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Science, Technology, and Industry in the 19th Century

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1. Introduction

The nineteenth century witnessed the rise of modern industry. From Western Europe to Britain to North America agriculture lost its preeminent role in societal reproduction and yielded to industrial manufacturing and technology-intensive services like railroads, steam navigation, and telecommunication, to name but a few. Dramatic changes in the social fabric and the face of landscapes spread from the North Atlantic region throughout the world and bore witness to a fundamental shift in human history. Both the number of people and artifacts grew at an unprecedented rhythm. This emerging modern world was driven by an unending stream of new products turned out by factories employing radically new technologies, skills, and organization. Technological innovations, being the most tangible results of this new, accelerated mode of reproduction, were soon understood to represent the rationale of nascent industrial society. Never before in history and never within a single lifetime had so much novel material culture been produced. This sudden leap of productive potential puzzled contemporaries and continues to preoccupy historians.

One of the many questions raised by this historical watershed concerns the sources of innovation in nineteenth-century industry. While social and economic historians have concentrated on skills and organization, historians of science and technology have debated the character of novelty in technology. How much did technological innovation owe to recent advances in the sciences? To what extent was nineteenth-century industry science-based? To what extent were developments in science and industrial technology independent of each other? Did science perhaps ultimately benefit more from technology than technology did from science?

The positivistic school, which dominated the field in the 1950s and 1960s, thought that industrial technology was applied science and technological innovation not much more than putting the results of scientific research to work. A. Rupert Hall provides a representative summary of this view. In 1962 he declared: “The late eighteenth century was the point in time at which the curve of diminishing returns from pure empiricism dipped to meet the curve of increasing returns from applied science. This point we can fix fairly exactly, and so we may be sure that if science had stopped dead with [Isaac] Newton, technology would have halted with [John] Rennie, or thereabouts. The great advances of later nineteenth century technology owe everything to post-Newtonian science.”[1]

Engineering appeared to be subordinate to enlightened progress in the “hard” sciences, with physics at their center. Recalling this earlier orthodoxy, Ruth Schwartz Cowan drew a parallel to gender relationships in her Presidential address of 1994 to the Society

[1] Hall, “The Changing Technical Act,” 511.

for the History of Technology (SHOT): “Technology is to Science as Female is to Male.”[2] It was the time when SHOT had been created “from a rib out of the side of the History of Science Society,”[3] and when historians of technology had begun to stress the autonomy and originality of technological knowledge and strategies vis-à-vis both science and economics, the two fields that had claimed to incorporate technology and its history as a subset. The “technology = applied science” controversy constituted the background against which the newly independent field of history of technology found its group identity. If “technology” could be subsumed under “science,” then could history of technology, at least for the nineteenth and twentieth centuries be placed under history of science?

In subsequent years, the formal separation of the academic fields of history of science and history of technology very much helped to distinguish the differences between science and technology during the two centuries of industrialization. In its early years, SHOT’s journal, *Technology & Culture*, focused more on the characteristics of science, technology, and engineering than on any other single subject.[4] With two special issues in 1961 and 1976, respectively,[5] as well as with a great number of scattered articles on science-technology relations over the years, the debate eventually moved from apodictic ontological battles to an elaborate discussion of the specificity of technological knowledge and practice. While the bitterness of secession has never been fully overcome, the sophistication of argument has benefitted immensely from this distancing under the scrutiny of the erstwhile parent discipline.

However, and regrettably, the distancing has gone to such an extent that by now the two disciplines nearly lost sight of one another. Courses in the history of technology and the history of science take little notice of what happened on the other side of the newly erected academic fence. And while historians of technology in their effort to prove the distinctness of technological knowledge and practice at least continue to discuss science, historians of science hardly ever enter the field of technology and industry, or at least no more than to offer some passing remarks. The very peripheral field of the history of scientific instrumentation is perhaps the only place where technology is to be found frequently discussed in their publications. Fairly recent companions to the history of modern science have been published wherein “technology” and “industry” are not given even allotted a single chapter and make only an extremely modest appearance in the subject index.[6] Mutual ignorance was the trademark of both fields during the years of unsettled claims of primacy and priority in the development of modern industrial civilizations.[7] It has taken joint meetings, stimulating input from science studies, and a new generation of historians unscathed by the wars of secession to enter into a new dialogue over the role of science and technology during the “post-Rennie world.”

Historians no longer see the historical relationship of science and technology relationship as one of epistemological hierarchy, ennobling one subject over the other. Rather,

[2] Cowan, “Technology is to Science as Female is to Male.”

[3] Staudenmaier, *Technology’s Storytellers*, 1.

[4] Ibid., chap. 3.

[5] *Technology & Culture* 2 (Fall 1961); and *Technology & Culture* 17 (October 1976).

[6] Olby, Cantor, Christie, and Hodge, eds., *Companion to the History of Modern Science.*

[7] Many scholars have made this observation; see e.g., Laudan, “Natural Alliance.”

they see a systemic interrelatedness of the two, which makes it difficult to separate them neatly, if at all. The metaphor of fields interpenetrating each other now seems more appropriate than that of bodies encapsulated in or juxtaposed on one another. It now appears as an almost ironic reversal of the earlier debate when some historians of science, inspired by twentieth-century European philosophy, claim that all science is technology.[8] With the missionary hubris of the Enlightenment ideal approaching dusk and with the reinvention of humanism,[9] the history of science and technology as they existed in practice now attracts more interest than the apologetic story of unfolding truth and progress that had once dominated much of the earlier literature. Still, this body of literature continues to be an invaluable source for the history of science, technology, and industry in the nineteenth century. Like all sources, it has to be read with its time and ideological background in mind. The same is of course also true, and more difficult to recognize, for contemporary historiographical outlooks.

This essay addresses the most important issues of the science-technology-industry triangle during the nineteenth century. Following a general discussion of the "science-technology push" (section 2), wherein hypotheses such as the "linear model" of "technology=applied science" are critically treated, the essay turns to the dispute over the role of science in the Industrial Revolution (section 3). This in turn leads to an assessment of the importance of science to engineering in early nineteenth-century industry (section 4). While Britain still holds center stage at this point, the emphasis thereafter shifts to the European Continent and America. The issues here include technology transfer and the tools employed by states and industries to catch up with Britain (section 5). The focus is on forms of knowledge and the early development of a school culture in engineering. The institutionalization of technological education as a deliberate effort to promote industrial development emerges as an important clue to understanding the complicated science-technology relationship. It turns out that, well before any measurable impact of the content of science, academic science and industrial technology were heading towards a common language that was instrumental in promoting intensified exchanges between the two fields (section 6). Engineering science, following a lengthy gestation, developed as an autonomous academic subject in the second half of the nineteenth century and played the successful intermediary between the findings of science and industrial application (section 7). A still quite limited number of science-based industries in chemistry, electric engineering, optics, and mechanical engineering eventually provided the empirical background for evaluating the contribution of science to technology and industry at the end of the nineteenth century (section 8).

2. A Science-technology Push?

Studying the relationship between science, technology, and industry during the nineteenth century can be done from the perspective of each of these three elements. The outcome of such a study is, however, very likely to reflect this a priori choice. Both the history of science and the history of technology, as they have come down to us, easily lend them-

[8] Wise, "Mediations," 253; and Shapin and Shaffer, *Leviathan and the Air Pump*, 25.

[9] Toulmin, *Cosmopolis*.

selves to an heroic "push-hypothesis," whereby science pushed technology and technology in turn pushed industry towards innovation. This "linear model," which in the past had pervaded and still today continues to a large extent to influence and legitimize public spending on research and development, has lost much of its persuasiveness over the last decades. If, on the other hand, we conceive of a triangle of science, technology, and industry and do so in terms of systemic interrelatedness, the result is a more complex and much more plausible pattern of multidirectional pushes and pulls to and from each of the three elements.

The largest of these elements in terms of the numbers of people and the amount of material resources involved was certainly industry. In the linear model, industry was at the end of the process, since science needed first to be transformed into technology before it was applicable to production. This brought the history of industry closer to the history of technology than to the history of science. And much of the history of technology is in fact hard to distinguish from the history of industry or even business history. This state of affairs is also revealed by certain professional preferences. Historians of technology are often to be found at conferences on and their writings often appear in publications on economic history, business history, and labor history; this is much less the case for historians of science. There exists a continuum between the history of technology and the various subfields of social and economic history which scarcely reaches into the history of science. In view of recent studies of industrial research, where the history of science and the history of industry meet, this restraint now seems outdated. Obviously, academic affiliations die harder than academic orthodoxies.

If the linear model is no longer seen to be a fair representation of the science-technology-industry relationship, then the demonstrable impact of science and technology becomes the appropriate starting point for an historical investigation rather than the threads for following their push to and through industry. Taking a broad view of nineteenth-century industry, science appears to be but on a few scattered islands on the seas of industry while modern technology, for its part, is not nearly as pervasive as many histories of technology would have us believe. It has long been the common opinion that industry owed little to the content of scientific knowledge during (at least) the first half of nineteenth century.[10] Looking at technology we do, to be sure, find a number of impressive examples of newly mechanized production sources like textile mills, iron works, machine shops, and the like. At the same time, however, much or rather most of mid-nineteenth century industry relied, as Raphael Samuel has reminded us in a seminal article, on hand labor rather than on machine technology.[11]

What was technologically new about mid-nineteenth century industry was not dominant. The organization of labor and space, information about markets, and a new entrepreneurial spirit seem to have been among the more prominent concerns of most new industrialists. Such issues as how to design a factory or where more labor was to be employed in order to move things around rather than to operate machines were probably the greatest challenges to be met until well into the twentieth century.[12] This is reflected in

[10] Mason, *A History of the Sciences*, 503.

[11] Samuel, "The Workshop of the World."

[12] Biggs, *The Rational Factory*.

two of the most influential texts about early industry, both of which were written by scientists who put the issue of the organization of factory production first. Both the chemist Andrew Ure, in his *Philosophy of Manufactures or An Exposition of the Scientific, Moral, and Commercial Economy of the Factory System in Great Britain* (1835) and the mathematician Charles Babbage, in his fundamental work *On the Economy of Machinery and Manufactures* (1835) concentrated on organization much more than on technology, let alone on science. These books certainly had more impact on the nineteenth century than Babbage's *Difference Engine* or his *Reflections on the Decline of Science in England* (1830).

Economic historians like Robert Fogel, a Nobel prize winner in economics, have shown that rapid economic growth in the nineteenth century did not necessarily depend on its most exciting technologies.[13] Fogel demonstrated how the United States, relying on a somewhat different combination of older technologies like land transport, river and canal navigation, could have developed equally well without railroads. With a wealth of hydraulic power, large parts of Switzerland, Italy, and California experienced successful industrialization without the use of coal and steam, the very symbols of nineteenth-century industry. Paul David, using examples from the late nineteenth century, has shown us just how contingent irrevocable decisions on technological development can be. Rather than always promoting the technologically and economically best-possible alternative, market forces might as well "lock in" suboptimal technologies and make further development "path dependent."[14] Irrespective of the inherent qualities of new technologies, complex social processes decided over their "success." There is no hidden logic in history that would eventually usher some "optimum" state, benefitting from the full potential of the stock of scientific and technological knowledge. What John Maynard Keynes exemplified for employment in the twentieth century was true for technologies and industries in the nineteenth as well: equilibria and optima did not by themselves converge.

Inevitability, determinism, and one-dimensional causality have been the prime victims of late twentieth-century social and economic studies. A reductionist view of nineteenth-century industry as an epitomization of accelerated technological progress is no longer defendable. A whole world has undergone a transformation wherein science and technology were but two elements among many. This transformation would have been undoubtedly quite different, probably unrecognizably different, without these elements. But the same is true for many other elements of this fundamental historical change: democracy, nationalism, labor movements, mass culture, service economies, secularization, religious revival, and so on. Privileging one element over one or more others to explain the dynamics of a systemic context will not help to understand either the system or the element in question. The contributions of science and technology to nineteenth-century history are not best understood by starting a historical investigation with science and technology. This, however, was legitimately the business of both the history of science and the history of technology. Following the perspective of the linear model of technological and industrial change, we learn but little about industry in studying just technology and but little about technology in studying just science. This observation alone would Hall's quotation in the introduction to this essay and the school that it stands for difficult to accept. At the same

[13] Fogel, *Railroads and American Economic Growth*.

[14] David, "Path Dependence in Dynamic Systems."

time this observation helps us to understand why we find so little about technology proper in general studies of nineteenth-century history and so little history of science in histories of nineteenth-century technology. It is not just parsimonial neglect, arrogance, or blindness; rather, to a large extent it is a quite appropriately balanced outlook. Science and technology are only two of the many elements of nineteenth-century history; moreover, they themselves hardly existed in their "pure" form. They are, instead, better understood as strategies within a complex of motivations and lifeworlds.

It is important to realize that industry had many more users than producers of technology. The textile industry, blast furnace works, gas works, sawmills, breweries, and dairies all used technology to transform raw materials into forms that were and are not recognized to be "technologies." This is still more true in the case of service "industries" like railroads and shipping companies which used complex technology to transport things and people. These very important industries did not create technologies but organizations, ways to do things rather than ways to produce things. They were buyers of knowledge encapsulated in knowledge-intensive artifacts produced by others. This is the world Babbage and Ure wrote their most influential books about. More often research was done on making people cooperate or handle machines and materials rather than on the machines and materials themselves. The science of industry was a social science with many faces from Ure through Karl Marx and on through Frederick Winslow Taylor. The "Human Motor" continued to be the most important power source of early industry, one which, however, in the first place posed social and political challenges. Only slowly and peripherally did an interest in its physical dimension grow through the century.[15]

3. Science in the Industrial Revolution

All efforts to understand the changing relationship between science, technology, and industry through the nineteenth century must start with the Industrial Revolution. While there is widespread agreement in the literature today that industry owed very little to science during the turn from eighteenth to nineteenth century, this agreement is neither total nor unqualified.

In their magisterial study, published in 1969, A.E. Musson and Eric Robinson argued forcefully for an applied-science model for understanding technological innovation in late eighteenth-century Britain.[16] They documented in great detail the debt of early industrial inventor-engineers to the knowledge gleaned from the new science of Robert Boyle and Isaac Newton, making the application of science a significant distinction of inventions created during the Industrial Revolution and earlier. While they did not argue that science was the single-most- important contribution to the Industrial Revolution, their account stood out by linking many inventions to direct scientific input and stressing the existence of a continuum from "pure" to "applied" science and eventually to technology, rather than juxtaposing the two worlds of science and engineering. To Musson and Robinson chlorine bleaching and the Watt steam engine were striking examples of applied science, of inno-

[15] Rabinbach, *The Human Motor*.

[16] Musson and Robinson, *Science and Technology in the Industrial Revolution*.

vations that benefitted immensely from their authors' embedment in the scientific discourse and the scientific communities of the time.

This position has met strong criticism not only from historians of technology stressing the independent nature of technological knowledge but also from established historians of science who were otherwise favorable to the view that technology increasingly became a form of applied science in the later nineteenth century. A.R. Hall summed up these reservations in a programatic article asking: "What did the Industrial Revolution in Britain owe to Science?" Hall argued that inventors during the Industrial Revolution in fact owed very little to contemporary developments in science. The mathematics that they often used for the first time in engineering was centuries if not millennia old. Moreover, references made to science could be shown to have been of no importance to the actual invention. On closer scrutiny they appeared as mere window-dressing to lend science's authority to engineering ingenuity. Hall argues that Nicholas Leblanc was guided to a useful reaction not by chemical science but by false analogy; that James Watt's separate condenser did not need a theory of latent heat; that Josiah Wedgwood's use of phlogiston-language "was no more than a way of rationalizing what was physically observable." Furthermore, he maintains that there are a number of examples where "scientific clarification postdated the technical improvements which it ought to have preceded." The core of Hall's argument, even if not expressed verbatim, remains that Musson and Robinson fell victim to a *post hoc ergo propter hoc* fallacy, the original sin of much historical theorizing.[17]

To Hall, "men like [John] Smeaton, Wedgwood, Watt, [Thomas] Telford, [Richard] Trevithick, [George] Stephenson, [and] Rennie were above all great technical engineers. Certainly they used more exact and sophisticated experimentation than their predecessors; they also relied far more on the analysis of quantitative data. But these novel characteristics–and their significance was still limited enough–should be regarded as rather incipient modifications of an ancient tradition, partly enforced by the desire to use new materials like cast and wrought iron, than as the effect of a revolution wrought within technology by an infusion of scientific theories and discoveries." He concluded: "The history of the Industrial Revolution in Britain shows amply how ready the technical innovators were to work out new ideas empirically when, as was then often the case, science had little guidance to offer." "Science" here standing for the content of science; as to the methodology of science, the story was quite different. It was in scientific procedure that Hall saw many "applications" to engineering work. These were "attempts to classify technical processes logically," "the employment of systematic experimentation, usually involving model[s]," and "the treatment of data quantitatively."[18]

Margaret C. Jacob has recently been the most sophisticated defender of the Musson-Robinson view of a causal relationship between science, technology, and industrialization along the linear model.[19] In her much refined argument, which bears witness to the cultural turn history has undergone in the past decades, she again gives Newtonian mechanics and the new chemistry of the eighteenth century a prominent place in the Industrial

[17] Hall, "What Did the Industrial Revolution in Britain Owe to Science,? quotes on 141, 145.

[18] Ibid., quotes on 148, 151, and 146, resp.

[19] Jacob, *Scientific Culture and the Making of the Industrial West*. This book is largely a sophisticated continuation of Jacob's earlier work, *The Cultural Meaning of the Scientific Revolution*.

Revolution. As she states at the very start of her study, she is convinced that "the elements of the natural world encoded in science were not peripheral to industrialization and Western hegemony; rather they were central to it."[20] Moreover: "The late eighteenth-century application of scientific knowledge and experimental forms of inquiry to the making of goods, the moving of heavy objects whether coal or water, and the creation of new power technologies dramatically transformed human productivity in the West."[21] Jacob infers from the strong interest in science, or rather "natural philosophy," at the time there was a growing "audience for science" that not only the forms of scientific investigation but also the contents became instrumental and indispensable for technological development at the very beginning of the nineteenth century. In her view, "the industrial entrepreneur girded with skill in applied science" was already the key figure of early European industrialization.[22]

However, it is hard to find positive evidence for Jacob's assertion. Proximity to science by prominent engineers is demonstrated more by association and mutual respect than by demonstrable input of scientific knowledge. Since Jacob's recent book largely concentrates on Watt and the steam engine, the centrality of which to economic and industrial development in early nineteenth century England has been previously much debated,[23] it is thus only a narrow segment of the Industrial Revolution that has been drawn back into the applied-science debate. Hall's paradigmatic criticism of Musson and Robinson is still applicable and the issue remains unresolved. While science was indisputably on the agenda of early nineteenth century industrial figures and very much influenced the way technological problems were discussed, there is still no conclusive evidence that it had an impact on technology beyond the sharing of a common methodology and ideology.

These common characteristics of science and technology have been much less contested, although there has been a hidden science-technology hierarchy in some of the literature. One example here is Stephen F. Mason's widely appreciated *A History of the Sciences*. Mason maintained: "Whilst the content of scientific knowledge did not have much influence upon the development of industry up to 1850, the method of science did."[24] This would constitute a linear model in the realm of methodology, with science emerging as the source of problem-solving strategies; a scientific approach to technology had thereby long existed before a measurable scientific input. More recent literature has shied away from this second-order determinism and rather stressed an equality and simultaneity in the science-technology relationship. "Twins" has become the powerful metaphor here. To Jacob, science and technology at the time of the Industrial Revolution were "fraternal twins, born into a family particularly eager for profits and improvement: they have different *personae*, different looks, but are still profoundly related."[25] To Edwin Layton, they were "mirror-image twins" later in the nineteenth century and sharing many of

[20] Jacob, *Making*, 3.

[21] Ibid., 4.

[22] Ibid., 177.

[23] Tunzelman, *Steam Power and British Industrialization to 1860*; and idem; "Technology in the Early Nineteenth Century."

[24] Mason. *A History of the Sciences*, 503.

[25] Jacob. *Making*, 9.

the same values but pursuing different ends and acquiring their own kind of knowledge in the process.[26]

As Ian Inkster has shown, the technology twin was, to be sure, often well educated in the sciences—in Britain more than in any other country prior to 1850[27]—but it was not always those who were best-educated scientifically who stood behind the most striking technological breakthroughs. Textiles, machine tools, and ironmaking developed into the backbone of British industry without noticeable scientific input or what could be taken as such. Textiles, the leading sector in the early stages of industrialization, thrived on improvements of basic inventions from John Kay's flying shuttle to Edmund Cartwright's power-loom, all of which had been made in the eighteenth century.[28] Even the steam engine is seen by most scholars of the Industrial Revolution as having been a great stimulus for science rather than its offspring.[29] As for chemistry, thought it was not the most important industry in early nineteenth century it does remain the one candidate to come to the rescue of what is left of the linear model. Yet even here opinion is split and in its majority leans toward the view that tinkering was more important for tangible results than any reasoning that could be called "scientific." No great advances have been made in the literature on this question since Charles Gillispie's work on the origins of the Leblanc process, wherein he showed that the invention of the process was unaffected by the contemporary "chemical revolution" of Lavoisier.[30] This does not, however, rule out the utility of wrong assumptions on the path to new technologies. It is in this respect that the "twins" showed a similar mindset that was hardly the privilege of either nascent science or technology but often enough a streak of luck for both in their heading for different ends through the nineteenth century.

4. Engineering in Early Nineteenth-Century Industry

During the nineteenth century engineering became the backbone of industrial development. As Akos Paulinyi has shown, material-forming processes were the common denominator of a revolution in technology that accompanied and pushed the early industrialization of Europe and North America.[31] Textiles and railways, the two leading sectors, relied heavily on inputs from mechanical engineering. Machine tools and heavy machinery for moving objects occupied center stage in the workshop of the world. Together with the rapidly developing skills of machinists, production engineers, and factory managers they were the enablers of an unprecedented advance of artifacts in everyday life. The pinnacle of early nineteenth-century technological knowledge was embedded in the output of machine shops from London through Birmingham to Sheffield.

If early engineers had participated in the rage for Newton's mechanics during the eighteenth century, then there was little of practical value to be found in it. Unlike celestial

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[26] Layton, "Mirror-image Twins."

[27] Inkster, *Science and Technology in History*, 72.

[28] O'Brien, Griffiths, and Hunt, "Technological Change during the First Industrial Revolution."

[29] Inkster, *Science and Technology in History*, 70.

[30] Gillispie, "The Discovery of the Leblanc Process."

[31] Paulinyi, "Revolution and Technology."

mechanics, terrestrial machinery was largely governed by the limitations of friction and various other forms of resistance and elasticity as much as by economic considerations, all of which very much limited a purely mechanical approach to its problems. Tremendous heat losses as reflected in efficiency quotients of less than 0.05 rather than in theories of heat were the order of the day in the design of steam engines. And gathering knowledge of what worked seemed a more attractive and promising strategy than theory building in a mechanical world far too imperfect to benefit from idealizations. Again, Hall insists that Watt's tables of empirical data on steam or his collection of guidelines, approximate figures, and proportions for mechanical problems constituted a more-lasting legacy than his acquaintance with Black's notion of latent heat.[32]

As the Dresden research group directed by Gisela Buchheim and Rolf Sonnemann have stressed in their collective "history of the sciences of technology," borrowing from architecture the method of ratios became the foundation of much of nineteenth-century engineering. John Farey made extensive use of this approach in his *Treatise on the Steam Engine* (1827). Ferdinand Redtenbacher and Arthur Morin brought it to the Continent. Academic teachers like Olinthus Gregory of Woolwich, and Thomas Young, professor at the Royal Institution, were instrumental in providing engineers with assistance in solving problems of practical mechanics such as friction, kinematics, force of resistance, and material strength.[33] Most importantly, according to the Dresden group, were the extensive collections of the values of material substances, specifications on dimensions, formularies, and general technical encyclopedias compiled or edited by experienced engineers like Peter Barlow, George Rennie, William Fairbairn, and– the theoretically most advanced member of this group—Thomas Tredgold.[34] Hans Joachim Braun in his essay on methodological problems of nineteenth-century engineering science has emphasized that some authors, like Julius Weisbach, for example, in their effort to accommodate the practical needs of engineers reduced the complexity of the mathematical tools to such an extent that their peers accused of being "unscientific."[35] This did not, however, render their books any less useful to the practitioner.

The situation was very different in France, where engineering was taught and researched at a much more abstract level in that it was firmly based on mathematics and theoretical mechanics. This, however, did not help domestic industry. The works of Claude Navier, Gustave Coriolis, Jean Poncelet, and Sadi Carnot as much as the *géométrie descriptive* of the school of Gaspard Monge did not connect to the contemporary problems of engineering in any useful way. In terms of industrial applications, the French scientific effort in engineering during the first half of the nineteenth century fell flat. In his magisterial history of industry in France, Denis Woronoff, an historian of French industry, gives no credit to any noteworthy contributions of science until the 1880s. He portrays an almost tragic situation where nothing came of the most-heroic efforts to promote industry through science. "All branches of mathematics, physics, and chemistry are being mobilized for the promotion of industry. In France in particular, this idea of applied science, which had been

[32] Hall, "What Did the Industrial Revolution in Britain Owe to Science?," 140.

[33] Buchheim and Sonnemann, eds., *Geschichte der Technikwissenschaften*, 182-183.

[34] Ibid., 185.

[35] Braun, "Methodenprobleme der Ingenieurwissenschaft, 1850 bis 1900."

so dear to Georges Cuvier and Jean Antoine Chaptal, this idea of the transfer of fundamental knowledge towards the 'arts,' is dominant. To say to the contrary is to submit to routine. It is to admit, however, that the results are hardly convincing. Not that the bridges are burned or that the inventors do not benefit from a scientific culture. But the era is one of unlikely encounters of theories without prospect and inventions without theory.'[36] Notwithstanding brilliant French science, competitive technology and knowledge about it continued to issue from Britain. Going to Britain and learning by doing in British firms proved to be the most successful way to transfer technology to the Continent and catch up with the leader.

5. The Tools for Catching Up

5.1 Academic Tools

Notwithstanding the very limited success of scientific education in France, a number of European countries took to teaching science and technology on an academic level with a view to fostering their infant industries. It was an effort to catch up with British industry in the absence of a wealth of factories and workshops that served as educational institutions for learning-by-doing. The academic teaching of technology was a second-best solution, with blackboards and laboratories often poorly substituting for real factories and real machinery. It is no surprise that the educational institutions of the military served as a model. The military was itself in a similar situation in that it had to educate its young officers in an art that could not easily be practiced at will. Unlike marauding troops of seventeenth-century mercenaries, politically disciplined eighteenth-century armies had to resort to blackboards and maneuvers to educate their junior officers. Moreover, the construction of fortifications and the build up of artillery required specialized education; such strong motives lay behind the near simultaneous creation of two Parisian institutions: the École des Ponts et Chaussées (1747), the school for civil engineering, and the École du Genie militaire (1748).[37]

A second impetus came from the experience of the royal mining schools on the Continent. These schools had been the earliest institutions of technological higher education and constituted a technological backbone for generating royal income from silver and copper production in early modern times. Two centuries of systematic investigation in mining, metallurgy, and its technology had led to the creation of mining academies in Freiberg (Saxony), Berlin, and Schemnitz (Slovakia) in 1770. These academies, together with the École Polytechnique of the French Revolutionary Army (1795), formed the background and model for the institutions of higher education in Continental Europe during the post-Napoleonic Reform era. Governments throughout Europe thought that the only lasting protection from revolutionary wars, invasion, and occupation in an age of mass mobilization was the erection of a powerful industry along the lines of the British model. Yet they understood industrialization as a task for the state to organize, promote, and control rather than one to be left to the unhampered initiatives of private enterprise alone.

[36] Woronoff, *Histoire de l'industrie en France*, 238.

[37] Buchheim and Sonnemann, eds., *Technikwissenschaften*, 68-69.

Within a few decades a great number of technological schools for higher education were established in central Europe, most of them in the German states, where they began to form a model of their own, the *Technische Hochschule*, or institute of technology. These institutes continued the tradition of the state's educating, organizing, and controlling its own technological experts. Like the French military *Écoles* and the German and Austrian *Bergakademien* (mining academies) the newly created polytechnical schools (in time known as *Technische Hochschulen*), turned out state civil servants. As Peter Lundgreen has stressed, the state qualifying examinations (*Staatsexamen*), like the officers patent, were the certificates sought by these schools' students.[38] With the vast majority of their students heading for a position in the state bureaucracy rather than in industry, there was little need for a separate, academic certificate. Lars Scholl and Cornelis Gispen have found that well into the second-half of the nineteenth century autodidacts outnumbered college graduates among engineers in German private industry.[39]

The same is true for France and its model institutions of higher technical education. There, more than anywhere else, engineers in state service were separate from engineers in industry. According to Terry Shinn, the evolution of these distinct occupational categories and the immense gap separating them constitute the principal theme in the development of French engineering between 1750 and 1880.[40] Industry had little to benefit from the prestigious Parisian *écoles*. Most of the latter's graduates during the nineteenth century served in the artillery, followed by the corps of bridges and roads[41]. Between 1830 and 1880 only 10% of the *polytechniciens* eventually ended up in industry. Most of them were in the mining (27%) and chemical (22%) industries and with the railway companies (18%). While those in mining might actually have been employed as *ingénieurs*, in other industries it is doubtful whether their formal education made them attractive to employers. Jean-Pierre Daviet found that they were employed to organize and rationalize manufacturing rather than to innovate technology. They were, in other words, appreciated as managers rather than as scientists or engineers. The organizational skills acquired in their military career after graduation made them valuable for industry.[42] Interestingly, tt was more along the lines of the themes of Babbage's and Ure's books on factory organization that, as in the military, formal rigidity and methodology entered the factory world. Or as Denis Woronoff, the historian of French industry, put it: "their intervention maximized the use of technologies [already] employed."[43] It is common opinion in the literature that, until well into the second-half of the nineteenth century, higher technological education on the Continent was meant to serve the state, not industry.

5.2 Technology Transfer

[38] Lundgreen, "Engineering Education in Europe and the U.S.A., 1750-1930," 44.

[39] Scholl, *Ingenieure in der Frühindustrialisierung*, 297; and Gispen, "Selbstverständnis und Professionalisierung deutscher Ingenieure," 49.

[40] Shinn, "From 'Corps' to "Profession'," 185.

[41] Ibid., 186.

[42] Daviet, *Un destin international*, 231-232.

[43] Woronoff. *Industrie*, 243.

Industry continued to rely on hands-on experience and early nineteenth-century government proved instrumental in facilitating it. Technical museums and royal institutions for the promotion of trade and industry were the places that disseminated technical knowledge among artisans, early engineers, and industrialists. While academic institutions strove for excellence in the sciences and continued to operate as a means of social stratification, as Fritz Ringer has argued persuasively,[44] Continental institutions devoted to promoting trade and industry focused on importing skills and empirical knowledge from Britain.

Textile machinery and steam engines ranked first among tangible products of new technology coveted by Continental governments to promote their infant industries. A more lasting effect, however, was the importing, legally or clandestinely, of machine tools. Machine tools were of paramount strategic importance for the autonomous development and emancipation of Continental industries. Machine tools represented the only technology that could be employed to replicate itself and at the same time provide all the tools of other industries. Machine tools was a sort of *perpetuum mobile* of industrialization. Kristine Bruland, drawing upon her extensive studies of Norwegian industrialization, has well summed up the important differences between textiles and mechanical engineering:

Norwegian cotton and wool entrepreneurs acquired machinery, expertise, information and labor from abroad in “packages” which were put together by British textile engineering firms. The entrepreneurs themselves required commercial and marketing skills: they could, and did, remain relatively lacking in technical expertise. In the engineering industry, by contrast, skill development and competence building were central: this is because engineering is not so concerned with the production of standardized products, but is much more a matter of technical problem solving in which competence is of critical importance.[45]

It was the capacity of a country to build its own machines rather than to mass produce textiles that was to be decisive in its growth path in the nineteenth century. Both British and foreign governments knew this all too well. The tools of and impediments to technology transfer have been an important subject to historians of Continental industrialization.

Akos Paulinyi has summed up the British policy to prevent this transfer: To protect its competitive advantage, at the turn of the century Britain banned the exporting of most production machinery. Beginning with knitting frames in 1696 and adding greatly to its catalogue between 1782 and 1795, Britain prohibited the exporting of most industrial machinery with the notable exception of steam engines, which were not thought to be of the same strategic importance. Knowledge embedded in machines was not to be handed over to Britain’s competitors until 1842, when smuggling had reached such a level as to make the protective efforts of the Board of Trade ridiculous. Skilled workmen, being carriers of tacit knowledge, had not been allowed to leave the country until 1824. A more liberal trade policy eventually won wide support: British trade, it was argued, stood to gain rather than lose from prosperous and developing neighbors. While scientific knowledge

[44] Ringer, *Education and Society in Modern Europe*.

[45] Bruland, “The Norwegian Mechanical Engineering Industry,” 266.

had always been allowed to circulate freely, until well into the nineteenth century craftsmen and machinery were understood to embody British industry's prowess.[46]

The mirror-image of this thorough protection was state-supported espionage, smuggling, and the illegal recruitment of highly skilled labor. Technology transfer from Britain to the Continent was largely illegal in the early years of industrialization. This, however, did not stand in the way of successful transfer, as numerous authors, like William Henderson on Germany and John Harris on France, have shown.[47] Paulinyi found that after 1815 the illegal exporting of British machinery became a normal if risky branch of international trade. British machine shops interested in selling as much of their product as possible were more than willing partners in this form of technology transfer. British entrepreneurs in mechanical engineering eventually convinced a Parliamentary commission in 1841 of the ineffectiveness of export bans. At the same time, these engineers were filled with praise and admiration for the achievements of the various institutions for the promotion of local industry in France, Saxony, Prussia, Switzerland, and Belgium.[48] The Conservatoire des Arts et Métiers in Paris, the Polytechnisches Institut in Vienna, the Gewerbe-Institut in Berlin, and the Polytechnischer Verein in Munich were among the major recipients of these early high-tech imports.

As Paulinyi has demonstrated with the example of the Prussian Gewerbe-Institut, the course curricula at these institutes were mainly about replicating "imported" machine tools.[49] This early form of reverse engineering extended knowledge and expertise as much as the stock of precious investment capital. Mechanical engineering, the linchpin of the whole new factory system, was firmly rooted in empirical knowledge. Very much relying on their mind's eye (to borrow Eugene Ferguson's felicitous metaphor) Britain's foremost engineers provided few abstractions of their work in written documents. Replication of this kind of knowledge followed the same path. Publications in the *Verhandlungen des Vereins zur Förderung des Gewerbefleißes in Preußen*, for example, were no substitute for personal experience; instead, they drew attention to innovations that had to be inspected on the spot or recreated from personal experience. The same is true of publications from private initiatives like the notable *Bulletin* of the Société d'encouragement pour l'industrie nationale, inspired by Chaptal. Pietro Redondi has stressed that these journals were of great intellectual authority but, as Woronoff has warned, at least until mid-century they were of limited practical value when it came to putting new technology in action.[50]

While there existed a number of very instructive manuals for textile manufacture, some of which had even been translated,[51] the technologically more sophisticated branch of mechanical engineering had to await the second-half of the nineteenth century before "books" were taken seriously on the shop-floor. Earlier literature had argued that the se-

[46] Paulinyi, "Die Umwälzung der Technik in der Industriellen Revolution," 470-73.

[47] Henderson, *Britain and Industrial Europe*; and Harris, *Industrial Espionage and Technology Transfer*.

[48] Paulinyi, "Die Umwälzung der Technik in der Industriellen Revolution," 473.

[49] Paulinyi, "Der Technologietransfer für die Metallbearbeitung und die preußische Gewerbeförderung (1820-1850)," 108.

[50] Redondi, "Nation et entreprise. La Société d'encouragement pour l'industrie nationale, 1801-1815"; and Woronoff. *Industrie*, 241.

[51] Paulinyi, "Technologietransfer," 118; Bernoulli (1829); Ure (1837); and Montgomery (1840).

cond quarter of the nineteenth century had already seen the "objectivication" of engineering knowledge and the "institutionalization" of technology transfer.[52]. More recent European research, however, has come to different conclusions. In a seminal article, Paulinyi, who has devoted most of his research effort to investigating the many forms of eighteenth- and nineteenth-century technology transfer to and through Continental Europe, has concluded "that at least until the mid 1850s personal contact among the carriers of technological knowledge, hands-on experience of new machinery, and availability of 'fine specimens' for reproduction were much more important instruments of technology transfer than printed text."[53] In an similar vein, David Jeremy has observed that, for the United States until 1830, "inanimate sources of technical information were inadequate as a vehicle of technology diffusion."[54] Similarly, Woronoff has written of France: "Between 1780 and 1840 a visit of the factories and mines across the Channel is to the elite of innovative manufacturers what the tour to Rome is to artists, an obligatory passage."[55]

5.3 Engineering Schools

In view of the inadequacy of academic institutions for promoting technical skills and immediately useful technological knowledge, several Continental states followed and eventually superseded the British model of establishing engineering schools of an intermediate level. As Charles Day has shown, in France the *écoles d'arts et métiers* turned out large numbers of students with good knowledge of elementary mechanics but little of science and mathematics. For most industrial purposes this level of education was quite satisfactory and students actually ended up in factories and workshops where they soon climbed up the ladder to management positions.[56] An effort to bridge the wide gap between the highly academic École Polytechnique, which had a reputation of offering little useful knowledge for an engineering career in industry, and the *écoles d'arts et métiers* was the creation of the École Centrale des Arts et Manufactures in 1829, which combined science, mathematics, and mechanics in a curriculum aimed at industrial application.[57] As various case studies have shown, graduates of this new school came closest to the ideal of highly competent innovators in industry.[58]

However, early on the École Centrale showed a drift towards an increasingly academic curriculum, just as was observed in the case of many of the German trade schools (*Gewerbeschulen*) or polytechnical schools. According to Wolfgang König, these technical schools had been created in the 1820s and 1830s and were based on the idea of comprehensive technical education (*technische Allgemeinbildung*), which was seen to serve the needs of industry better than an academic education along the lines of the famous French Écoles. The German trade schools, like the *écoles d'arts et métiers*, were training institutions for future employees in private industry; future state civil servants, by contrast, continued to

[52] Redlich, "Frühindustrielle Unternehmer und ihre Probleme," 343.

[53] Paulinyi, "Technologietransfer," 128-129.

[54] Jeremy, *Transatlantic Industrial Revolution*, 72.

[55] Woronoff, *Industrie*, 242.

[56] Day, "The Making of Mechanical Engineers in France."

[57] Weiss, *The Making of Technological Man*.

[58] Daviet, *Un destin international*, 252-259.

come from the universities or, later, the institutes of technology. In the absence of engineering programs at universities, outside dominating Prussia and Hesse-Darmstadt, however, the German trade schools in a number of German states also had to meet the need for state civil servants.[59]

It is common opinion that outright academicization of technical education had to await the 1870s, when a number of polytechnical schools were renamed as institutes of technology; these last claimed higher academic status and incorporated a greater share of university-level mathematics and science in their curricula. Until the late 1860s, however, there was little engineering education of an academic character available in the German states. The situation was not so different from, say, northern Italy, where the *scuole tecnici* and the *instituti tecnici* provided a similar level of technical education. As Anna Guagnini has shown, Italy in fact preceded Germany in establishing courses in engineering leading to degrees at university level (at Milan, in 1862).[60]

Until the last-third of the nineteenth century German industrialization owed little to high-powered scientific or mathematical education, and even the oft-claimed positive effect of the trade schools for German industrial success has met with some reservations. In a recent synthesis of the German literature, König rather soberly concludes "that the influence of technical education on industrial performance was overestimated by contemporaries and is overestimated by historians today. ... we are justified only in stating that the German system of technical education was not a constraint on the development of industry."[61] At the same time König stresses the importance of formal technical education for engineers gaining status; this was the policy of the German Association of Engineers (Verein Deutscher Ingenieure) ever since its creation in 1856. The applicability of Ringer's analysis of the social effects and motives of higher education seems even more widesweeping in the era of nineteenth-century technical education than the author himself had anticipated.

In recent literature, technical education in its different forms has lost much of its earlier explanatory power when it comes to analyzing the different paths of economic growth during the nineteenth century. In his comprehensive overview of the literature, Lundgreen warned: "It is one of the dubious retrospective extrapolations from the present to assume that formal education, such as the academic training of engineers, is somehow necessary, if and when the private economy is about to become industrialized."[62] Lundgreen found that before 1870 a great variety of institutional arrangements for higher technical education existed and that there is no convincing evidence in the literature that any of these forms contributed measurably to the industrial development of the respective nations. Referring to Monte A. Calvert's work on American engineering education,[63] Lundgreen suggests that "we should do well to assume a dualism between an older shop culture and the

[59] König, "Technical Education and Industrial Performance in Germany," 66-67.

[60] Guagnini, "Higher Education and the Engineering Profession in Italy," 512.

[61] König, "Technical Education," 81.

[62] Lundgreen, "Engineering Education," 39.

[63] Calvert, *The Mechanical Engineer in America*.

encroaching school culture that eventually gave way to a universal school culture."[64] But that was not to happen before the end of the nineteenth century.

The main results of research in technical education prior to 1870 are, to sum up, some important "Nots." France did not lack a system of technical schools producing successful technicians and engineers for industry. The German system of technical education cannot be shown to have substantially contributed to the country's rapid industrialization. And with the whole discussion over French economic performance during the nineteenth century now reopened,[65] it is not at all clear as to which model was superior and to what extent.

Sobering as it might be, recent revisionism of the importance of institutionalized technical education during most of the nineteenth century leaves an unsatisfactory picture. Even if nineteenth-century Europe, and especially Germany, were status-ridden societies, it seems difficult to believe that all these continued efforts to establish a system of scientific, mathematical, and technical education would not have had more tangible effects. The situation is similar to that of a related great topic, the Industrial Revolution. Here again, many "Nots" have been learned from sophisticated testing of longstanding orthodoxies about the importance of foreign trade, transport innovation, steam power, and investment in factories. Donald McCloskey, having gone through the revisionism of the preceding twenty years of research, comes to the conclusion that "the task of the next twenty years will be to untie the Nots."[66] The same seems appropriate for understanding the claimed contributions of science to technology and industry at this most important and institutionalized interface of technical education. In the absence of new perspectives for understanding the science-technology interrelationship during the first seven decades of the nineteenth century, historians of science and technology might well have to accept the verdict of ruthlessly quantitative economic history, again as well expressed by McCloskey: "Few parts of the economy used much in the way of applied science in other than an ornamental fashion until well into the twentieth century. In short, most of the industrial change was accomplished with no help from academic science."[67]

6. Creating a Common Language

Beyond drawings, the "alphabet of the engineer" as Marc Isambard Brunel calls them, and so well analyzed by Ferguson,[68] the language of science was to become the dominant tool for analyzing a technological process or an artifact. The transition from "nonverbal technology" to "verbal technology,[69] which, according to Jeremy, played such an important role in technology transfer, had only just begun. New technology, encapsulated in standardized language and stripped of its context, was transferred in an idealized form. After many failures simply to translocate British technology, the ability to explain

[64] Lundgreen, "Engineering Education," 39.

[65] O'Brien and Keyder, *Economic growth in Britain and France*.

[66] McCloskey, "1780-1860: A Survey," 253.

[67] Ibid., 266.

[68] Ferguson, *Engineering and the Mind's Eye*.

[69] Jeremy, *Transatlantic Industrial Revolution*, 25.

"scientifically" a process became the proof that it had been understood well enough to justify the expense of introducing it at home. The "secret" which made every investment a risk began, thanks to reassuring science, to be lifted. This again failed as often as it succeeded, but knowledge that could not be expressed in terms of science and mathematics seemed no longer legitimate and trustworthy. Hans-Lüdiger Dienel, in his study of nineteenth-century refrigeration technology, one of the showcases of science-led innovation, insists that one of the foremost "applications" of science in this industry was to give credibility and legitimacy to new technologies.[70]

"Scientific analysis" in this perspective became the tool of a backward industry in need of government support to catch up quickly with the advanced engineering practice and routine of the Workshop of the World. Unlike traditional travelogues, which sometimes read like novels, "scientific analysis" is based both on a formal language, which makes it easier to communicate widely without personal contact, and on the assumption that all reasoning along scientific lines is valid. Using the restricted code of scientific language very much helped to create a common language among engineers, civil servants, and university experts who had to cooperate in order to help develop an infant industry. Lundgreen drew attention to a division of labor between "state engineers ... and civil engineers along the lines of supervision and execution.[71] Both groups, although educated quite differently, needed a common language, which, given the asymmetry of power, had to be the language of the academically educated supervisors. More research in this direction, however, needs to be done before we can fully understand this important dimension of the science-technology relationship in the nineteenth century.

The revisionist view that scientific and academic technical education at universities, the *Technische Hochschulen*, and the *Grandes Écoles* had little material effect on innovativeness in nineteenth-century industry is less puzzling when seen in the perspective of creating a common language among state civil servants, who had to decide over large technical projects like railways and mining operations, and practical engineers in industry. As we know from Max Weber, rationalization and bureaucratization in modern societies need objective, transparent, and reproducible procedures. Mikael Hård explicitly put his history of the "scientification of refrigeration and brewing" in a Weberian framework.[72] To Weber, depersonalization and objectification of knowledge are among the great achievements of modern rationality, for they increased the regularity and calculability of action. Alexander Gerschenkron, for his part, showed us that industrialization in Continental Europe, unlike in Britain, relied heavily on modern institutions from investment banks to nation-states.[73] More recently and more generally, John Staudenmaier, in his analyses of publications in *Technology & Culture*, stresses that "the inventor must communicate the value and the nature of the new design concept to an appropriate audience before his/her idea becomes a real invention. The role of engineering theory in such cases is to provide a language for such communication." And referring to studies by Thomas Hughes, Otto Mayr, Lynwood Bryant, and others, he writes: "These examples suggest that enginee-

[70] Dienel, "Professoren als Gutachter für die Kälteindustrie."

[71] Lundgreen, "Engineering Education," 40.

[72] Hård, *Machines are Frozen Spirit*.

[73] Gerschenkron, "Economic Backwardness in Historical Perspective."

ring theory is aptly described by the metaphor of language."[74] Hård and Andreas Knie have successfully employed a linguistic concept of competing grammars to a comparative history of German and French diesel engineering in the early twentieth century.[75] The history of nineteenth-century technology would greatly benefit from a similar approach.

Science and mathematics were powerful tools for putting technical projects in writing, incorporating them into the rational-legal system of the modern world and thus making them both intelligible and manageable for political decision makers. In this perspective, the surprisingly high rate of state recruitment among graduates from academic institutions of technical education would indeed materially contribute to promoting the industrialization of Continental Europe. At the same time, it would reconcile the strong view of contemporaries and most of the older literature that high standards of technical education helped industry to develop faster than elsewhere, on the one hand, with, on the other, the more recent findings that the students of these schools did not end up as the motors of innovation in industry.

In learning a common language for catch-up with British industry, state civil servants, scientists, and engineers on the Continent forged an alliance that did not exist to a similar extent in Britain. When industries eventually made their appearance that needed substantial imports from the academic world, however, this alliance had a headstart. Especially Germany, with its twentysome universities and nine institutes of technology, looked best-prepared for the new, coming scientific age.[76]

7. "Engineering Science"—"Sciences of Technology"

Authors from different backgrounds and concerns agree that the "scientification" of engineering and technology did not gather momentum before the mid-nineteenth century. The emergence of a substantial body of engineering theory during the second-half of the century, however, giving rise to early "science-based industries" has been widely accepted as heralding a new era of the science-technology relationship. It was not, however, simply science being adopted by engineering in ever more fields; it was also engineering developing its own scientific approach.

Klaus Mauersberger, in his work on the formation of technological mechanics, has elaborated on the line between useful knowledge and abstractions detached from shop-floor problems. In discussing the "theoretic kinematics" of Franz Reuleaux,[77] arguably the most theoretical of German engineers in the nineteenth century, he characterized the shortcomings of this "over-theoretical" approach which was understood to become the universal language of engineering. To Mauersberger, Reuleaux and his school failed to understand "that if it was possible to interpret a machine as a kinematic chain, it was still impossible to make out a distinct machine from a pre-given language, which in the end limited his language ... to kinematic analysis."[78] When Reuleaux's approach ultimately

[74] Staudenmaier. *Technology's Storytellers*, 110.

[75] Hård and Knie, "The Grammar of Technology."

[76] Lundgreen, "Natur- und Technikwissenschaften an deutschen Hochschulen."

[77] Reuleaux, *Theoretische Kinematik*.

[78] Mauersberger, "Die Herausbildung der technischen Mechanik,"28.

failed, it was because "engineering practice itself ... had become a corrective against the onesidedness of a kinematic approach to engineering design.[79] The battle between theorists and practitioners, however, raged on during the last decades of the nineteenth century. It took until the early twentieth century before engineering theory descended "from the lofty heights of theoretical mechanics to the practical demands of engineers."[80] At the same time, Mauersberger acknowledges that, with hindsight, increasing theoretical abstraction in technological mechanics at German universities proved indispensable to establishing the subject as an autonomous discipline of academic engineering that would bear fruit in the next century.[81]

The Anglo-Saxon world obviously experienced a less-agonizing transition from celestial to terrestrial mechanics than did the Germanic. David Channel, in his study of the evolving engineering science of W.J.M. Rankine of Scotland, author of a number of standard textbooks for university-trained engineers during the second-half of the nineteenth century, stressed the effort to reconcile theory and practice in "a framework in which scientific laws could be modified so that they could accommodate material bodies."[82] Late nineteenth-century engineering science as developed by Rankine and others was a distinct body of research and education that could not be reduced to "applied science." As Channel observed, "the concept of efficiency, for example, is in some sense a mathematical measurement of the degree in which ideal theories are modified by actual materials."[83]

Building on the work of Calvert,[84] James E. Brittain and Robert C. McMath, Jr., in their study on the early development of the Georgia Institute of Technology under Robert H. Thurston, present the advent of school culture and the progressive division of labor in engineering.[85] Thurston was explicit about the technical skills used on the shopfloor as being an application of the theories mastered by academically trained mechanical engineers. He also strongly advocated the view that the ability to codify knowledge and express technology in mathematical terms dramatically enhanced the precision and productivity of industrial processes. The "Russian" system of education that he had first introduced at the Stevens Institute of Technology was to become a model, drawing on inspirations from an exhibit of the Imperial Technical School of Moscow at the Philadelphia Centennial Exhibition. Showing great sympathy for authoritarian European approaches, Thurston was convinced that only the import of the European system of higher technical education would fully mobilize the intellectual potential of American engineers.

In several articles published during the 1970s, Layton put forward the most-influential interpretation of engineering theory unfolding in nineteenth-century America.[86] He very

[79] Mauersberger, "Die 'Maschinenelemente' Carl von Bachs," 160.

[80] Mauersberger, "Die Herausbildung der technischen Mechanik," 21.

[81] Ibid., 29.

[82] Channell, "The Harmony of Theory and Practice," 52.

[83] Ibid.

[84] Calvert. *The Mechanical Engineer in America.*

[85] Brittain and McMath, "Engineers and the New South Creed."

[86] Layton, "Mirror-image Twins"; idem, "Technology as Knowledge"; idem, "American Ideologies of Science and Engineering"; and idem, "Scientific Technology, 1845-1900."

much stressed the epistemological differences between science and engineering theory while acknowledging the similarity in methods and language employed. Science and technology as represented by their respective communities looked to him like mirror-imaged twins—superficially very much alike yet fundamentally different in their outlook and objectives. In an article programmatically entitled "American Ideologies of Science and Engineering," Layton stated the main differences between the two theoretical approaches: "Engineering theory and experiment came to differ with those of physics because it was concerned with man-made devices rather than directly with nature. Thus, engineering theory often deals with idealizations of machines, beams, heat engines, or similar devices. And the results of engineering science are often statements about such devices rather than statements about nature. ... By its very nature, therefore, engineering science is less abstracted and idealized; it is much closer to the 'real' world of engineering. Thus, engineering science often differs from basic science in both style and substance.[87]

From the late 1960s, scholars in the Soviet Union, Eastern Europe, and East Germany undertook a most-comprehensive effort to investigate the emergence of engineering theory, the building of school culture in engineering, and the institutionalization of engineering on an academic level.[88] The initiative came from Yuri S. Meleshchenko and his research group at the Leningrad department of the Institute for the History of Science and Technology of the Academy of Science of the USSR. Starting in 1969, they studied the methodological and social problems involved in the history and formation of the "technological sciences." The Russian team first developed a periodization of technological knowledge and science, identifying a period of formation of technological science from the mid-eighteenth until the end of the nineteenth century. They saw this as a time when technology succeeded in making increasing use of science and mathematics and when the "technological sciences" managed to establish themselves as a number of disciplines and a field separate from science proper. Only in the twentieth century did the "classical" period of "technological science" begin with robust and durable forms of interaction between technological science and science proper, which increasingly took the lead in developing new technology. In the late twentieth century, according to this periodization, a unified system of science, technology, and production eventually unfolded, a process characterized as the "scientific-technological revolution."[89]

While the Russian team did not produce many case studies and mostly concentrated on twentieth-century problems, the historical dimension of this approach was taken up and much refined and elaborated at the Center for the History of the Sciences of Technology at the Dresden University of Technology, created in 1978 by the ministry of higher education. Similar smaller- scale efforts were also undertaken in Bulgaria, Rumania, and Czechoslovakia. In East Germany, the Russian "tekhnichesky nauky" was translated literally into "Technikwissenschaften" (sciences of technology), which again was understood to be different from and more precise than the established German notion of *Ingenieur-*

[87] Layton, "Ideologies of Science and Engineering," 695.

[88] A very useful account in German is Blumtritt, "Genese der Technikwissenschaften."

[89] Meleshchenko, "Kharakter i osobennocti nauchno-tekhnicheskoy revolyutsii"; Ivanov, Cheshev, and Volossevich, "Die Besonderheiten der Entstehung und Entwicklung der technischen Wissenschaften"; and Ivanov and Cheshev, *Entstehung und Entwicklung der technischen Wissenschaften.*

wissenschaft (engineering science).[90] Unlike the Russians, the Dresden team produced a large number of case studies, mostly dissertations and many of them on nineteenth-century subjects. Unfortunately, this wealth of dissertations has remained unpublished, although some results have by now (2000) found their way into the twenty-six issues of the *Dresdner Beiträge zur Geschichte der Technikwissenschaften* (Dresden Contributions to the History of the Sciences of Technology) and, in highly condensed form, into the collective volume on the history of *Technikwissenschaft* edited in 1990 by Buchheim and Sonnemann.[91] The Dresden school's work was highly appreciated by their West German peers; it quickly became the authoritative institution on the history of academic engineering in Germany. In recognition of its academic achievements, the Dresden institute hosted the ICOHTEC-congress in 1986 and presented its approach before the international community of historians of technology.[92]

As presented by the Dresden school, the "sciences of technology" were to apply the "know- why" approach of science, together with its methodology and (mostly mathematical) language, to the man-made world. The "sciences of technology" appears as an appropriate concept to better understand the evolving school culture of technology during the nineteenth century and avoid the inconclusive debate about the line of demarcation between science (of nature) and engineering. The Dresden school acknowledged that an increasing amount of research has been conducted on artifacts and the processing of resources for the production of artifacts and, further, that this research has been emancipating itself from the narrow horizons of application, the school has refocused the intersection of modernity's theoretical approaches to nature and technology. This acceptance of a true intersection of the sciences of nature and the sciences of technology was different from Layton's mirror-image twin metaphor, which stressed the epistemological differences between science and technology.

The sciences of technology, adopting the cognitive ideal of science (of nature), placed theoretical knowledge above empirically achieved recipes, which nevertheless continued to be a backbone of successful innovation in industry, at least during the nineteenth century. To the Dresden school, the epistemological dividing-line thus ran within technology rather than between technology and science. Disciplines rather than fields of engineering emerged as the sciences of technology. Although the Dresden approach is far from complete, it remains the most comprehensive attempt to understand the cognitive dimensions of the changing science-technology-industry interplay during the nineteenth century. It does not yet conclusively answer the question as to how qualitatively, let alone quantitatively, important the evolving sciences of technology were to the industrial prowess of late nineteenth-century Europe and America. The level of scientific activity in technological fields is coupled rather loosely to industrial success at large. In some industries, however, this coupling appears to have been pertinent to early leadership.

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[90] For a programmatic statement by the group leader see Sonnemann, "Vorwort"; and for a history and an assessment of this approach see Hänseroth and Mauersberger, "Das Dresdner Konzept zur Genese technikwissenschaftlicher Disziplinen."

[91] Buchheim and Sonnemann, eds., *Technikwissenschaften*. The original dissertations are available in Dresden, Munich and Berlin.

[92] Sonnemann and Krug, eds., *Technik und Technikwissenschaften in der Geschichte*.

8. Science-based Industries

Electrical engineering, organic chemistry, optical instruments, and cryogenics—these were the fields where scientists played an important role in the development of industrial technology and new products. At the same time these were the technologies where British industry proved strikingly less responsive than its rivals in the United States and, especially, Germany. These science-based industries became the showcase of the German innovation system between the end of the nineteenth century and the First World War. Decades of investment in academic institutions for technical education seemed to have come to fruition with a singularly successful cooperation between the triade of universities, institutes of technology, and trade schools (*Gewerbeakademien*), on the one side, and industry, on the other. Scientists and engineers moved freely between these two realms, and built hybrid careers at the interface of science and technology. As Eda Kranakis has shown, this was not only a German phenomenon; it also characterized of many outstanding engineers in the nineteenth century.[93]

8.1 The Chemical Industry

The most extensively studied of the late-nineteenth-century, science-based industries is organic chemistry, in particular the German dyestuffs industry which by 1900 was turning out close to 90% of world dyestuff production. The reasons for this preeminence range from a favorable patent law to managerial skills in defending an early lead. Prominent in all accounts, however, is the high quality of human capital available to industry. Lutz F. Haber, the historian of the German chemical industry, claims that the "German manufacturers ... were able to draw on a large reservoir of extremely capable chemists whose enthusiasm for research, often of a painstaking, routine nature, was unmatched in other countries, except Switzerland.[94] Between 1877 and 1892 alone, the German universities established seventeen new chemical laboratories, while at the same time the number of students in science departments multiplied, giving rise to concerns of an oversupply of scientists.[95] Germany became the center of academic education in chemistry. In contrast "the native Englishman seeking a chemical education before the rise of the civic universities had to resort to a variety of different ways of scraping an education. One way was to go to Germany ... Virtually all the English professors of chemistry of the later part of the century had undergone this experience.[96]

What made German academic chemistry unique in the eyes of many historians was the ease with which professors cooperated with industry, and the benefits to science at universities derived from industrial technology. Key figures in this two-way exchange—chemists like Carl Graebe, Carl Liebermann, and Adolf Baeyer—had started their careers at the trade schools, which had been explicitly created to foster industry.[97] On the other

[93] Kranakis, "Hybrid Careers and the Interaction of Science and Technology."

[94] Haber, *The Chemical Industry during the Nineteenth Century*, 129.

[95] Wetzel, *Naturwissenschaften und chemische Industrie in Deutschland*,. 129-135.

[96] Sanderson, "The Universities and British Industry 1850-1970," 19. Similarly, Beer, *The Emergence of the German Dye Industry*, 15.

[97] Borscheid, *Naturwissenschaft, Staat und Industrie in Baden, 1848-1914*, 127-128.

side, as Anthony Travis has shown, early immunology and chemotherapy benefitted greatly from technological developments in industry.[98] The principal agents of this bidirectional exchange were professors who had research contracts with industry. In the most recent book on research in the German dyestuffs industry, Carsten Reinhardt confirms the well-known picture of graduate students and assistants in university laboratories researching along paths of interest for one of the major chemical companies.[99] Eventually an ideal-typical situation developed wherein the university partner would develop and publish on more scientifically fundamental aspects of these joint research programs while the head of the industrial laboratory would concentrate on technologically useful dimensions. Likewise, chemists going back from industry to universities would bring technological projects with them. Conflicts over secrecy in the run-up to patenting were inevitable in this setting and usually followed the preferences of the industrial company concerned. In the end, however, it was a very fertile symbiosis for both partners, with science playing a crucial and indispensable part. Since the days of the classic study by John Beer, there has been no controversy over the science-based character of this industry in the literature.[100]

8.2 The Electrical Industry

The second important "science-based" industry was electric engineering. It had its research and innovation centers in both Germany and the United States. And in Thomas Alva Edison it industry had the most-productive inventor of all times in terms of the number of patents and the as the inventor of "a method of invention," if we accept one of his most frequent self-characterizations. Edison was convinced of the value of scientific input when it came to mechanical and electric problems.[101] Thomas Hughes, in his comparative study of American inventors, characterizes him as someone who built on and expanded tacit understanding. "In this sense he was an applier of electrical science, but his intimate knowledge of the behavior of electrical devices and his ingenious application of accumulated tacit knowledge distinguished him from most scientists, who tended to be more verbal and theoretical."[102] This did not protect him from wasting much of his accumulated wealth in a futile attempt to separate by magnetic means iron ore at reasonable cost. In this he was similar to another nineteenth-century genius of tacit knowledge, Henry Bessemer, who grew rich on a technologically brilliant steelmaking process, whose chemistry he had not understood, and who lost a fortune in the attempt to turn the technology of his converter plant in stabilizing a seagoing vessel to prevent sea-sickness. Tacit knowledge, which had long worked so well for both men, subsequently let them down towards the end of their careers, thus betraying its unpredictability.

Wolfgang König has extensively researched the emergence of electrical engineering as an academic discipline in Germany and its relationship to industry. He confirmed the view of much of the earlier literature that mid-nineteenth-century theories of electromagnetic machinery had little impact on and use for practitioners, and he found a transitory

[98] Travis, "Science as Receptor of Technology."

[99] Reinhardt, *Forschung in der chemischen Industrie. Die Entwicklung synthetischer Farbstoffe*, 332-333.

[100] Beer, *The Emergence of the German Dye Industry.*

[101] Hughes, *American Genesis. A Century of Invention and Technological Enthusiasm*, 32-33.

[102] Ibid., 68.

phase towards a theoretical penetration of electromagnetic machinery at the end of the century.[103] According to König, the developments in the 1860s and 1870s were still governed by trial and error, the 1880s saw increasing application of empirically won formulae, while theoretical penetration of engineering problems had to await the 1890s.[104] König's findings corroborate Ronald Kline's earlier case study on the development of the induction motor.[105] If science contributed to solving major engineering problems in the design of electric motors and generators, it did so only at the very end of the nineteenth century. Still, much earlier science did provide the language to express and communicate problems and empirically-won solutions alike.

Like the discussion of the relationship between thermodynamics and the steam engine, König has turned the phrase "science-based industry" on its head and called electric engineering before the First World War an "industry-based science"[106] As he has shown using historical statistics, there was a "shift from theoretically educated professors in the 1880s to professors who possessed practical experience in the 1890s" at the German institutes of technology, which, at the time, dominated higher education in electrical engineering worldwide.[107] "Whereas in the 1880s the institutes and state bureaucrats saw it [electric engineering] as applied science, they later came to see electrical engineering as a practice-oriented science.[108] The more successful electrical industry became in Germany, the less "scientific" was academic education.

This situation was very different from the one in the United States as described by Kline. American technical colleges were expected to "teach basic principles and leave practical training to corporations."[109] Given the contemporary excellence of both national systems in promoting innovations in the electrical industry, there is no reason to believe that either strategy was more successful. By recruiting an increasing number of professors from industry, the German institutes of technology imported practical knowledge in electrical engineering and "were more concerned with normal design than with innovation."[110] Only after the turn of the century, with the creation of extensive laboratories along the American model, did they begin to play an important part in applied research. These American industrial laboratories, above all the General Electric Research Laboratory, have been the focus point of the debate on the science-technology-industry triangle before the First World War.[111] The GE laboratory is to the history of science in electrical industry

[103] Buchheim and Sonnemann, eds., *Technikwissenschaften*.

[104] König, *Technikwissenschaften. Die Entstehung der Elektrotechnik aus Industrie und Wissenschaft*, 305.

[105] Kline, "Science and Engineering Theory in the Invention and Development of the Induction Motor."

[106] König. *Technikwissenschaften Die Entstehung der Elektrotechnik aus Industrie und Wissenschaft*, 227-296; and idem, "Science-based Industry or Industry-based Science?"

[107] König, "Science-based Industry or Industry-based Science?," 82.

[108] Ibid., 87.

[109] Kline, *Steinmetz: Engineer and Socialist*, 167.

[110] König, "Science-based Industry or Industry-based Science?," 89.

[111] Birr, *Pioneering in Industrial Research. The Story of the General Electric Research Laboratory*; Wise, *Willis R Whitney, General Electric, and the Origins of U.S. Industrial Research*; Reich, *The Making of the American Industrial Research. Science and Business at GE and Bell, 1876 -1926*; Carlson, *Innovation as a Social Process. Elihu Thomson and the Rise of General Electric, 1870-1900*.

what the Bayer laboratory is to the history of science in chemistry. Both were places where efforts to find a solution to a specific problem might draw on and turn to "basic" research. From the optical industry one might add the laboratory of Ernst Abbe at Carl Zeiss in Jena to this category, although its impact on industrial development in general was much more limited.[112]

8.3 Mechanical Engineering

The history of mechanical engineering has certainly not been at the forefront of the science-technology debate in the way that organic chemistry and electric engineering have. Mechanical engineering was more concerned with standardization, systems of measurement, mass production, single-purpose machines, and the "scientific" exploitation of the human motor and human skills, and so mechanical engineers towards the end of the nineteenth century became above all organizational innovators, as epitomized in the books of Alfred Chandler and Philip Scranton on American industry.[113] Successful mechanical industry, big or small, relied almost exclusively on shop-culture.

Mechanical engineering worthy of the designation "science-based" was found only on the fringes of the industry. One notable example was late-nineteenth-century refrigeration technology that was, it seems, single-handedly put on a scientific foundation by Carl Linde. The story of Linde, cryogenics, and the science-technology-industry triangle has been concurrently and independently researched by Hård and Dienel.[114] Linde was close to unique among successful inventors in mechanical engineering in that he was both a university professor and an exponent of theoretical engineering, "insisting," in Dienel's words, "on a deductive, scientific penetration of practical technology." Linde was the student of famous school-culture proponents like Franz Reuleaux and Gustav Zeuner, and, as Hård has written, he "first stipulated that the most efficient refrigeration process ought to be identical with the reverse Carnot cycle and then determined what refrigerant it ought to apply. He deduced what an optimal ice-machine should look like and what degree of efficiency would be its possible maximum. The outcome of this exercise was the 'disenchantment' not only of nature, but also of mechanical refrigeration per se." While acknowledging this (self)description of Linde and his work, Dienel, in contrast to Hård, concludes that "this was a problematic precondition for practical work," and refutes Linde's assertion that his first experimental prototype of 1873 was already a "complete success" of his theoretically based forecast. In the end, some of Linde's assumptions turned out to have been wrong and thermodynamics played no role whatsoever during the agonizing years of engineering design, testing, and development.[115] Nonetheless, Linde was convinced that his extensive experimenting was firmly rooted in theory and during the famous theory-practice debate in German engineering (in 1895) he was in the theory-camp.

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[112] Cahan, "The Zeiss Werke and the Ultramicroscope."

[113] Chandler, *The Visible Hand. The Managerial Revolution in American Business*; and Scranton, *Endless Novelty. Specialty Production and American Industrialization, 1865-1925*.

[114] Hård. *Machines are Frozen Spirit*; and Dienel, *Ingenieure zwischen Hochschule und Industrie. Kältetechnik in Deutschland und Amerika, 1870-1930.*

[115] Dienel. *Ingenieure zwischen Hochschule und Industrie*, 104-5 (quotes), 326; and Hård, *Machines are Frozen Spirit*, 231.

Rudolf Diesel, Linde's student and later refrigeration engineer, took from Linde's lectures on the Carnot cycle the idea of designing an optimal internal-combustion engine. However, according to Diesel's own writings and the most book-length study of his invention,[116] Diesel always acknowledged that intuition rather than "science" had been the main source for his invention. Science played an important role in directing his curiosity and testing the consistency of his reasoning, but it did not simply translate into technology. On the other hand, there is no account of Linde's refrigeration process or the Diesel engine that can avoid crucial information from science. Technical thermodynamics as it was introduced into industry in the last decades of the nineteenth century is inconceivable without recourse to school culture. To be sure, it was still not the mainstream of mechanical engineering, but it was important in industrial terms. And as Dienel has shown convincingly, practitioners very soon were ahead of engineering scientists, again restoring the shop-school hierarchy of the steam engine in technical thermodynamics.[117]

There are not many cases in engineering where science was unequivocally leading to technological development. Instead and more often, we find evidence that science was used for window dressing or confirming and expressing in standardized language what had been found out earlier. David Mowery and Nathan Rosenberg, who have surveyed the literature on metallurgy, one of the most central disciplines of nineteenth-century technology, have concluded that it "was a sector in which the technologist typically 'got there first', developing powerful new technologies in advance of systematic guidance by science. The technologist demanded a scientific explanation from the scientist of certain properties or performance characteristics.[118]

In the end it was the scientist's skill at measuring and testing for properties, that is, technical skills developed in the pursuit of scientific experiment, which made him indispensable for industrial enterprise. Materials testing became one of the major fields of employment for scientists, as we learn from the literature on laboratories–initially quite small–in the steel industry.[119] On a larger scale, even governmental research institutions like the Physikalisch-Technische Reichsanstalt, described by David Cahan as "masters of measurement,[120] turned out to be in good measure service agencies for industry's need to quantify and standardize rather than to push scientific research ahead. At the same time, however, this development confirms that authority increasingly rested with the institutions of science.

9. Conclusion

The historiography of the relations of nineteenth-century science, technology, and industry has shown that science was but one instrument for innovation, and certainly not the most important one. Designing the organizational framework of factories, craft knowledge, tinkering, and building on experience that mushroomed with much-intensified in-

[116] Knie, *Diesel: Karriere einer Technik. Genese und Formierungsprozesse im Motorenbau*.

[117] Dienel. *Ingenieure zwischen Hochschule und Industrie*, chap. 5.

[118] Mowery and Rosenberg, *Technology and the Pursuit of Economic Growth*, 33.

[119] Livesay, *Andrew Carnegie and the Rise of Big Business*, 114.

[120] Cahan, *An Institute for an Empire: The Physikalisch-Technische Reichsanstalt*, chap. 4.

dustrial activity—all these together continued to constitute more productive venues of industrial growth that science. Notwithstanding Margaret Jacob's insistence, talk of science among early industrialists was not recognized to have been equivalent to making use of its findings. Through most of the nineteenth century, science seems to have been much more a mental than a material foundation of industry. In this respect, it was accepted as one of the most-important tools for catching up with British industry. Together with mathematics, science became the universal and legitimate language for conversing about technology, rendering other forms of knowledge "tacit." Debates about appropriate forms of engineering education reflect the unresolved issue of theoretical versus practical knowledge through the century. Even "science-based industries" at the end of the century did not escape critical reassessment of the importance of inputs from science. The linear model is now dead; but it has not yet been successfully replaced by a new orthodoxy.

It would be tempting to run a counterfactual test on the performance of nineteenth-century industry in the absence of science in the way that Robert Fogel did for the American economy without railways. Maybe economic growth would not noticeably have been affected, with technology and industry taking a somewhat different, but not necessarily slower, path. In view of the sobering insights about the many "Nots" on the Industrial Revolution, it would not even be a big surprise. Yet it would not be the history of our nineteenth century with its importance of science so firmly rooted in the minds of both the actors and the public, whereby it is hard to draw a fine line between its ideological and its "material" impact. If science and technology are social activities, then they constitute the actor's minds and make them act as they do. Science was certainly and increasingly the shaper of the minds of engineers, state civil servants overseeing the building of infrastructure, the military, and the public at large when it came to make sense of technological achievements. We do not know, nor can we even guess, what society would have looked like had it not begun to believe in the power of science more than seems justified by historians' recent revisionts accounts of the history of contributions of science to technology and industry during the nineteenth century. But then, this would not be our history anyway.

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