important in engineering, and it produces knowledge of a peculiarly engineering character and intent. Some of the elements of the methodology appear in scientific activity, but the methodology as a whole does not.
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> "The engineering utility of the methodology rests primarily on the fact....that there is no essential relation between experimental parameter variation and physical theory. Indeed,

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also offers some illuminating observations on the growth of engineering knowledge. See also Rosenberg and Vincenti (1978) where the method of experimental parameter variation was employed to circumvent the absence of a theory that would account for the buckling of thin-walled tubes in constructing a railroad bridge of drastically new design.

[30] Vincenti (1990:158)

> the strength of experimental parameter variation is precisely its ability to provide solid results where no useful quantitative theory exists."[31]

As important as these technological developments were for airplane design their translation into commercial practice benefitted from the American and Federal policy. The US is a continental nation where moving freight and people quickly over long distances had obvious commercial potential. However, translating this principle into practice was not straightforward. Competition between small and large air freight (mostly serving postal contracts) companies, the supply of aircraft and the demand for air transport services were all influenced by government policy as was the ultimate emergence of larger companies able to finance the purchase of larger aircraft.[32] As for technological support, Federal funding for the National Advisory Committee for Aeronautics (NACA) provided an important complement to the activities discussed here although the total funding for NACA in the entire period 1915-1940 totaled $25 million. With this level of funding, NACA was largely engaged in similar experimental engineering work to that of foundation and corporate sponsored research.[33]

The greater degree of sophistication in aeronautical research methods that resulted from the Stanford experiments made an important contribution to the maturing of the American aircraft industry in the 1930s, a maturity crowned by the emergence of the DC-3 in the second half of that decade. But the success of the DC-3, the most popular commercial transport plane ever built, owed an enormous debt to another educational institution, the California Institute of Technology. Cal Tech's Guggenheim Aeronautical Laboratory, funded by the Guggenheim Foundation, performed research that was decisive to the success of Douglas Aircraft, located in nearby Santa Monica.[34] Both technical features such as durability and reliability of components, and economically important features such as passenger carrying capacity, were largely the product of the Cal Tech research program, highlighted by their use of multicellular construction, and the exhaustive wind tunnel testing of the DC-1 and DC-2. The wind tunnel tests, part of a commercial project for Douglas Aircraft, led eventually to major improvements in the DC-3.[35].

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[31] Vincenti (1990:166)

[32] Mowery and Rosenberg (1981); van der Linden (2002)

[33] Mowery and Rosenberg (1981:352-4) and Constant (1980)

[34] The founder of Douglas aircraft, Donald W. Douglas was the first graduate of MIT's aeronautical engineering degree programme in 1914 and was a research assistant to Jerome Hunsaker (see above), Francillon (1988:2,45).

[35] Anderson Jr. (1997:331-2)

The commercial value of the extensive design improvements in the DC-3 may be simply stated: by 1938, DC-3's were carrying no less than 95 percent of all commercial air traffic in the US, and these same aircraft were being used by 30 foreign airlines.[36] It should be emphasized that the DC-3 did not incorporate any truly major technological improvements that were not already available to the aircraft industry in the first half of the 1930s. Rather, the superior performance, and especially the lower operating costs attained, were the product of innumerable small modifications and design improvements based upon the existing state of aero-engineering knowledge at the time.[37]

For example, perhaps the most important sources of piston engine improvement in the interwar years related to fuel chemistry. It has been frequently estimated that at least 50% of the increase in power that was delivered by gasoline piston engines during the interwar period resulted from greater sophistication in the use of fuels in internal combustion engines. These improvements, in turn, required not only changes in engine design to accommodate higher temperatures, greater pressures and stresses, but also improved fuel pumps and fuel tanks, lubrication, controls – and, of course propellers.[38]

World War I and its turbulent postwar aftermath had a great deal to do both with Germany's failure to fully exploit its early leadership in aerodynamics and with the transatlantic transfer of that body of scientific knowledge. It was the darkening cloud of political extremism and virulent anti-semitism that encouraged Prandtl's most distinguished student, Theodore von Karman, to accept an invitation to join the faculty of Cal Tech in 1930.[39] von Karman's leadership played a critical role in Cal Tech's subsequent success in aeronautical engineering.

Still, it is far from clear that the sophisticated aerodynamic concepts developed at Gottingen would have had as rapid an application to commercial aircraft design as the research at Cal Tech came to have, even if the times and the circumstances had been more propitious. Prandtl regarded his research as applied physics rather than engineering, and it is doubtful that he would,

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[36] Miller and Sawers (1970:102)

[37] For a broader discussion of some of these issues, see Rosenberg (1982)

[38] See Constant (1980), Chapter 5, especially pp. 118-122. Constant concludes: "The remarkable achievements in aircraft piston engine development between 1915 and 1945 signify the evolution of a well-defined, highly specialized, and well-integrated research, development, and implementation system. Government research establishments, aero-engine manufacturers, accessory manufacturers, airframe manufacturers, fuel producers, and user communities cooperated to make the piston engine-propeller system an unparalleled success," p. 129.

[39] See Hanle (1982) and Goodstein (1991), Chapter 8. von Karman has been described as "...probably the leading aerodynamicist of the 1920-1960 time period.," Anderson Jr. (1997:330).

himself, have participated in the very practical aircraft design exercises that von Karman became involved in for Douglas Aircraft at Cal Tech, beginning in 1932.[40]

Simple, but significant, design improvements came out of von Karman's wind tunnel. "The DC-1 was plagued by unusual buffeting in the region where the wing joined the fuselage. The sharp corner at the juncture caused severe flow field separation, which resulted in high drag as well as shed vortices which buffeted the tail. The Caltech solution, which was new and pioneering, was to fair the trailing edge of the wing smoothly into the fuselage. These fairings, called fillets, were empirically designed and were modeled in clay on the DC-1 wind-tunnel models. The best shape was found by trial and error. The addition of a fillet...solved the buffeting problem by smoothing out the separated flow and hence also reduced the interference drag. Since that time, fillets have become a standard airplane design feature." [41]

The division between pure and applied science that had been accommodated in the US by the land grant institutions and urban industrial universities was addressed quite differently in Germany by the introduction of the Technische Hochschule in the second half of the 19th century to teach technical subjects that were not regarded as fitting for universities. The hochschulen were not allowed to award the coveted doctoral degree until a decree in 1900 by Kaiser Wilhelm himself authorized them to award the degree of Doctor Ingenieur. Clearly, such attitudes also exerted a significant impact upon the development of an engineering discipline and its practical applications.[42]

Before leaving aeronautical engineering, and also as a prelude to a consideration of chemical engineering, some further observations on why it is inappropriate to think of technologies as simply the legitimate offspring of scientific disciplines seem to be called for. Scientific progress over the past 500 years has proceeded precisely by abstracting from problems that are at the heart of the concerns of the engineering disciplines. Physics has, for example, like other scientific disciplines, made great progress by confining itself to problems for which it can offer rigorous mathematical treatment and solutions. This has entailed abstracting from phenomena for which conceptual generality or rigorous solutions appear to be impossible. Thus, in formulating the

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[40] von Karman wrote in his autobiography : "I enjoyed climbing into the ten-foot wind tunnel with a wad of putty, and imagining myself being the airplane I tried to feel where I might be pressed by an element of air." von Karman (1967)

[41] Anderson Jr. (1985:332).

[42] For a useful examination of the intellectual environment in which Prandtl worked and thought, see Hanle (1982), Chapters 3-5.

classical laws of physics, Newton ignored the effects of friction in determining the acceleration of a falling object. Engineers, however, do not have the luxury of ignoring friction, viscosity, or turbulence when designing new machinery or equipment.[43] They have had to develop designs that solve problems for which no scientific theory exists to provide guidance or where scientific theory provides answers only by ignoring additional influences which, outside the laboratory, cannot be prevented from operating. Of necessity they have therefore taken to experimentation with small-scale working models. At times they have had to confront awesomely complex problems in inferring the behavior of a projected full-scale prototype from the experimental performance of an observed, small-scale working model. How, in particular, does one adjust for scale effects? This is perhaps the single most persistent challenge in chemical process plant design.

The main point is that the engineer's development of design data, particularly in the historical context we are discussing, may be informed in a general way by science, e.g. the knowledge that air has fluid properties, but is not the result of a solution to a scientific model, e.g. the analytical or numerical solution of a fluid dynamics model. Nor does the engineer's solution illuminate some more fundamental features of the phenomena under investigation, although it might uncover anomalies that influence scientific models. Nevertheless, the empirically derived coefficients are adequate for the design of industrial equipment that performs the required functions with a high degree of predictability and reliability. Importantly, engineering data developed by empirical experimentation can be used for generating design data for the prototype size by making use of dimensionless numbers. The best-known dimensionless number is the Reynolds number, with which it is possible to predict the critical point at which the transition from laminar to turbulent flow will take place in an enclosed pipe or, later, for a moving object immersed in a fluid, in this case, air. Osborne Reynolds formulated this relationship in 1883 as a result of some ingenious experiments, and the Reynolds number has remained fundamental to the design of chemical process plants to this day as well as to the practical design of scientific apparatus.[44]

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[43] Modern computers, by opening the door to simulation techniques, have powerfully expanded the tools at the disposal of the present generation of engineers.

[44] "Boundary layer thickness, skin friction drag, transition turbulent flow, and many other characteristics of viscous flow depend explicitly on the Reynolds number. Indeed, we can readily show that the Reynolds number itself has physical meaning - it is proportional to the ratio of inertial forces to viscous forces in a fluid flow. Clearly, the Reynolds number is an extremely important dimensionless parameter in fluid dynamics." Anderson Jr. (1985:162), also see pp. 162-166 for further discussion. For a number of interesting historical observations on dimensionless numbers, see Layton Jr. (1988:24), who observes "What made Reynolds's papers such a historical turning point in the history of engineering? ...On the technical front, Reynolds was addressing the idealization of physical theory. Messy phenomena such as turbulence and friction had been idealized out of physics. The reasons were good; these

This last sentence, though made in the specific context of chemical engineering, would apply equally well in aeronautical engineering. In the hands of Ludwig Prandtl in the opening decade of the twentieth century, the Reynolds number provided the basis for the boundary layer concept that remains basic to the design of aircraft and thus made possible the calculation of drag on an airplane in flight. Note that in both aeronautical and chemical engineering the phenomenon of turbulence, for which predictive scientific theory remains limited to this day, is absolutely central to the design activities of engineers.

The general point is that aeronautical engineering has made extensive use of sources of information that do not draw upon fundamental science because the specificity of aircraft designs requires information that cannot be deduced from the scientific principles of aerodynamics. Thus, America's great successes in the aircraft industry in the first half of the 20th century drew, in an essential way, upon a variety of non-scientific sources: (1) Reynolds numbers; (2) design data drawn from wind tunnel experiments performed by the National Advisory Committee on Aeronautics, the predecessor of NASA, established in 1915, as a formal mechanism to rescue the US from what has been called its aeronautical "dark ages"; and (3) the ten year experimental study of the optimal shape of aircraft propellers carried out by Durand and Lesley at Stanford.[45]

Chemical Engineering

American leadership in introducing a new engineering discipline into the university curriculum, even at a time when the country was very far from the frontier of scientific research, was nowhere more conspicuous than in the discipline of chemical engineering early in the 20th century. There was, however, one spectacular exception to the statement that the US was far from the scientific research frontier, but it serves to reinforce our point that the country was

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phenomena did not lend themselves to theoretical treatment. The price of progress in natural philosophy had been that these phenomena be ignored. But turbulence and friction were central problems in engineering that could not be ignored. Engineers used various empirical expedients; but the result was a gap between physical theory and engineering practice. It was Reynolds's significance that he played a critical role in the process whereby certain important gaps between theory and experiment in engineering were largely closed. To do this he developed scale-model experiments and a dimensionless parameter that was to prove of critical importance for bringing the archetype of chaotic phenomenon under the rule of law."

[45] Interestingly, as late as the mid-1930s Durand edited a six-volume encyclopedia on the science of flight, published in Germany: Durand (1934-36). This huge publishing project received a grant from the Guggenheim Fund, and Prandtl was one of the several consultants on the project. Hanle (1982:40) stated: "Durand's encyclopedia made available much of aerodynamics to America. It remained a useful reference in aerodynamics more than thirty years after it was published."

heavily preoccupied with research of a more practical nature. In 1876 and 1878 Josiah Willard Gibbs published a two-part paper in an obscure American journal (the Transactions of the Connecticut Academy of Arts and Sciences) titled “On the Equilibrium of Heterogeneous Substances”. This long paper created, at one fell swoop, a fully developed new science of chemical thermodynamics, whose phase rule was to transform metallurgy and several other branches of chemistry. Gibbs’ contribution was, however, totally ignored in the US until it was discovered, in 1883, by the great German chemist, Ostwald (and also by James Clerk Maxwell in England). Ostwald translated Gibbs’ paper into German, as a result of which it eventually received world-wide recognition, even in America.[46]

At the beginning of the 20th century, Germany was, by an overwhelming margin, the world leader in the science of chemistry, most particularly organic chemistry. Nevertheless, the need to design and to operate chemical process plants at increasing volumes of output, which is what chemical engineering is primarily about, led to the emergence of a research and teaching program, not in Germany, but in US universities. The reasons for this are connected, at least in part, with differences in the emerging patterns of industrial specialization in the two countries, especially the spectacular growth of the automobile industry in the US in the second and third decades of the 20th century, along with the subsequent huge demand for liquid fuels.[47] Nevertheless, a central part of the story was the ease and flexibility shown by US universities in making room for the introduction of a new discipline, and a new department, as soon as the case for the utility of such a discipline had been established and, it must be added, as soon as outside sources of funding became available. In the highly decentralized US university system, universities were not constrained by the budgets of government ministries, or by government-established quotas with respect to faculty or students, but they were desperately constrained by funding limitations. Indeed, leadership in the introduction of new fields of study, for which a growing market for trained graduates was anticipated, would offer budget-constrained universities the possibility of charging higher tuition. Where those fields would be relevant to corporate needs for knowledge, further support was possible, a pattern that was extended after World War II to the rise of the Federal government research funding.[48] In the case of

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[46] One source says of Gibbs that “...few of his countrymen knew his work until well into the 20th century. Gibbs’ publications were translated into German by Ostwald and into French by Le Chatelier in the 19th century; they were reprinted in English in 1906 in London and not reprinted in the U.S. until 1928.” Skolnick and Reese (1976:11).

[47] For a discussion of the role played by differences between the US and Germany in the composition of demand for chemical-based products, and how these differences may have influenced the approach in each country to the discipline of chemical engineering, see Rosenberg (1998)

[48] For a case in point, consider MIT, see Servos (1980) and Lecuyer (1995).

aeronautical engineering, as we have already seen, a private foundation provided the leadership with financial support for research.

Significantly, some of the central concepts of chemical engineering, including the key insight that many of the problems confronting the chemical industry were really reducible to a small number of common engineering problems, had been first articulated by an Englishman, George E. Davis, in a series of lectures in the Manchester Technical School in 1887. These lectures eventually grew into a two-volume Handbook of Chemical Engineering in 1901, but it failed to give birth, in British universities, to a chemical engineering curriculum. Although a chair in chemical engineering was established in Imperial College, London, in 1922, Cambridge University did not establish its chemical engineering department until after the Second World War. Davis' British contemporaries continued to regard themselves as chemists with expertise in the specific product of a particular industry, and not as members of a professional group that shared a broad commonality cutting across the boundary lines of a large number of industries.[49]

In the middle of the 19th century Britain's chemical industry, which was overwhelmingly inorganic, was the largest in the world. The British industrial demand for chemical products was dominated by the enormous needs of textile manufacturers for such essential inputs as bleaches, mordants, and detergents, as well as the huge requirements of the glass industry for soda and, therefore, sulfuric acid.

For our present purposes, it is essential to see the parallelism of the discipline of chemical engineering with that of aeronautical engineering. Chemical engineers, in the past, have been mainly concerned with the design, construction, and operation of large-scale petroleum refineries and chemical-process plants.[50] But chemical engineering does not (cannot) achieve its goals through an application of the science of chemistry, although it is of course also obvious that, without the science of chemistry, the chemical industry would be the merest shadow of what it is today. The point is that chemical engineering is not applied chemistry. New products in the chemical industries have, historically, typically emerged out of laboratory research conducted by bench chemists making use of Bunsen burners, small beakers, test tubes, and retorts. However,

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[49] See Scriven (1991). Perhaps it was no accident that a great theoretical contribution by an American – Gibbs – had to await discovery, translation and recognition in Europe while it was ignored in US, while the very practical conceptual insights of an English engineer – Davis – failed to lead to the emergence of a new engineering discipline in Britain but had to be independently redeveloped in the US.

[50] See Landau (1966). In more recent years chemical engineers have gone in large numbers into the semiconductor, electronics and biotechnology industries.

such laboratory research does not provide the information required for scaling up to commercial production. In the most practical sense, scaling up the original equipment to a size appropriate for commercial production is often physically impossible and hardly ever economically feasible. One cannot, for example, readily scale up with glass containers. Instead, scaling up requires recourse to apparatus of an entirely different sort, involving entirely different materials that can sustain extremely high pressures and temperatures, as well as the use of pumps, compressors, piping, and vats of a very large scale. “Many significant effects appear in plant-scale operation which escape detection on a bench scale, such as changes in flow patterns, fouling of heat exchangers, deactivation of catalysts, and variations in feed composition....”[51]

Consequently, for products with large scale demand, the optimal scale for commercial production requires experimentation[52] of a sort that is entirely different from that which led to the original development of the product. Optimal plant size cannot, for many reasons, be achieved by a simple linear extrapolation from a small-scale model. The key experimental tool of the chemical engineer is therefore the pilot plant, and *inferences drawn from experimental data* provided by such plants. Such optimal size will be found to differ from one chemical product line to another.[53]

It is worth noting that American chemical engineers were drawing upon skills in mechanical engineering and machine building in which the country had developed a distinctive competence at an early date in its industrial development.[54] This ability to deal with large-volume production, and eventually to do so with continuous process technology invented and designed by chemical engineers, was to become a central feature of the world chemical industry in the course of the 20th century.

The central concept in the discipline of chemical engineering, when it first made its appearance in an academic context, was that of “unit operations.” A.D. Little presented this concept in a report to the Corporation of the Massachusetts Institute of Technology in December 1915. In Little’s words:

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[51] Hougen (1965:230)

[52] There is, of course, also an important dynamic interaction between the broader industrial use of certain chemicals (e.g. petrochemicals used in the manufacture of plastics) which enlarges demand and the supply of methods for the large scale manufacture of such chemicals.

[53] For further discussion, see Rosenberg (1998:Chapter 7).

[54] Rosenberg (1969)

> "Any chemical process, on whatever scale conducted, may be resolved into a coordinated series of what may be termed 'unit actions', as pulverizing, mixing, heating, roasting, absorbing, condensing, lixiviating, precipitating, crystallizing, filtering, dissolving, electrolyzing, and so on. The number of these basic unit operations is not very large and relatively few of them are involved in any particular process...Chemical engineering research...is directed toward the improvement, control and better coordination of these unit operations and the selection or development of the equipment in which they are carried out..." [55]

A critical feature of the concept of unit operations is that it went well beyond the purely descriptive approach of industrial chemistry by calling attention to a small number of distinctive processes that were common to many product lines. This act of intellectual abstraction laid the foundations for a more rigorous and, eventually, more quantitative discipline. It is tempting to call Little's manifesto an attempt to provide a General Purpose Technology for the chemical sector [56] Chemical engineering was now in a position to be able to accumulate a set of methodological tools that could be refined and that could provide the basis for a wide range of problem-solving activities connected with the design of chemical-process plants. Not least important, it now had the basis for a curriculum that could be taught.[57]

In 1920, just a few years after Little's formulation, chemical engineering achieved the status of a separate, independent department at MIT, under the chairmanship of W. K. Lewis. But in 1916, only a year after A.D. Little's report, MIT had already established its School of Chemical Engineering Practice. This school "...gave students access to the expensive industrial facilities required to relate classroom instruction in unit operations to industrial practices, but still under the supervision of a faculty member."[58].

The teaching of chemical engineering was organized around the concept of unit operations for the next few decades, but the concept underwent substantial alteration in its intellectual content almost from the very beginning. An academic environment created strong pressures toward analytical rigor, internal consistency, and generality. One of the first major steps in this direction

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[55] Little (1933:7). A. D. Little and the firm that he founded were key links between university research and industrial application.

[56] See Rosenberg (2000a)

[57] Pigford (1976:191)

[58] Landau and Rosenberg (1992:89)

occurred very quickly, in the form of an immensely influential textbook by three MIT professors, Walker, Lewis, and McAdams, which was published in 1923. This book, *Principles of Chemical Engineering*, focused on a limited number of operations that were widely practiced in industry and also provided a conceptual framework that would be useful for addressing a range of unsolved problems common to chemical manufacturing processes. An important feature of the book was its demonstration that many separate unit operations could be compressed into a small number of principles involving momentum, mass and heat transfer. The book remained extremely influential in the training of chemical engineering students for 25 or 30 years. It amply fulfilled the statement of purpose of the authors: “We have selected for treatment basic operations common to all chemical industries, rather than details of specific processes, and so far as is now possible, the treatment is mathematically quantitative as well as qualitatively descriptive.” [59]

An engineer trained in terms of unit operations could mix and match these operations as necessary in order to produce a wide variety of distinct final products. Such an engineer was much more flexible and resourceful in his approach to problem solving. Of key importance is that he was now well equipped to take techniques and methods from one branch of industry and to transfer them to other branches. Experience in one place could now be readily transferred to other, apparently unrelated places.[60] This capability was especially valuable in the innovation process - particularly as new materials and new products emerged. Thus, research that improved the efficiency of any one process was now likely to be more quickly employed in a large number of places due to the ‘dis-integration’ of chemical processing operations. Putting the point somewhat differently, the identification of a small number of unit operations common to a large number of industries meant that it became possible to identify specific research topics, again often empirical in nature, for which new findings could be confidently expected to experience widespread utilization. Indeed, these developments may be seen in our own context as an early development of modularization. Needless to say, this point is of great significance in the growth of an engineering discipline. Chemical processing plants existed in many industries besides the chemical industry proper. Some of the larger ones included petroleum refining, rubber, leather, coal (by-product distillation plants), food processing, sugar refining, explosives, ceramics and glass, paper and pulp, cement, and metallurgical industries. More recently, as already mentioned, chemical engineers have come to play prominent roles in semiconductors, electronics and biotechnology.

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[59] Walker, Lewis et al. (1923:vii)

[60] See Spitz (1988:58-59)

Although the episode is not well-known, these recently-acquired technical skills of the chemical engineer played a crucial role in the introduction of penicillin, probably the most important medical innovation of the 20th century. Alexander Fleming's brilliant insight, that common bread mold was responsible for the bactericidal properties that he had observed in his Petri dish, came in 1928. Nevertheless, penicillin remained unavailable at the outbreak of the Second World War. Producing penicillin on a very large commercial scale during that war required a crash program in which the eventual solution came not, as would normally be expected, from the pharmaceutical chemist, but from chemical engineers who designed and operated pilot plants. These engineers successfully demonstrated how the technique of aerobic submerged fermentation, which became the dominant production technology, could be made to work by solving apparently intractable problems of heat and mass transfer.[61]

An important aspect of the relationship between the scientific and technological realms should be noted here. Industrial progress has often proceeded in a sequence in which fundamental science first opened new product categories but then had to await further development until the appropriate methods of manufacturing were worked out. In the case of the modern petrochemical industry, which emerged during, and especially after, the Second World War, many of the processing methods had already been developed in the interwar years, largely in the petroleum-refining industry. The modern postwar petrochemical industry had its origins in fundamental research on long-chained molecules that was initiated by Hermann Staudinger in Germany in the 1920s. But, when the fruits of this earlier scientific research finally became available in the form of new products made possible by plastics, synthetic fibers, and synthetic rubber, basic processing technologies were **already at hand** as a result of the earlier accomplishments of the chemical engineers who had developed the methods of producing the necessary chemical feed stocks before and during the Second World War.

Thus, the transformation of the US chemical industry, as it existed in 1920, into the petrochemical industry that matured after World War II, was in large measure the achievement of the chemical engineering profession, and especially of the newly-formed chemical engineering department at MIT. Beginning in the 1920s, "The major oil companies quickly hired large numbers of MIT chemical engineers, and for a number of years these men practically

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[61] Elder (1970). The discipline of chemical engineering, of course, had numerous applications in medical technologies during the second half of the twentieth century. One of the earliest was the research on blood flow and dialysis conducted by Edward W. Merrill of the MIT Chemical Engineering Department in conjunction with Boston hospitals. Weber (1980:46)

dominated the industry. The chemical engineering senior faculty was almost completely hired as consultants or permanent employees by the oil industry."[62]

Responding to the advice of a long-time consultant, Warren K. Lewis, the chairman of the MIT Chemical Engineering Department, Standard Oil Company asked Robert Haslam, at the time the head of MIT's Chemical Engineering Practice School, to head up a team of fifteen MIT faculty and graduates to set up a research organization at Baton Rouge, Louisiana.

This team was responsible for much of the new technology of petroleum refining that was developed before the Second World War. With the continuing advice of Lewis, and later of MIT Professor Edwin R. Gilliland, Baton Rouge produced a sequence of new process technologies that were of critical importance to petroleum refining, including hydroforming, fluid flex coking and, by far of greatest later significance, fluid catalytic cracking. This last technology ultimately became the most important raw material source for propylene and butane feed stocks in the postwar petrochemical industry.[63]

Students in the MIT Chemical Engineering Department were intimately involved in the crucial problem of the handling of the catalyst for catalytic cracking in the production of aviation gasoline, an innovation that would be of enormous economic and strategic importance. In 1938, Lewis and Gilliland, in their role as consultants to the Standard Oil Development Company, "…. Suggested that the tube in which the reaction took place should be vertical rather than horizontal. They were asked to investigate the behavior of finely divided particles in vertical tubes and so initiated a research program at MIT. Two graduate students (John Chambers and Scott Walter) carried out the experiment and derived some of the engineering relationships underlying the fluid technique." [64] As Edward Gornowski of Exxon Research and Engineering Company (the successor of Standard Oil Development Company) was later to observe: "…To our surprise, we found that the solids density was higher in the upflow legs than in the downflow ones. *Doc Lewis quickly put some of his students to work* measuring solids density as a function of flow direction, gas velocity, and solids flow rate in glass apparatus…and shortly the dense fluid bed regenerator became more than a gleam in the eye."[65]

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[62] Weber (1980:26). For a detailed treatment, see Landau and Rosenberg (1992).

[63] For further details, see (Rosenberg 1998); Enos (1962), Chapter 6; Gornowski (1980) and Landau and Rosenberg (1992:90-91)

[64] Enos (1962:200)

[65] Gornowski (1980:308), emphasis added.

The development of the discipline of chemical engineering offers a vivid example of how the interaction between industry and universities can, in some cases, result in valuable contributions to both. In chemical engineering, the interface between university and industry was unusually intimate - to the extent that MIT students undertook research topics, drawn from the immediate needs at the technology frontier, when their professors returned from their consultancy excursions. At the same time, the most significant findings drawn from the consulting experiences of the MIT faculty were quickly transmitted to students through swift changes in the content of the teaching curriculum. As long as professors maintained an active role in a teaching capacity, they were under a natural pressure to place the knowledge acquired from their problem-solving activities as consultants in a larger and more general context. This meant fitting that knowledge together in an internally consistent way with other knowledge in their discipline. When reverting to their teaching roles, they needed to systematize their knowledge as an essential precondition for writing textbooks and other forms of publication. This systematization had profound implications for the diffusion of new technical knowledge, not just because open universities “naturally” diffuse their knowledge, but because the need to systematize knowledge for teaching purposes meant that they had to spend time and sustained effort in further activities that inevitably facilitated the spread of useful knowledge.[66]

The prominent role played by an academic institution devoted to teaching and to research was of great importance for a related reason. Even though students in chemical engineering programs went to work in different firms or organizations, they had all been taught a common language of concepts, theories and methods. This shared language facilitated the development of a professional community of people who could easily communicate with and learn from one another, and vastly reduced the barriers to the diffusion of technical knowledge across organizational boundary lines. This ability was what made chemical engineers, after the introduction of the concept of unit operations, so different from the earlier industrial chemists, who tended to speak in very distinct, idiosyncratic, industry-specific, or even firm-specific languages.

Of course, the fact that the discipline of chemical engineering was located in universities in the US had other longer-term consequences. In the years immediately after Little’s formulation of the concept of unit operations, research in chemical engineering sought to acquire a deeper understanding of each operation in order to establish mathematical regularities that would

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[66] See Arora and Gambardella (1994).

improve the efficiency of the design process and reduce the cost of operating the equipment that eventually was designed. Eventually these separate operations were reduced to more inclusive and rigorous concepts such as fluid mechanics and heat transfer. In time, chemical engineers attempted to codify the basic physical phenomena underlying momentum (viscous flow), energy transport (heat conduction, convection, and radiation) and mass transport (diffusion). It is continual advances like these that have led recently to the claim that chemical engineering has achieved the status of an “engineering science.” Beginning with the concept of unit operations as a way of abstracting from the particularities of specific artifacts, it eventually moved to a deeper level: expressing the processing activities of chemical plants in terms of basic molecular and transport phenomena. As a result, much of the designing activity of chemical engineers is now understood at a more fundamental level, while the design of chemical processing equipment still draws upon empirical regularities that have stood the test of time, even when these regularities cannot be accounted for at a fundamental level that would satisfy the more rigorous demands of the scientist.

Thus, a critical achievement of the initial concept of unit operations was that it clarified the objectives of research. In this sense, it served as a focusing device. By providing an intellectual platform for science, it eventually altered the nature of the platform itself. Consequently, it can be said that chemical engineering did not emerge out of prior science but rather that, as it matured, it strengthened the opportunities for focusing scientific concepts and methodologies upon the problems with which it dealt. As a result, chemical engineering eventually **became** more scientific.

A final postscript

Little has been said here, or elsewhere, about how the development of the engineering disciplines historically, has exercised some effect in the industrial world on the incentive to undertake research of a scientific nature. We argue that this effect has been a powerful one. It has been expressed through several different channels. In part, the rise of ‘scientific engineering’ has served to meld the empirical and practice oriented methods of knowledge generation of the period we have examined into the pursuit of scientific understanding. As a consequence, in recent years, industrial firms have accounted for significant fraction of the economy’s scientific research. Even if we focus exclusively on the narrow category of basic research alone, the NSF reports that, in 2007, 20.5% of all basic research in the US was performed by industry and 17.1% of this total was funded by industry.[67]

We suggest that the longer term trend toward rising private sector performance of basic research is closely connected to the maturing of the engineering disciplines. This is because improvements in the engineering disciplines serve to raise the prospective financial payoff to research of a more purely scientific nature. The presence of these disciplines enhances the possibility of converting the findings of purely scientific research into marketable products. In this sense it can be said that they have been strengthening the endogeneity of science in advanced capitalist economies.[68]

In addition to the story of maturation, which can be associated with the rise of 'scientific engineering,' we wish to call attention to the continued existence of engineering knowledge that has yet to be integrated in a scientific paradigm. Empirical observation and the value of experimentation without the benefit of a predictive scientific model may still play important roles in generating useful knowledge. As we have observed, the predominance of 'science' as the presumed progenitor of useful knowledge in our era suggests that efforts to discover useful knowledge may be clothed as science, by making reference to predictive scientific theories and models. Whether the university is presently as appropriate a home for such research as it was in the historical period we have discussed is an issue that merits further examination.

Our account of the history of the useful knowledge concept in the first decades of the 20th century is one of institutional adaptation by universities, some of which seized upon the opportunities provided by new experimental techniques and frameworks to generate useful knowledge, knowledge that was often beyond or outside the scientific models available, and much of which simply could not be explained by predictive scientific models. Instead, empirical and experimental processes of search and discovery were conducted in purpose built laboratories, field research sites such as agricultural experiment stations, and active collaborations between practitioners and university researchers. In the disciplines that we have examined, the institutional forms that were developed varied widely, some relying on public

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[67] National Science Foundation (2010: 10). As noted by the NSF, "from 1980–98, non-federal support for basic research grew at the remarkable rate of 6.4 percent per year in real terms" National Science Foundation (1999) and more recently, the level of non-governmental funding support for basic research has ranged from 34 to 39%, National Science Foundation (2010:10)

[68] See Rosenberg (2000b)

support, but many depending on private enterprises or foundations established by industrialists to advance useful knowledge.

The legacy of this process is that, while the undertaking of contemporary basic scientific research may not be undertaken with specific objectives, there is considerable confidence that, whatever the specific research findings within a given industrial sector, a well-developed engineering capability will raise the likelihood of being able to use the findings to bring new or improved products to the market. From this perspective, there is a serious sense in which the economist may argue that research in the science of chemistry should be thought of as an application of chemical engineering - or, at the very least, as a response to progress in chemical engineering. We do not want this point to sound too paradoxical. We refer to the long established trend whereby profit-oriented firms to commit additional resources to long-term scientific research, research that has similarities to the scientific research conducted with public support including the publication of results in scientific journals and the definition of research purpose in terms of the advance of knowledge rather than by the prospect of immediate application, leading to such investments being classified as 'basic' research by the National Research Council.[69] The prospective value of such projects is strengthened by the ability of engineers and product designers to create new products out of recently-acquired scientific knowledge.

What is at issue here is the appropriability problem with respect to the conduct of basic scientific research. A private firm can increase the likelihood of overcoming the appropriability issue connected to its conduct of basic scientific research if it can also acquire private engineering knowledge. This makes it more likely that it will be able to exploit the scientific findings quickly and, thereby, appropriate the rents that may flow from these findings. Otherwise the intellectual property rights will remain unassigned and free rider problems may be expected to loom large.

This argument seems particularly pertinent to the realm of chemistry. In the US, at least, polymer chemistry is a field that has been dominated by the industrial research community for many years. The fundamental research contributions of Wallace Carothers at the du Pont Corporation, beginning in 1928, owed a great deal to the increasing maturity of chemical engineering - itself a discipline to which du Pont had made significant contributions.[70] Carothers' major scientific research findings resulted in the discovery of nylon, the first of many synthetic fibers. However,

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[69] Rosenberg (1990)

[70] See the splendid book on R&D at du Pont, Hounshell and Smith (1988), especially chapter 14.

a gigantic development effort was required, involving an intense concentration of effort on the part of chemical engineers over a period of 11 years, before the first pair of nylon stockings became available. It is doubtful that du Pont would have made such a substantial commitment to fundamental research in polymer chemistry in the absence of the progress in chemical engineering in the decade preceding 1928. This progress in an engineering discipline vastly strengthened the firm's confidence that it would be able to convert the findings of scientific research expenditures into commercializable products, a confidence that, in this case at least, later turned out to be abundantly justified.

The implications of the creation of new and experimentally-based useful knowledge as a progenitor of scientific investigation and the need to embed such experimental and experiential knowledge in the university to provide a means of distributing this knowledge to new generations suggests a need to extend the historical examples offered here to include other sectors. Proceeding from the period which we examine to the present suggests the following candidates for similar examination: the electrical power industry, the use of new materials and methods in creating prototype designs, medical devices and instruments employed in clinical medicine, the design and implementation of products relying on complex control systems, and the interactions between the ever richer information resources related to genomic studies and the vast stores of information on cell, organ and organism physiology, morphology, and biochemistry. Indeed, the extent to which large scale databases that are accumulating as the result of improved instrumentation, of the efforts to digitize information recorded in other forms or derived from artifacts in museums and archives, and of the worldwide search for new biological and physical information provide vast new bodies of empirical information subject to search, sometimes guided by pre-existing theory and others simply by the discovery of pattern or order in data.

In each of these areas, and in many others of a more specialized nature, there are gaps or discontinuities between the useful knowledge arising from practice, the incorporation of this knowledge in the research and education conducted in universities, and the possibilities for generating a fertile interplay between useful knowledge and the more circumscribed and controlled processes of creating predictive scientific models that explain parts of the whole but may better represent an aspiration for completeness and prediction than a readiness to generate and rapidly diffuse useful knowledge. Closing these gaps and bridging these discontinuities in the future is likely to require institutional innovations as dramatic as those that we have recounted in this historical examination.

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