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Background Paper Series

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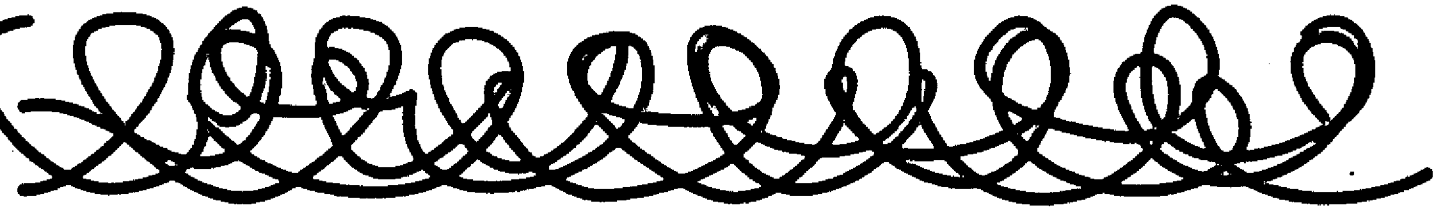
Historical Patterns in the Co-evolution of Higher Education, Public Research, and National Industrial Capabilities



UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Industrial Development Report 2005 Background Paper Series

Historical Patterns in the Coevolution of Higher Education, Public Research, and National Industrial Capabilities

Roberto Mazzoleni

June 2005

Office of the Director-General

This series includes the background papers commissioned to cover specific aspects addressed in the Industrial Development Report 2005 "Capability building for catching-up – Historical, empirical and policy dimensions". The digital versions are available, together with the full report, on the IDR 2005's website at www.unido.org/idr.

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Introduction

Various aspects of the emerging international trade order, particularly changes in the regime of intellectual property rights and regulatory harmonization, as well as the growing scientific basis for many industrial technologies suggest that technological capabilities are increasingly important determinants of national economic performance. As a result, developing countries' prospects for economic catch-up will hinge increasingly on the ability to nurture the rapid accumulation of indigenous technological capabilities (Albuquerque, 2001; Amsden, 2001; Bernardes and Albuquerque, 2003). If this assessment is correct, processes of capability-building must be of central concern to industrial development strategies. To be sure, successful experiences of catching up do indicate that in the past rapid economic growth occurred alongside rapid growth of national educational attainment levels (Easterlin, 1981), and processes of institutional change that led to the creation of a national knowledge infrastructure of higher education and public research institutions.

These institutions have long been recognized as playing an important role in the evolution of technological capabilities in national systems of innovation of advanced economies. Here, a complex web of relations among economic actors characterizes the production, transmission, and absorption of technological knowledge (Lundvall,1992; Nelson, 1993). The role of universities and public research institutions in this web has attracted scholarly interest, and our knowledge of their characteristics and of their relationship to innovative activities in advanced economies is sufficiently detailed (Nelson, 1990; Klevorick et al., 1995; Cohen et al., 2002). The same cannot be argued with respect to the immature innovation systems of developing economies. More significantly, our knowledge of the transformations of these institutions and of their interaction with the process of industrial development is rather limited at present (Lundvall et al., 2002).

This paper will present an exploration of the historical patterns according to which national systems of higher education and public research developed alongside the emerging industrial sectors of catching up economies. What influence did these systems have on the pattern of accumulation of technological capabilities at business firms? What were their contributions to the development of national industries? How did they respond to changes in the sectoral structure of the economy and to changes in the organization of national industries?

A better understanding of these matters should provide useful lessons on the role that academic and public research institutions can play in the accumulation of technological capabilities in today's developing economies. This manuscript's contribution is based on a selective historical survey of the development of higher education institutions and of the activities of public research institutes across a number of countries whose economies can be argued to have entered a phase of catching up development at different times in history. While a few references will be made to experiences of other countries, the focus of the survey will be on the features of the educational and public research systems of Germany, U.S. and Japan around the turn of the last century, and of the Republic of Korea and Taiwan Province of China during the second half of the twentieth century. Hopefully, this survey will contribute to stimulate future research and contribute to present debates on development policies emphasizing the role of education and technological capabilities (UNIDO, 2002; World Bank, 2003).

While at a certain level of abstraction it is useful to consider the process of catching up with contemporary economic leaders as a relatively invariant process, in practice economic catch up is understood to occur along different paths in different countries (Kim, 1999; Perez, 2001). Moreover, to the extent that the process of catching up aims at replicating structural and institutional features of contemporary advanced economies, it should be recognized that such features have changed considerably since the nineteenth century.[i] From the perspective of this manuscript, the most important change has to do with the different relationship between *industrial practices and codified forms of knowledge, including scientific knowledge* (Mokyr, 2002; Arora and Gambardella, 1994). Today, many industries implement technologies that have strong ties with fields of scientific and engineering knowledge. At the time of British economic leadership, the development of industrial technology proceeded almost entirely on the basis of empirical methods of investigation and of experiential learning (Landes, 1969; Rosenberg, 1970; Wengenroth, 2000).

This difference is reflected among other things in the characteristics of the labor force educational attainment, and of the knowledge infrastructure of advanced and developing economies alike. At the end of the nineteenth century, Britain held on to the role of economic leader even as its educational system—with the exception of the Scottish universities—had not been at the forefront of the reform of academic institutions and the development of schools of engineering and other applied sciences. These important processes, which laid the foundation for the contemporary systems of higher education, had their origins in Germany and France around the end of the eighteenth century. The experiences of these same countries influenced developments elsewhere.

The next section provides an overview of the quantitative dimensions of the transformation of national higher education systems that accompanied specific phases of economic development across the countries of interest. Subsequently, I will provide a historical account of institutional developments in higher education first in continental Europe (France and Germany) and the U.S., and next in Japan, the Republic of Korea, and Taiwan Province of China. The curricular and research activities at sciences and engineering institutions will then be examined, focusing on their relationship to industry and to the learning of technological capabilities by industrial firms. It will be seen that in most countries, public support of research was directed to specialized research institutions. These played an important role in several instances of industrial development, giving employment to early cohorts of indigenous scientists and engineers, acting as a node for the diffusion of foreign technology to domestic firms, and providing an array of industrial services (including R&D) to local firms. A final section of the paper will highlight common threads across the historical cases reviewed and sketch the policy lessons that can be drawn.

Enrollment Rates in Tertiary Education: A Cross-Century Perspective on Catching Up

It is useful to begin by reviewing briefly the historical evidence on the growth of enrollments in higher education since the last third of the nineteenth century. Until then, the reform of higher education in continental Europe had failed to lead to sustained increases in enrollments. University education remained a rather exclusive option in Germany, where the accession of scientific disciplines to the academic curriculum was pioneered. Much of the growth in enrollments toward the end of the century occurred in the Technische Hochschulen, the polytechnic schools specialized in the teaching of engineering subjects. A different pattern can be seen in the U.S. where the number of colleges increased rather sharply since the eighteenth century and so did enrollments. Already in 1870 the university enrollment rates in the U.S. were between two and three times the rates in Germany or any other European country. As will be discussed later, the significance of this difference has to be evaluated carefully, given the differences in the quality of programs and admission standards at higher education institutions. It is however well established that the German and French systems' design tracked students beginning in the secondary schools and admission to higher educational institutions was thereby restricted. In the U.S., admission policies were much more lax and in general not subject to centralized decision-making by government.

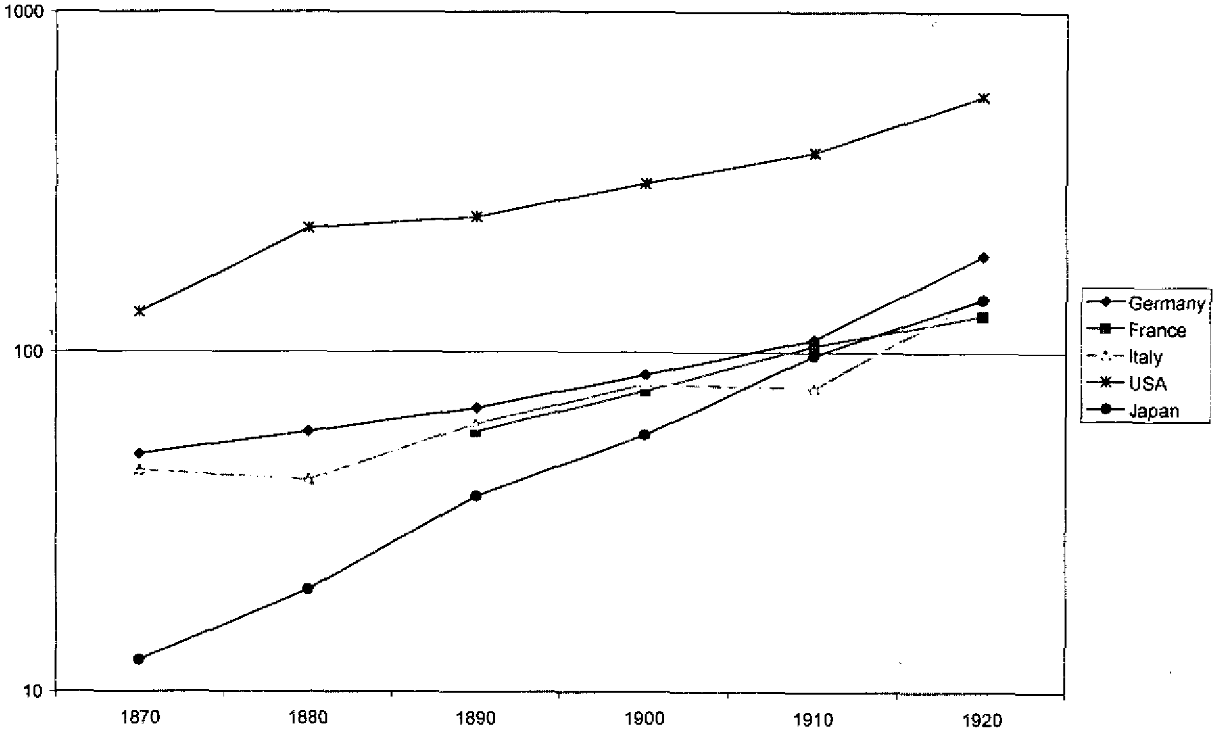
The data presented in Figure 1 include enrollment rates in Japan, where the economic catch up process got underway since 1868, the first year of the period known as the Meiji restoration. Japan was the first country where the inward transfer of scientific and technical knowledge was an explicit target of government policy and institutional design. To this aim, a key instrument was the development of a system of higher education largely modeled after the institutions of the western economies, Germany, Britain and the U.S. The magnitude of the Japanese effort is impressive. Over the half century between 1870 and 1920 student enrollments at Japanese higher education institutions grew by nearly a factor of twenty, compared to a factor of about eleven in the U.S. and six in Germany. As a result, Japanese student enrollment rates had substantially caught up with the Western European countries by the 1920s.

Figure 2 presents trends in university enrollments for another half a century period, from 1950 to 2000. During this period, the Republic of Korea and Taiwan Province of China are the most successful instances of economic catch up and once again it is useful to review the pattern of growth of their higher education system against the backdrop of events in more advanced economies, including the U.S., Germany, and Japan. The period has been characterized as marking the rise of mass education in the advanced economies where enrollment rates in secondary education soared (Goldin, 2001). This phenomenon bears clearly on the higher education enrollment rates, which increased at a steady rate through much of the period, reaching in the case of the U.S. nearly 80%. In light of these trends, it is legitimate to argue with Amsden (1989) that the countries behind the frontier were (and perhaps, are) increasingly further behind.

At the end of the Japanese colonial period in 1945, the Republic of Korea and Taiwan Province of China had only a minimal higher education infrastructure. The Republic of Korea's university student population was about 8,000 in 1945. At that time, 40% of the labor force had no schooling and another 53% had only primary education. Taiwan Province of China's situation was analogous, with only about 6,600 tertiary level students in 1950. Over the following decades, both countries made big strides in their population's educational attainment.

Figure 1

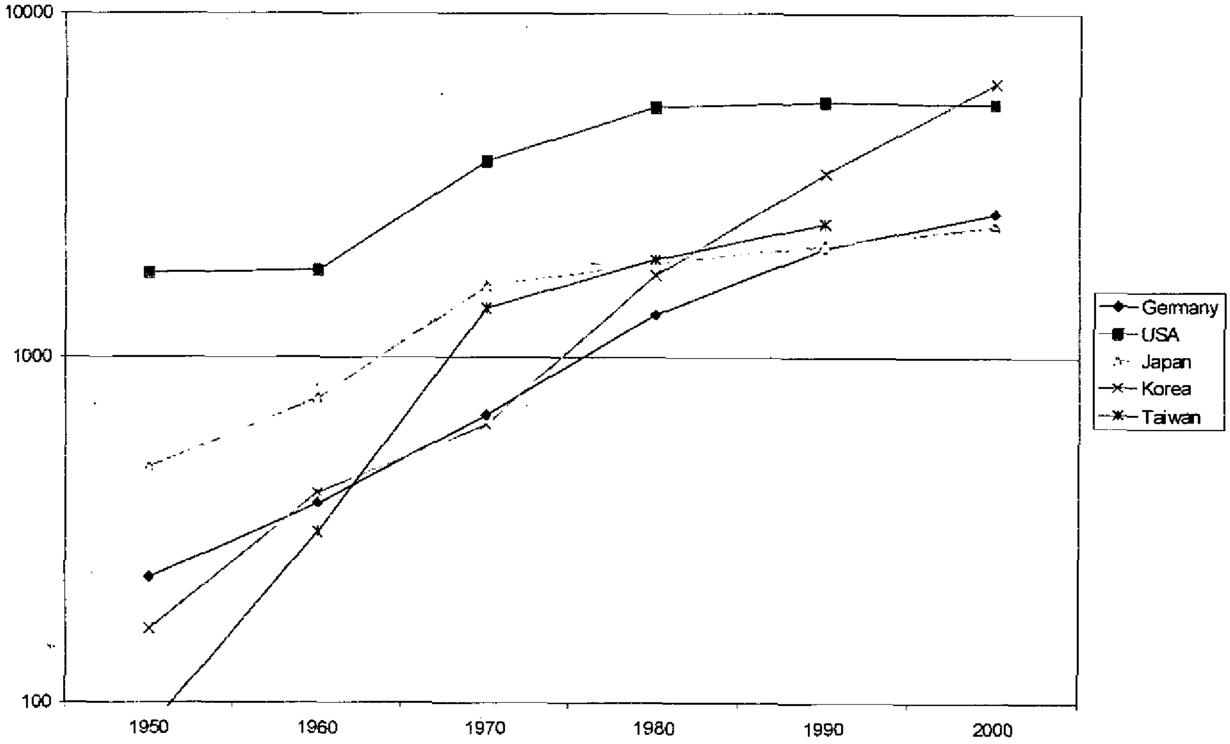
University students per 100,000 population (1870-1920)



Author's elaboration; data sources: Mitchell (1995, 2003a, 2003b)

Figure 2

University students per 100,000 population (1950-2000)



Author's elaboration; data sources: Mitchell (1995, 2003a, 2003b); Korean Statistical Yearbook, Japan Statistical Yearbook, UNESCO Demographic Yearbook (various years)

The Republic of Korea achieved universal education at the primary level within a decade and saw its university students' population grow by a factor of nearly ninety between 1950 and 2000. At the turn of the century, Korean enrollment rates for tertiary education are comparable to those of the U.S., and significantly higher than the country's erstwhile colonizer, Japan. The pattern of growth in tertiary education in Taiwan Province of China follows much the same pattern. The growth of enrollments in tertiary education was particularly strong during the 1960s. At the end of the decade, students enrolled in tertiary-level institutions were about 17% of the number of Taiwanese aged 20 to 24, a higher percentage than Germany or Japan, and more than twice as large as the corresponding value for the Republic of Korea. By the end of the period, educational attainment levels in Taiwan Province of China had substantially caught up with the U.S.

There are clearly similarities between the patterns observed during these two periods, particularly between the catching up in tertiary enrollments that occurred in Japan since the late nineteenth century and that experienced in the Republic of Korea and Taiwan Province of China more recently. However, the scale of the higher education systems has changed dramatically, a phenomenon that cannot be entirely explained as the result of the growing economic significance of knowledge and human capital (Schofer et al., 2000). Today, the educational attainment of many developing economies appears rather large when compared to the nineteenth century data. In 1870, the German system of higher education served only less than one percent of the relevant age group and yet constituted a model system for other countries to learn from. This enrollment rate is puny by the standards of contemporary economies, in fact of most contemporary developing economies. Of course, a proper evaluation of this evidence, and its economic significance, requires that we look more closely to the evolution of higher education systems in qualitative terms.

The origins of the modern universities and specialized schools

The modern university began to emerge from reforms introduced in Germany since the early nineteenth century. To be sure, a few new German universities (Halle and Gottingen) pioneered the introduction of natural science in the curriculum already in the eighteenth century (McClelland, 1980). But research and communication in the fields of natural science had been mostly the province of the activities of scientific societies and academies. These activities were inspired by Francis Bacon's view of scientific knowledge as instrumental to greater control over nature through technological advances. This instrumentalist perspective was embraced in France with the creation of specialized engineering institutions, separate from the universities, whose primary goal was to provide the government apparatus with a technically skilled bureaucracy. On the contrary, the 1810 reform of the German universities reflected, in principle at least, the views of Alexander von Humboldt, Education Secretary of the Prussian government, who intended academic education and research as worthwhile endeavors as such, a means for spiritual rather than material betterment. These different views of education and science continue to be an important key to understanding the multifarious social and economic demands that higher educational systems are expected to satisfy across the world's nations (Schofer and Meyer, 2005).

Humboldt's policy brought the teaching of natural science firmly within the scope of universities' curricula, but fostered the institutional segregation of engineering education in a specialized class of polytechnic schools. Unlike France where the specialized engineering schools had a greater status than universities in the resulting dual tier system, German polytechnic schools had a vocational orientation through at least the first half of the century, and were considered of lower status than the universities. The centralized governance of higher education institutions in the German states regulated access to universities and polytechnics on the basis of differentiated secondary institutions, and likewise reserved different professional careers in the public bureaucracy and elsewhere to the graduates from different institutions. Through much of the century the professoriate in the German polytechnics, later called Technische Hochschulen, was engaged in an effort to see the status of their own institutions rise to that of universities. From this paper's perspective, it is important that such efforts influenced the curricular activities of students at these institutions and the latter's relation to the incipient patterns of industrial development.

The evolution of the engineering curriculum was very much driven by the desire to bolster the scientific credentials of their graduates and to establish engineering knowledge as an abstract form of knowledge, largely expressed in mathematical form. It seems legitimate to consider the French Ecole Polytechnique (established in 1794) as the model for later efforts in the direction sketched above. This institution became the fulcrum of a system of schools providing general training in sciences and engineering, as well as specialized training in various branches of engineering (including the Ecole des Ponts et Chaussees, founded in 1775, and the Ecole des Mines, founded in 1783). Few graduates of the Polytechnique found employment in industry. Vocational training for the industrial arts was provided by a system of secondary institutions, the Ecoles des Arts et Metieres, created in 1803. Only in 1829, a private institution, the Ecole Centrale des Arts et Manufactures (ECAM), was created through private initiative in order to train highly qualified technical personnel for industry. This institution was quite successful in supplying technically skilled graduates to industry, although the alumni were more likely to have administrative and managerial jobs than jobs related to the engineering of operations or the development of new techniques. Moreover, the curriculum of the Ecole Centrale increasingly took on the heavy emphasis on mathematics and pure sciences that characterized the Polytechnique.

The development of the Hochschulen in Germany followed along similar lines (Torstendahl, 1993). The polytechnic school in Karlsruhe was among the first to find inspiration in the model of the Ecole Centrale, largely under the influence of professors who during the 1840s and 1850s played an important role in the creation and diffusion across continental Europe of a scientific approach to mechanical engineering. Among these was Ferdinand Redtenbacher, chair of mechanical engineering, who counted among his students Franz Reuleaux. After a stint at the newly formed technical university in Zurich (ETH), Reuleaux was invited to the chair of mechanical engineering of the Gewerbe Institut in Berlin. As director of the Institut from 1868 to 1879, Reuleaux oversaw the establishment of the Berlin Technische Hochschulen, resulting from the Institut's merger with the Bau Akademie, a school focused on civil engineering and architecture whose graduates had access privileges to the civil service. More broadly, Reuleaux promoted the reform of engineering education at the German polytechnics along the lines of a proposal drafted in 1864 by Franz Grashof, the president of the first national association of engineers, the Verein Deutscher Ingenieure (VDI).[ii]

This proposal expressed the ambitions of the academization movement (Manegold, 1978), and its members' hope that "it will be possible to reach the highest goal: namely, to gradually transform the field of mechanical engineering into a pure science." (citation attributed to Professor Hormann by Gispen, 1989, p.74). Part of the consequences of these aspirations was the estrangement of the industrial community from the evolution of the Hochschulen. As practical workshop experience was neither a requirement for admission to the Hochschulen, nor a component of the latter's educational curricula, the graduates were shunned by industrialists who often preferred to recruit their technical workforce from the ranks of the alumni of the secondary-level trade schools. The Hochschulen graduates' predilection for abstract theorizing and their disdain for practical considerations such as manufacturability of product designs and production costs vastly reduced their appeal for industrialists.

The result of these tendencies was that at the same time that the German polytechnic schools had acquired a certain prominence in international academic circles, thus providing the inspiration for American engineering schools, their contribution to the growth of German industry was generally considered to be insignificant at best. Indeed, after the beginning of a long recession in 1873 and the scathing criticism of German machinery builders filed in 1876 by Franz Reuleaux from the World Exhibition in Philadelphia, several industrialists spoke quite openly of the academic pretensions of the Hochschulen as an obstacle to enhancing the contributions of their graduates to the upgrading of the technological capabilities of German firms. A reform movement only gathered steam during the 1890s, but already in the two earlier decades there were various signs of change associated with the formation of laboratories at the Hochschulen in various locations in Germany. Curiously, as will be discussed in greater detail later, the diffusion of teaching and research laboratories at the Hochschulen was at least partly inspired by the character of engineering schools in the U.S., and by the example of chemistry education at German universities.

It is perhaps ironic that the kind of laboratory-based empirical investigations that mechanical engineers at the Hochschulen increasingly disdained, were rather common aspects of teaching and research in the chemistry, physics, and medicine at universities. This kind of applied work and the experimental practices learned by students were the factors that made academic science in the fields of chemistry and physics relevant to industrial development. It turned out to be so in spite of the fact that at least early on scientific work had to be presented under the gloss of pure scientific investigation, even as it clearly addressed practical problems of agricultural and industrial practice.

Work of this kind was conducted for example by Louis Pasteur at Lille, whose research on fermentation and the manufacture of alcohol and sugar from beets was inspired by his awareness of problems of industrial practice (Stokes, 1997; Böhme et al., 1978). His lectures in chemistry were accompanied by visits to factories, and while the dean of the faculty in 1854-1857 he marked the end of the academic year by organizing trips to chemical and metallurgical establishments in the region (Paul, 1980). Pasteur's work at Lille was representative of the strong utilitarian bent that dominated the faculty of sciences in France since the mid-nineteenth century and led to the formation of specialized technical institutes across the country.

Laboratory-based seminars in medicine and the natural sciences became increasingly common at the German universities too, particularly since the 1870s. Most importantly, these laboratories became permanent features of the universities' organization. It was otherwise earlier in the century, when individual professors organized the laboratories for their own research activities supplementing with their own personal funds the meager public support available.[iii] The rise of applied science depended on the universities' success at securing greater public funds for the expenses of institutes and their laboratories. Such funding increased during the century more or less across all the German universities. In Berlin, for example, the overall university budget increase by 200% over the 1820-1870 period, but the budget item related to institutes grew by 1,000% (McClelland, 1980, p.204). At the end of the period, expenses on institutes became a larger expense than professorial salaries. Growing public support for academic institutes signaled both a growing recognition that valuable research in natural sciences and medicine required adequate funding, and a response to the dependence on laboratory research of a growing number of doctoral students.[iv]

The development of engineering education in the U.S. illustrates a common pattern in the diffusion of institutional templates across countries. According to this pattern, foreign institutional models were adapted to local cultural, social, and economic conditions that ultimately gave the American system significant originality. In particular, the characteristics of professional education in the curricula and the formation of new institutes reflected the U.S. penchant for the practical applications of science noted early in the nineteenth century by

Tocqueville (1876), and the dominance of a utilitarian conception of education. Two features of the American higher education system are particularly noteworthy. First, the segregation of engineering from the universities that emerged in continental Europe was not replicated in the U.S. in spite of the substantial influence that European institutions exerted on their American brethrens. Second, the growth of the system was to a much larger extent the result of private initiative, so that institutional arrangements were much more varied than in Europe.

Since the eighteenth century, the inward transfer of technology to the U.S. received a great contribution from the arrival of skilled immigrants (Pollard, 1981; Rosenberg, 1970). But over time, this infusion of technical skills and knowledge became increasingly complemented by the *formation of a technically competent indigenous workforce. A great deal of credit for the* development of canals, railroads, bridges, and turnpikes during the nineteenth century can be given to the earliest engineering school established in the U.S., the Military Academy at West Point (New York), whose foundation in 1804 aimed at training the members of the U.S. Corps *of Engineers.*

The first civilian college institution aimed at the cultivation of mechanical arts and agriculture was created in 1823 as the Rensselaer College, whose founder Stephen Rensselaer hoped to promote the "application of science to the common purposes of life." The man called to make this happen, Amos Eaton, drew inspiration from the teachings of science in the Prussian universities and polytechnics. In 1835 the College offer the first four-year degree in civil engineering in the U.S. The transformation of the college in an engineering school was completed in 1846 when the president Franklin Greene reorganized the curriculum according to the model of the Ecole Centrale in Paris, and renamed the college as the Rensselaer Polytechnic Institute in 1849.

The 1850s witnessed the beginning of instruction in the field of mechanical engineering at U.S. schools. The first degree program in mechanical engineering was offered in all likelihood at the Polytechnic College of Pennsylvania, an institution founded in 1853. Emmerson (1973) describes the design of the curriculum at this school as striking a balance between the educational and professional needs of prospective students and the director's desire to model the curricula after those of ECAM and the polytechnic school in Karlsruhe. The Worcester Polytechnic Institute established in 1865 in Massachusetts provided a degree in mechanical engineering whose curriculum involved significant amount of workshop training. Indeed, the school awarded its degree to the students only after four years of honorable service in engineering practice beyond graduation.

The diffusion of engineering education proceeded largely through the creation of new specialized institutes, such as Union College, or the Massachusetts Institute of Technology. Older elite colleges that considered engineering not to be a suitable discipline for their students' education, established sister institutions aimed at providing scientific and engineering training. Thus, the Lawrence Scientific School was established in 1847 as a branch of Harvard University thanks to the endowment provided by the merchant Abbott Lawrence, whose wish was to promote the application of scientific education to engineering, mining, and the invention and manufacture of machinery. Ultimately, the school program emphasized the teaching of the sciences, rather than engineering. Yale College followed in Harvard footsteps with the creation of the Sheffield Scientific School in 1858, again thanks to a gift by a railroad entrepreneur. By the year 1880, 85 engineering schools were active at the college level.

Unlike in Germany, where the development of the polytechnic schools was supported by the public sector and heavily influenced by the requirements for the engineers' admission to public service, the development of the U.S. colleges was largely the result of private investment.[v] Private institutions, dependent on tuition revenues for their financial viability, were naturally inclined to respond to the changing needs of a growing society by providing professional education in any field, with hardly any prejudice regarding the academic standing of the subject matter. This orientation was encouraged by the federal government, whose first legislative effort in the field of higher education was the Morrill Act of 1862. Indeed, Geiger (1986) attributes the reorientation of the U.S. academic system toward utilitarian goals to the Morrill Act.

The Act authorized a grant of federal land to the states for the purpose of maintaining at least one college where the essential focus of learning would be agriculture and the mechanical arts. In a number of states the purposes of the Morrill Act were pursued at already existing colleges and schools. Thus, private institutions like the Sheffield Scientific School, M.I.T. or the University of Michigan came to play the role of land grant colleges for their states. In others, the provisions of the Morrill Act were realized through the creation of altogether new academic institutions, either public (such as the University of Illinois (1867) and the University of California (1868)) or private. Among the latter, Cornell University (founded in 1868) was the first institution successfully providing educational programs in science, humanities, and practical subjects. Indeed, by its third year of operation Cornell had the largest entering student class in the country's history.

These observations can be summarized in two points. First, the system of higher education in the U.S. was characterized by an enormous adaptive capacity. New schools formed in a relatively short time to fill niches that were poorly served by existing institutions. At the same time, the successful experience of innovative schools like Cornell University, or the spread of the elective system from Harvard College to other schools, signaled the value of a considerable degree of flexibility in the educational programs of individual institutions.[vi] Second, the engineering curricula in the U.S. colleges often represented an adaptation of European models to local conditions. Among the latter, differences in the standards of secondary education and the much greater emphasis given to practical work were of paramount importance.[vii] As a result of these factors, the 'academisation' of engineering that characterized developments in Germany and France was hardly a problem in the U.S., in spite of the fact that many engineering schools drew inspiration from European institutions and very often adopted the same textbooks.

European influences on U.S. schools were partly the result of personal contacts among professors and of the fact that many U.S. professors were trained in Europe.[viii] In particular, the German academic system's emphasis on scientific research and teaching provided the archetype for the first incarnation of the modern graduate school in the U.S. at the Johns Hopkins University, founded in 1876. Under the leadership of his first president, Daniel Coit Gilman, Johns Hopkins' faculty reached 53 units in 1884, "13 of whom had German doctorates and nearly all of whom had studied in Germany." (Emmerson, 1973, p.288). As documented by other scholars (for example, Ben-David, 1977), the U.S. universities quickly acquired original characteristics, including the departmental structure with an administrative chair.

Further development of the U.S. universities need not be followed in as much detail here. Suffice to say that the German influence on U.S. academic institutions was stronger in the organization of graduate programs in the sciences than it was in engineering, where in general the U.S. universities held onto a curriculum that placed distinctly less emphasis on scientific training and more on practical learning.[ix]

The development of the higher education systems in Japan, the Republic of Korea, and Taiwan Province of China

This pattern of international influences among countries in the design of scientific institutions continued to manifest itself through the nineteenth and twentieth centuries, not only among Western European countries and their colonies. A particularly important instance of the phenomenon is represented by nineteenth century Japan. In turn, the Japanese system had great influence on the academic systems that evolved since the middle of the twentieth century in the Republic of Korea and Taiwan Province of China who endured Japanese colonial domination for nearly half a century. It will be important to review these cases in some detail.

After the long period of commercial isolation during the Tokugawa dynasty (1603-1868), the acquisition of Western knowledge became during the Meiji restoration an important focus of government policies. The acquisition of knowledge and the creation of a higher education system were believed to be essential in order to catch up with the advanced western economies. Foreign influences on the institutions designed in Japan resulted from what Japanese administrators and educators learned from their experiences abroad, as students in various disciplines or merely as students of the institutions themselves, and from the large number of foreign professors who were invited to Japan in order to help laying the foundation of a system that within about fifty years achieved a size comparable to those of most western European countries.

The Japanese higher education system began to develop as a mixed system, with both private and public colleges and institutions. However, private academic institutions particularly in scientific and engineering disciplines were not well regarded by the government, which withheld from them recognition of their academic status until 1918. Thus, while a few private science-oriented institutions were founded since 1874, they struggled financially because of the limited ability to attract students away from public institutions and the cost of providing laboratories for educating small student populations. In a pattern that was repeated later on in other countries, the private institutions survived through the first few decades by focusing on the study of traditional culture, humanities, law, and economics. Only during the 1910s, the growth of the student population created the conditions for private colleges to begin offering anew courses in science and engineering. By then, government opposition to this had grown weaker and private academic institutions were given official recognition in 1918 (Nagai, 1971).

The 1918 University Ordinance also promoted the creation of public institutions at the prefectural and municipal level, marking the incipient decentralization of an academic system that had grown progressively more centralized over the previous fifty years. In fact, while early on much of the efforts at institution building focused on specialized schools, since the 1870s the general university model that can perhaps be associated with the U.S. became dominant. Moreover, the public university (named Imperial University since 1886) operated only at one location, Tokyo, for nearly twenty years. A second location for the Imperial University was agreed to only in 1897, and nearly one more decade had to pass for a third campus to be created. By 1918 the Imperial University included five centers including Tokyo (1886), Kyoto (1897), Sendai/Tohoku (1906), Fukuoka/Kyushu (1910), and Sapporo/Hokkaido (1918).

Engineering education figured prominently in the public efforts at creating the country's knowledge infrastructure. A specialized school in science and engineering was organized in 1873 as the Imperial College of Engineering. The development of the curriculum, faculty recruitment, and management of the institution were entrusted to a British engineer, Henry Dyer. Dyer recruited an additional eight British professors and designed the curriculum along the lines of that at ETH in Zurich (Gooday and Low, 1998). Three years of practical laboratory work were necessary to obtain the degree. Students could fulfill this requirement by working at either university laboratories, or at any of the government laboratories operated by the Ministry of Industries or others (Bartholomew, 1989; Odagiri and Goto, 1993). Later on, in 1886, the College merged with Tokyo University to become the Department of Engineering of the Imperial University of Tokyo.

The reorganization of Tokyo's universities coincided with the opening of a new campus with significantly improved teaching laboratories. These were necessary to support the activities of students pursuing the newly created doctoral degrees (hakushi). During the following thirty years, 1,360 students received this degree. Half of them were in medicine, a quarter in engineering, and only about 5% of doctoral degrees were awarded in the sciences and mathematics (Bartholomew, 1989). In addition to these doctoral degrees, the Ministry of Education provided since 1869 financial support for Japanese students to travel and pursue degree programs at foreign universities. A central goal of these policies was to train the future cohorts of academic teachers, such as to reduce the need for inviting foreign professors to national academic institutions. The latter practice was rather expensive, and in light of the universities' mixed record in selecting personnel, it was the subject of frequent criticism directed to the government.[x]

The instrumentalist view of academic education that informed Japanese government policy was largely responsible for the decision to provide little support to research activities within universities. As will be discussed later, Japan established instead a rather extensive system of public institutes and laboratories where various kinds of research activities related to Japanese industry and agriculture were carried out.[xi] The course of Japanese government policy was influenced at least partly by the German system of universities, Hochschulen, and research institutes, which was perceived to have provided critical support to the country's industrial development.

The teaching orientation of universities, as well as the country's reliance on research institutes in order to carry out publicly funded research, appear to be characteristics of the Japanese system that were largely replicated in the development of the Korean and Taiwanese knowledge infrastructure. Much like the Japanese government during the Meiji era, the Korean and Taiwanese government committed sizeable financial resources to the development of national universities, including foreign aid directed to infrastructural investments in education. In fact, as documented above, the magnitude of the effort was that much larger around 1950.

The Republic of Korea's tertiary level educational infrastructure at the end of the Japanese occupation consisted of a handful of colleges established by religious missionaries during the late nineteenth century, and only one modern academic institution, Keijo Imperial University, established in Seoul by the Japanese government in 1924 to provide higher education for the Japanese expatriates. Korean students accounted for only between a quarter and a third of the total, and only very small numbers of Koreans attended universities in Japan (Lee, S., 1989). The growth of students' enrollment since 1945 owed a great deal to the financial aid provided by the U.S. government. McGinn et al. (1980) estimate that between 1952 and 1963 19% of the $100 million in aid for education provided by the U.S. government were spent for higher education, with the bulk of the funds ($17 million) being used to upgrade the faculties at Seoul National University, as Keijo Imperial University was named after the Republic of Korea's liberation from Japan.

In fact, the growth of the university system was characterized by a number of problems. First, the growing number of private institutions supported the rise of tertiary enrollments to levels that were beyond the economy's capacity to create adequate job opportunities, and led therefore to unemployment problems among college educated Koreans. Second, while the Park government managed to raise enrollments in science and engineering, creating job opportunities for these graduates proved to be a more elusive task. As a result, growing numbers of Korean students went abroad to pursue graduate studies or professional opportunities in science and engineering.

During the 1960s, Korean universities began to offer graduate programs. While the number of universities offering graduate degrees increased rapidly from the 1960s to the 1980s, four universities accounted effectively for 50% of the degrees awarded. In particular, the government decided to focus activities at Seoul National University to graduate education, and to reorganize a specialized graduate institution for the sciences and engineering by forming the Korea Advanced Institute of Science and Technology (KAIST). Within five years, KAIST could count on a faculty of 142 members, recruited mostly among the ranks of foreign-degree-holding Koreans. As noted by Kim (1993 and 2000), while the government supported the recruitment of returning Koreans, the universities received little in the way of research funding, which was instead largely concentrated on specialized research institutes.

Taiwan Province of China's experience shows a great deal of similarities with the case of the Republic of Korea. While the overall level of education of the Taiwanese was higher than that of Koreans, the number of universities was only seven in 1950, with about 1,000 faculty members and a student body of 6,600 units. Thirty-six years later, 22,000 faculty provided instruction to 440,000 students in 105 tertiary institutions (Hsieh, 1989). Such rapid growth was sustained by government's investment in education which reached 5.83% of GNP in 1985. Even in Taiwan Province of China, government policies intended to harness the enhanced educational opportunities and achievements of the population to the country's economic development. As a consequence, the Taiwanese government managed students' enrollments at the national universities with the goal of increasing the supply of science and engineering graduates. As it turns out, the government overinvested in science and engineering graduates who as a result contributed to a significant brain drain. Through the 1960s and 1970s, around 20% of Taiwanese students enrolled in tertiary degree programs were abroad. The percentage was even higher in the sciences, where one third of students migrated to foreign institutions (UNESCO, 1972). U.S. universities accounted for about half of the Taiwanese students abroad. A sizeable fraction of the students did not return home after graduation, choosing instead to find employment in the U.S. (Hou and Gee, 1993).

The large number of foreign-trained Taiwanese proved instrumental to staffing the growing number of higher educational institutions, as well as research institutes and laboratories in the public and private sector. During the 1980s, graduate programs in science and engineering became increasingly common and created the opportunity to lure back to the homeland many educated Taiwanese. A 1989 study of the National Taiwan University and the National Tsing Hua University revealed that respectively 74% and 84% of the faculty had received their degrees abroad (Hsieh, 1989). Likewise, the Academia Sinica, a public research institute, was in the late 1980s almost entirely staffed by Chinese Americans who had maintained their ties with academic activity in Taiwan Province of China. As will be argued later on, these opportunities added to those provided by the public research laboratories connected to the electronics and computer industry, and the creation of science-based industrial parks. For example, more than one half of the new firms based in Hsinchu Science-based Industrial Park since 1980 had been established or supported by returning foreign-trained Taiwanese (National Science Council, 1997).

Effectiveness of higher education and public research laboratories as sources of technological capability in industry

The historical evidence reviewed above provides a brief overview of the process of development of the higher education system across a set of countries that at different times in the past and from different initial conditions entered a phase of economic catch up. In this section we will attempt to discuss in more detail the relationship between the design of higher education institutions and the accumulation of technological capabilities among national firms. Two observations are warranted.

First, while there is evidence from cross-country data of a positive correlation between tertiary enrollment rates and measures of per capita income, there is less support for the proposition that the former is an important determinant of national economic growth. Yet, the evidence on the centrality of scientific and engineering education to technological capabilities and on the latter's effects on economic growth is sufficiently strong to invite further qualitative investigation. Second, the relationship between tertiary education in science and engineering and the formation of technological capabilities has been mediated often by the activities of public research institutions. These have benefited on the input side from the domestic supply of scientific and engineering talent produced by the local universities and polytechnics. On the output side, they have provided assistance to indigenous private and public firms with the inward transfer of technology, or even the performance of locally innovative R&D, and with other kinds of technology-based business services. Thus, the following discussion will bring into focus the activities of public research institutes as necessary.

The following discussion will necessarily be selective in its coverage of industry sectors, areas of education, and countries. An important objective of the selection is to bring to the fore a variety of conditions characterizing the university-industry interactions that may contribute to the development of a set of archetypes. It is well known from contemporary research on innovation systems that industrial sectors differ in their reliance on scientific and engineering knowledge and research results. Moreover, there are differences across sectors with respect to the mechanisms and channels for the transmission of knowledge and information across the university industry interface. The following review will therefore attempt to encompass a sufficiently varied set of case studies.

The nineteenth century chemical and electrical equipment industries are often argued to have been the first science-based industries. It is useful then to begin reviewing the role played by universities and Hochschulen in the development of these industries. Then, their case will be compared to that of the machinery industry.

University-based laboratory training in chemistry supported the acquisition of technological capabilities for chemical firms whose activities included the first forms of systematic R&D in an industrial setting. Already in the 1830s, the University of Giessen in Germany had established itself as the leading center of research in organic chemistry, thanks to the reputation of Justus von Liebig's laboratory. The university attracted students from Britain, even if the latter was host to the world leading firms in the production of inorganic chemicals. British students returned to their home country upon completion of their studies, and so did numerous German students. In fact, the number of chemists trained at the German universities exceeded the local industry demand for scientific talent, so that some of them had to either accept alternative job opportunities at home or seek employment as chemists abroad, most notably in Britain. German chemists then represented an important source of scientific personnel for British firms and research institutions until developments in the German industry induced them to return to their home country (Haber, 1958; Murmann and Landau, 1998).[xii]

Since the 1860s, the German chemical firms pioneered the creation of in-house research departments staffed with scientists. To this aim, they could draw upon the pool of scientific and engineering graduates from local universities and the Hochschulen where chemistry was part of the curriculum. Academic programs in chemistry were so effective at providing industry with needed scientific personnel because students learned the practice of laboratory research. The university system of chemical research was among the key reasons for the rise to leadership of the German chemical firms in the production of synthetic dyes.

It was argued earlier that in spite of the success of laboratory research at the universities, practical experimentation was all but eradicated from the mechanical engineering programs of the Hochschulen under the influence of the various Redtenbacher, Reuleaux, and so on. It should be noted how this direction in curricular development was largely determined by a professorial elite whose familiarity with industrial practice and technological needs was limited. In part, this reflected the weakness of the industrial community itself. German machinery firms of the mid-nineteenth century were likely to be generalist shops. Reuleaux's Letters from Philadelphia in 1876 described German machines as "cheap and bad" imitations of British equipment. But among the assessments made during the following years of the conditions of German industry and the role of the Hochschulen in this regard, a recurrent theme is the irrelevance of the knowledge and competence that Hochschulen provided to mechanical engineers. Prime culprit for this condition was the lack of opportunities for practical work and laboratory practice.

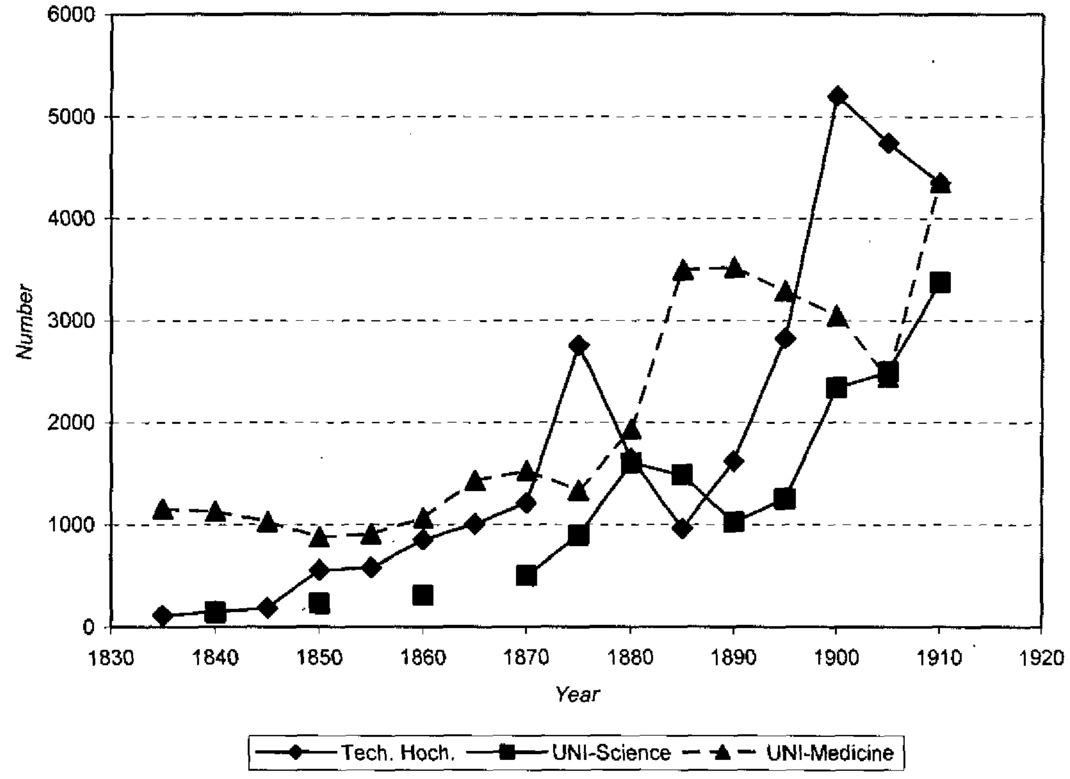
In fact, experimental laboratories began to appear at the Hochschulen since the late 1860s. First was a materials-testing laboratory in Munich established in 1868, followed by a Mechanical-Technical Experimental Station in Berlin which was annexed to the Hochschule in 1877. These laboratories began to be used for instruction later on, largely under the example of chemical and electrical engineering labs.[xiii] It is noteworthy that one of the German visitors of the Philadelphia exhibition in 1876, Hermann Wedding, an instructor at Berlin Mining Academy, took the opportunity to visit American engineering colleges including Rensselaer Polytechnic Institute, M.I.T., and Stevens Institute of Technology. In his report to German steel industry representatives, Wedding mused about the importance of the laboratories he visited in these schools, offering to students the opportunity to participate in experiments with materials, engines, and various machines. He described the labs as the "connecting link between science and industrial practice" that German schools had been missing until then (Gispen, 1989).

The reorientation of the mechanical engineering curriculum at the Hochschulen got under way then and received a great acceleration in the 1890s when the new leadership of the professional society VDI sponsored a resolution calling for large scale laboratories at the Hochschulen and laboratory training. Alois Riedler, professor of mechanical engineering at Berlin's Hochschule since 1888, was the most vocal supporter of this resolution. As a result of these transformations, the curriculum in mechanical engineering became much more oriented to practical needs of industry. Graduates found it easier to be employed in industry, and enrollments at the Hochschulen increased rapidly during the last decade of the century (Figure 3). Among the outcomes of this reform trends at the Hochschulen, it is worth singling out the appointments of Georg Schlesinger and Adolf Wallichs to newly established chairs in machine tool technology at the Hochschulen in Berlin (1904) and Aachen (1906), respectively. These professors proved instrumental to the diffusion of machine tool design and construction principles among German firms, as well as the spread of Taylorist principles and mass production techniques.[xiv]

The development of electrical engineering education presented similar themes. However, unlike the chemical industry, which indeed built upon a body of knowledge created at universities, the electrical equipment industries began to grow in advance of the formation of degree programs in electrical engineering. In fact, the development of industrial technology had progressed without substantial assistance from academic institutions, which early on struggled to provide adequate training for prospective electrical engineers. König (1996) advances the thesis that electrical engineering was an industry-based science in the 1880s. At the heart of his claim is the fact that physicists and mechanical engineers with little knowledge of industrial technology were first invited to teach courses in electrical engineering. The problem was corrected first by recruiting industry personnel as special instructors, while professors began to spend study periods at industrial firms in order to familiarize themselves with contemporary technology. By the late 1880s, the professoriate in the field consisted of graduates of electrical engineering programs with some amount of professional experience in industrial firms. The Technische Hochschule in Darmstadt, perhaps the leading program in this field, began then to attract a considerable number of foreign students.

Figure 3

Students at Prussian universities and technical institutes (1835-1900)



Source: McClelland (1980).

These developments in the German Hochschulen mirrored the kind of intense interaction between educational institutions and industry that had emerged earlier in the U.S. Furthermore, they suggest that perhaps a crucial determinant of an effective relation between university and industry is the degree of responsiveness of educational curricula and activities to the emergence of new areas of industrial technology or specialized sectors. This responsiveness has been noted by many historians as the most remarkable feature of U.S. universities. Since there is an extensive literature on this matter, only brief mention will be made of the central role played by U.S. engineering schools and departments in the development of many new domestic industries. Their contributions to industrial development have been celebrated in the context of the growth of the electrical equipment, chemical, and later aircraft industries. Among the many institutions, the Massachusetts Institute of Technology deserves special attention because its creation was prompted by the Boston industrialists' desire to create an institution devoted to supporting their production activities through research and education in the applied sciences and engineering. The success of the institution, both from a scientific and technological standpoint, made it into a model for efforts elsewhere at establishing advanced engineering institutions, of which a few will be discussed below.

While the MIT's contributions ranged across many areas of engineering and applied science, Rosenberg (1994) has drawn attention to the particular role played by this institution in the genesis of the field of chemical engineering, "a distinctly American achievement." (ibid., p. 193). Until the early twentieth century, the industry's technical challenges in scaling up chemical processes hatched in the laboratory were the concern of mechanical engineers. The field was altered radically by the introduction of the concept of "unit operations" by Arthur D. Little. Little first articulated the general characteristics of chemical processes, defining a coherent agenda for the field of chemical engineering. This favored the institutionalization of chemical engineering as an independent department at U.S. universities, beginning with the M.I.T. itself in 1920. Such development –Rosenberg argues- could not occur in Britain where universities hardly considered industry needs to be a valid focus for academic activity. In Germany, which by the early twentieth century had established a strong leadership in branches of the chemical industry, the concept of "unit operations" did not have the same success in providing an organizing framework for research on chemical processes (Buchholz, 1979). As a result of differences in the product specialization of the German chemical industry, the engineering of chemical plants and processes did not coalesce into an autonomous field of academic research until later on. Chemical engineering research was largely industry-based (IG-Farben) until the 1930s.

It may be worth comparing the context for chemical technology research in the U.S. and Germany with that in Japan. As mentioned in the previous section, the Japanese government did not support university-based research, preferring instead to establish specialized research institutes. In doing so, Japan could be argued to have followed the lead of the public research institutes sprouting up in Germany (e.g., the Physicalische Technische Reichsanstalt, and later the Kaiser Wilhelm Gesellschaft laboratories), Britain (National Laboratory), the U.S. (National Bureau of Standards) among others. In these countries, private firms particularly in industry sectors like chemicals and electrical equipment, had begun carrying out R&D activities in-house. Not the same was true in Japan, where domestic firms in these industries relied upon the adoption of foreign technology and to a lesser extent publicly funded research.

Public funding of research was modest. Important programs were created in the medical field (largely thanks to Kitasato's Institute of Infectious Diseases) but hardly any in sciences and engineering until the end of the century. Public support for research aimed at industrial development increased as the access to foreign technology began to be restricted. Thus, in 1900 the Tokyo Industrial Experiment Laboratory was established to conduct testing and analyses on a contract basis for national firms. From two divisions in industrial chemistry and chemical analysis staffed with technicians, the Laboratory was expanded in 1906 in the aftermath of the Russo-Japanese war to include divisions for ceramics, dyeing and electrochemistry in 1906. While the amount of resources for research in chemistry was considered insufficient at the onset of World War I, the Industrial Experiment Laboratory was the source of technologies that were put to fruition by local firms, particularly for electrochemical processes (Uchida, 1979). The lack of access to imported chemicals occasioned by the beginning of the world conflict raised the significance of indigenous technical activities and led to the creation of the Research Institute for Physics and Chemistry in 1917.

This institute was patterned after the German Physicalische Technische Reichsanstalt, its research mission encompassing both basic research in the fields of chemistry and physics and applied research aimed at industrial technology. The institute grew considerably in size and range of scientific and technical fields since the mid-1920s when the current director Okochi Masatoshi addressed the financial constraints on the activities of the institute by making a push toward the commercialization of technologies patented by the Institute (Cusumano, 1989). Note that even after the creation of the Research Institute, the Tokyo Industrial Experiment Laboratory continued to operate, providing indigenous technology (to wit, an adaptation of the Haber-Bosch process) for the production of synthetic ammonia to Showa Fertilizer Co. in the late 1920s (Mikami, 1979).[xv]

In addition to chemical technology, the Industrial Experiment Laboratory was putatively in charge of conducting some research and testing on iron and steel. However, its contributions in this area of industry were overshadowed until 1915 by the activities of the state-owned steelworks Yawata, and later on by the research activities of the Iron and Steel Institute of Japan and of the Institute for Metal Research at Tohoku University. Production at Yawata Works represented the first foray by Japanese companies in the area of large scale steel production. Yawata became a center of technological learning and of technology diffusion, partly by providing technical assistance to other firms and partly through the migration to other companies of trained personnel. Indeed, the Iron and Steel Institute of Japan established in 1915 represented the industry's institutional venue for conducting cooperative research and broadly disseminating technological knowledge. The Institute played an important role in the standardization of iron and steel products, and their diffusion among domestic firms. The Institute's membership enjoyed extensive representation from both the academic and the industrial community, including not only iron and steel producers but also users.

The same form of partnership between institutions was also responsible for the establishment of the Institute for Metals Research. The proposal for this research center was formulated in 1915 by the physicist Honda Kotaro of Tohoku University, who invented a steel alloy (cobalt steel) in the context of research supported by the head of the Sumitomo zaibatsu. The government did not intend to provide more than 50% of the research funds requested, so that the university president turned to Sumitomo Metals for financial support. The Institute began operating in 1916 (Yonekura, 1994).

The beginnings of the iron and steel industry in Japan indicate that a large public steel works became an essential component of the sectoral system of technological learning. While the industry benefited from the training of metallurgists and mining engineers at domestic universities, Yawata Works appears to have been a crucial element in the development of indigenous technological capabilities. The Brazilian iron and steel industry represents an interesting comparison with the Japanese pattern of development.

In Brazil too, as early as the 1850s the owner of the then largest forge in Brazil, Jean Monlevade, had noted the importance of a model iron works as a center for technological learning necessary for the creation of indigenous capabilities. However, a couple of decades later public support for the industry materialized in the form of a higher education institution, the Escola de Minas, a school dedicated to mining and metallurgical engineering, modeled after the French Ecole des Mines. The impact of this school on the development of the local industry was rather limited for several decades since its creation in 1876, largely because of the insignificant level of investment and enterprise formation in the industry until the 1910s (Carvalho, 2002; Gomes, 1983; Paula, 1983). Both members of the faculty and graduates of the Escola became involved with furnace design and plant management activities during the 1910s and 1920s, when a number of new iron and steel firms was formed, thanks in part to government financial support. But even the new plants were of limited scale by contemporary global standards. Since the 1930s, production experience and foreign technical assistance became the most relevant channels for technological learning. This was the case during the construction of the plant of the Companhia Siderurgica Belgo-Mineira in Monlevade, of the plant of the Companhia Siderurgica Nacional in Volta Redonda, and the plant of Usiminas in Ipatinga (Gomes, 1983; Dahlman, 1984).[xvi]

These observations support the general proposition that the role of academic institutions and public research laboratories in the accumulation of technological capabilities differs across industrial sectors and across the phases of the life-cycle of national industries.

A striking illustration of this phenomenon can be found in the development of the aircraft industry in Brazil during the post-World War II period (Cassiolato et al., 2003; Kanatsu, 2004). The origins of the industry go back to 1945 when the Ministry of Aeronautics created a research center in aeronautical engineering, the Centro Tecnico Aerospacial (CTA), which was to coordinate research and training activities aimed at the development of indigenous capabilities in aircraft design and production. With assistance from M.I.T., a specialized engineering college was created two years later. The graduates of the Instituto Tecnologico de Aeronautica, whose first director was MIT professor Richard H. Smith, provided the personnel to staff the emerging cluster of institutions focused on aircraft technology. Among these the Instituto Pesquisas & Desenvolvimento (IPD, established in 1954) was in charge of the first projects on jet propulsion engines, and a revolutionary helicopter design (Convertplane). Foreign specialists were recruited from the U.S. and Germany in order to work on these projects with Brazilian engineers, either trained at ITA or abroad. A critical project was launched in 1965 aimed at the design and construction of a twin engine turbo-prop plane for the Air Force. The resulting aircraft (named EMB-110, or Bandeirante) became the basis for the creation in 1969 of Embraer, a state-controlled enterprise. Embraer's technological capabilities were acquired thanks to the recruitment of a staff of some 150 engineers and technicians from the IPD, which as a result found its research capacity drastically reduced.

Embraer continued to be a primary outlet for the engineering programs at ITA, but the decision to enter the field of commercial aircraft required that Embraer's strategy for technology acquisition and development be broadened to include licensing agreements with foreign firms (Piper Aircraft Co. and Aermacchi). Most importantly, Embraer began to develop its first jet airplane (ERJ-145) in 1989 by leading a network of risk partners in the role of system integrator. From the perspective of this paper, it is important to notice that the role of ITA as supplier of engineering talent today is much less significant than it was fifty years ago. The growth of a high-technology aeronautics cluster in Sao Jose do Campos has attracted engineering graduates from a larger set of national institutions, while local research centers offer post-graduate courses and research opportunities in fields associated to the aerospace industry. While ITA continues to attract excellent students to its undergraduate programs in engineering, its graduates are today much more likely to go on to pursue graduate studies and professional careers outside the region.

A tentative comparison between the cases of the Escola de Minas and ITA suggests that the lattter's affiliation with the CTA and the IPD first, Embraer later, provided the demand for advanced technical knowledge that ITA's programs were designed to provide to students. On the other hand, the Escola de Minas operated for many years in such a context that the institution would not have survived as a specialized school for mining engineering. A plausible conclusion is that complementary policies aimed at the creation of a demand for technological skills may be necessary if investment in advanced educational institutions is to be at all successful in assisting local firms with the accumulation of technological capabilities. Most instances of brain drain can be ascribed in part to the imbalance between the domestic supply of scientific and engineering talent and the demand for it by national firms. Moreover, the scope of the contributions of universities and public research institutes to capability building in an area of technology evolves with the nature of the technological activities carried out by national firms, their access to other sources of technological knowledge, and the structural characteristics of the evolving industry (i.e., the presence of large corporations, or clusters of small and medium size enterprises, etc.). This evolutionary process is prominent in the development of electronics and semiconductor industries in the Republic of Korea and Taiwan Province of China.

Both countries experienced during the 1960s and 1970s a significant outflow of nationals who had either received training at domestic institutions or whose migration coincided with their enrollment in foreign educational institutions. During those decades, national firms were starting to produce electronic goods, targeting relatively mature technologies whose replication at home relied only modestly on design and manufacturing capabilities. Furthermore, the entry in these sectors occurred typically through licensing agreements and other contractual arrangements with established firms in advanced economies and local subsidiaries of transnational corporations. During this phase, the creation of a skilled workforce of engineers was the most important contribution of universities to capability building. It was at a later stage of industry development that the governments of the two countries became more actively involved in the upgrading of local technological capabilities through the acquisition and diffusion of sophisticated technological knowledge, supporting entrepreneurial efforts at entering markets that were in technological terms closer to the frontier.

In Taiwan Province of China a crucial aspect of government policy was the 1973 consolidation of three existing public research laboratories (Union Industrial Research Laboratories, Mining Research & Service Organization, and Metal Industrial Research Institute) into the Industrial Technology Research Institute (ITRI). These laboratories were soon complemented by a new one, the Electronics Industrial Research Center (later renamed Electronics Research and Services Organization, ERSO). ERSO was established to spearhead a national effort to develop indigenous capabilities in semiconductors design and manufacturing. Through a license agreement with RCA, ERSO acquired its C-MOS technology in 1976 and established a pilot fabrication plant in 1977 that could serve as a training facility. Later on, the technology was handed over to a spin-off firm, the United Microelectronics Corporation (UMC), whose ownership was only in stages turned over to private investors. UMC's technical staff included at birth many engineers from ERSO.

ERSO promoted capability building in the industry through both the transfer of technology to firms and the training of specialized engineering and scientific talent.[xvii] The same strategy was adopted through the 1980s and 1990s in order to develop a capability in component technologies for the electronics sectors. These included VLSI and DRAM chips design and manufacturing, fabrication masks, CD-Rom, DVD-ROM, and TFT-LCD display technology, among others. For virtually all these technologies, ERSO identified suitable foreign partner to acquire a license or enter a technology transfer agreement, and proceeded to establish a laboratory or pilot plant as a center for technological learning and capability building based on training and experimentation. In most cases, technologies and capabilities developed in this way were then spun off to newly formed enterprises. This was the case with Taiwan Semiconductor Manufacturing Corp. (TSMC), formed as a joint venture with Phillips for manufacturing VLSI chips, with Taiwan Mask Corporation, spun off from ERSO in 1989 as a specialized producer of fabrication masks, and with Vanguard International Semiconductor, a spin-off firm that established itself as the leading DRAM manufcaturer. In other cases, the relevant technology would be licensed to the relevant firms or in fact the firms would simply rely upon capabilities learned through their cooperation with ERSO in order to develop their own technology or to enter licensing agreement with other firms.

The structure that emerged in the Taiwanese semiconductor industry is characterized by a considerable degree of firm specialization. UMC and TSMC have adopted the business model of pure chip foundries, serving the manufacturing needs of a large number of chip design firms. The interactions among firms in the sector are concentrated around ERSO headquarters and the neighboring Hsinchu Science Park. The growth of chip design firms was facilitated by the Multi Project Chip undertaken by ITRI to provide universities with CAD tools for chip design as well as chip foundry services. Nine universities participated in this initiative, training scores of specialists in chip design whose firms were then able to contract with other firms in the cluster for manufacturing and other downstream activities.[xviii]

Until recently then, the electronics industry in Taiwan Province of China has been very much fueled by a process of creation of new entrepreneurial firms based on the technology transfer activities carried out by various divisions of ITRI, such as ERSO and the Computer and Communications Laboratory. The model has been replicated by other government agencies including the Institute for Information Industry, established in 1979 to support the development of domestic PC manufacturers, as well as laboratories and institutes aimed at other technology areas. Public R&D expenditure has hovered around 40% of national R&D through much of the 1990s, the vast majority performed at science and technology institutions and universities. By contrast, the development of the Korean electronics sector has been characterized by an initial phase during which government research institutions played a key role in technology transfer, followed by the growing domination of R&D by the large chaebols, Samsung, Goldstar, Daewoo, and Hyundai. Public funds account today for only around one fourth of national R&D expenditures, and yet the beginnings of the electronics sector in the Republic of Korea followed a pattern similar to that we observed in Taiwan Province of China.

During the 1960s, foreign direct investment was the basis for the growth of the semiconductors industry. But FDI focused on old technologies and stages of the production process with high labor content. Government efforts at upgrading indigenous capabilities in engineering and sciences led to the establishment in 1968 of the Korean Institute of Science & Technology (KIST), and in 1972 of a graduate level educational institution, the Korea Advanced Institute of Science (KAIS). KIST's broad research mission was pursued through the creation of several specialized research centers. Research on semiconductors design and fabrication was conducted since 1975 at the Semiconductor Technology Development Center (STDC), whose first project was a collaboration with Goldstar to develop a bipolar IC design through reverse engineering. STDC merged in 1977 with another research department at KIST to create the Korea Institute of Electronics Technology (KIET).

Over the following years, KIET embarked on a series of projects aimed at the development of bipolar ICs for applications in consumer electronics and telecommunications, and of MOS microcontroller designs. While KIET coordinated these projects, all of them featured the participation of the leading electronics firms, including Goldstar, Samsung, Daewoo, and Hyunday. The significance of these projects for the chaebols' accumulation of capabilities in semiconductor technology receives different evaluations. Wade (1990a and 1990b) argues that these research collaborations provided the chaebols with technological capabilities that, coupled with other forms of industry support by the government, enabled the chaebols to move into the fabrication of semiconductors. On the other hand, Hobday (1995) and Pack (2000) regard the role of KIET as secondary at best, arguing that the relevant sources of technology transfer were foreign firms.

In 1985, KIET was combined with another public research institute to form the Electronics and Telecommunications Research Institute (ETRI). This reorganization appears to have been motivated by the scope of business and technological interests of the chaebols. While the focus of research activities at ETRI might have shifted toward more basic and applied research (Wade, 1990a), the chaebols have continued to collaborate with ETRI and to have a considerable influence on the allocation of public R&D funds to technology areas. Furthermore, the magnitude of government funded research in the industry has declined, largely because of the rapid increase in R&D spending in the private sector.

Conclusions

If history is of any guide, there are solid grounds for arguing that processes of economic catch up will continue to be fundamentally influenced by the coevolution of higher education, public research and industrial capabilities. While the various instances of such processes reviewed above support this proposition, they present us also with a variety of coevolutionary patterns, resulting from differences in the sectoral profile of economic development processes, in the features of higher education institutions, as well as in the scope and significance of public research activities. It will be useful then to conclude this study by identifying explicitly what are common threads in the case histories reviewed and what have been essential features of the contributions made by higher education and public research infrastructure in the process of economic catch up. This exercise will not only sharpen our comprehension of the historical differences, but most importantly will serve as a conceptual bridge to contemporary development policy debates.

It seems fitting to structure these concluding observations according to the two basic economic functions of the academic and public research infrastructure, namely: (1) to communicate existing knowledge through educational degree programs; and (2) to produce, locate, and communicate knowledge to economic actors through research, extension services, consulting work, cooperative problem-solving and the like.[xix]

The primary role of higher education institutions is to enhance the national absorptive capacity with respect to social and physical technologies that are already available. But even the seemingly simple task of imparting the necessary education to the citizenry presents challenges that have grown more and more complex over time. In addition to the greater demand for education across all societies, scientific and technical knowledge has become increasingly specialized, wreaking upon contemporary society the need for more complex academic structures. Present and past experiences in the design of these structures provide useful lessons and models for contemporary policy aimed at the organization of domestic systems of higher education. This is by no means a new development.

An important aspect of the historical evidence reviewed in the paper concerns the relationship between growing educational system at home and foreign institutions. Developments in any one country are intertwined with developments elsewhere. An important form of international influences on domestic matters is connected to the adoption of basic institutional templates from abroad. While there are undoubtedly great advantages in being able to borrow ideas and practices from abroad, it is also apparent that creating an effective system of higher education requires that such foreign templates be adapted to local circumstances. These adaptations take into account not only the character of secondary level educational institutions, but also local economic conditions, and their influence on labor markets. In particular, the design of curricula should be well-adapted or responsive to the demand for skills and knowledge expressed by local firms and industries. The task of creating effective educational programs is sufficiently complex that teething problems are bound to occur, as well borne out by the historical evidence.

Institutional failures in this regard have been central to the appearance of two phenomena, the migration of skilled scientific and technical personnel (brain drain) and rising levels of unemployment or underemployment among the educated segments of the population. Both of these phenomena left their mark on the development of the Republic of Korea and Taiwan Province of China during the late twentieth century, and were also somewhat prominent in Germany at different times during that country's development. These problems highlight a central difficulty confronting policies that intend to leverage greater levels of educational attainment for nationals for industrial development. Coordinating the growth of the higher education system with the evolving need for capabilities in the economy has proven to be time and again an elusive goal for policy makers. The clearest exception to this proposition is perhaps the U.S., where the expansion of tertiary education institutions occurred largely thanks to private initiatives or to local policy makers' efforts. This pattern of development proved remarkably capable to adapt to local socio-economic circumstances, including to the conditions of local labor markets. Essential in this regard was the system's capacity to provide training in non-traditional practice-oriented fields of knowledge.

The "brain drain" phenomenon in the Republic of Korea and Taiwan Province of China requires at least one further comment. While the brain drain signals an imbalance in the national supply and demand of skilled personnel, there is also sufficient evidence that the migration of students to more advanced economies was motivated by the search for advanced training opportunities. In this regard, the experience of Koreans and Taiwanese students during the twentieth century mirrors that of Japanese students since earlier times, or of those Americans whose wish to pursue research in the sciences brought them to European academic institutions until the Second World War.

These historical experiences present important differences with respect to the activities that followed completion of graduate degree programs. Accordingly, Americans were very likely to return to their home country, and by and large so did the scores of Japanese students who visited European and U.S. schools. But for many Koreans and Taiwanese things worked out differently, and many stayed because there was nothing to go home to. A reverse flow of scientific and engineering talent had to await the creation of suitable work opportunities. This should not obscure the important fact that the acquisition of scientific and technological knowledge through education need not be entirely based on domestic institutions. Indeed, developing countries may not want to try to establish an all-encompassing array of advanced or specialized educational programs before a sustained period of economic development provide clearer directions to such efforts. This brings us to a very important aspect of the historical evidence reviewed.

While it would be desirable that sufficiently well articulated needs from industry guide the evolving structure of the educational system and the design of curricula in various areas of engineering and sciences, this is often not the case in the context of a developing economy. This state of affairs reflects either the weakness of business firms in the relevant industry, or the lack of interaction between university and industry.

The case of Brazil's Escola de Minas, reminds us that the creation of educational institutions does not suffice in and of itself to trigger sustained processes of industrial development. The potential role of universities as suppliers of educated scientists and engineers can only be fulfilled if complementary policies are adopted in order to favor the creation and growth of firms or other organizations whose needs for knowledge and capabilities become the focus of the educational programs. As noted earlier, the creation of ITA in Brazil was part of a broader effort at establishing a domestic aircraft industry. Had the Brazilian government not created the demand for capabilities in aeronautical engineering, ITA as an educational institution would have had a different fate. On the other hand, the creation of the Korean Advanced Institute of Science followed the launch of KIST and the proliferation of its laboratories, with its attendant need for scientific personnel.

The mere existence of industrial firms is by no means sufficient to ensure that academic programs and structures will be adapted to emerging economic needs. History shows how difficult it has been for curricula in applied sciences and engineering to achieve the proper balance between an orientation to practical problems and that to scientific foundations and mathematical abstractions. When the latter orientation prevailed, higher education institutions have been more likely to operate in the 'ivory tower' mode. When the former did, they have been berated for their vocationalism. While the best antidote against these excesses is a system characterized by considerable institutional diversity, developing countries seldom can afford the expense of such a system. But then it is of crucial importance that the governance of the higher education system gives sufficient opportunities for the industrial community to provide its input on educational policies.

The same principle ought to apply to policies regarding the creation and activities of public research institutions. In all country experiences that were reviewed, public research institutes were centrally involved in the process of industrial development. Of these institutes can be said that, much like universities, their economic significance required that the research activities that they focused on, be relevant to an actual or potential user community. Particularly in Japan, the Republic of Korea, and Taiwan Province of China, this goal was pursued by effectively concentrating public support for industry-related research activities outside of the academic institutions. From this perspective, these countries differ from the U.S. system where universities became a significant locus for research activities funded by local government as well as industry.

Looking beyond the institutional differences across countries, it appears that effective systems of public research emerged under conditions that were favorable to two-way interactions between the research institutions and the industrial community. These interactions provided an organizing framework for identifying economically useful activities to be carried out at the research institutions. It should be noted that in many instances reviewed, the public service orientation of academic or stand-alone laboratories manifested itself in their availability for testing and experimentation activities of broad industrial usefulness. While these activities presented only limited scientific significance, they were clearly useful to complement firm-based capabilities in the early phases of industry development across a broad range of technologies. Additional areas of activity involved licensing arrangements with foreign firms, the coordination of inward transfer of foreign technologies for the benefit of national firms, reverse engineering, and the creation of pilot facilities where industry personnel could be trained and local businesses' technological capabilities could be honed.

To a significant extent, the link between public research programs and industrial development needs was created and kept in place by the institutions governing the allocation of research funding and capabilities. Thus, KIST's research portfolio during the first decade of its life was determined by industry contracts, and therefore aligned to the needs of business firms. Similar effects can be attributed to the governance system determining the allocation of research funds at ITRI. Moreover, the mobility of technically skilled personnel between research institutions and firms created substantial awareness of industry needs and problems.[xx]

The key lesson from these examples is that successful public research efforts required sufficiently flexible governing structures that could respond to industry needs and adapt to the evolution of technological capabilities and the scope of the research activities carried out by national firms. Significantly, this capacity to adapt did not only involve the ability to support efforts in new technology areas, but also that to withdraw resources from areas of activity that were to become the province of business enterprises. In this regard, the record of Korean and Taiwanese institutions in electronics has been remarkable.

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Notes

[i] Important reasons why today's processes of economic development are bound to differ are related to changes in the global economic environment, including those of a regulatory character such as they pertain to international trading regime, intellectual property rights, etc.

[ii] Grashof had at that time substituted Redtenbacher at Karlsruhe, after becoming a lecturer at Berlin's Gewerbe Institut in 1955. Since the formation of the VDI, Grashof had been its president and exerted a great influence on the position that the association took on matters related to engineering education.

[iii] Even the chemist Justus von Liebig had to provide at least in part with personal funds for his famous laboratory created at the University of Giessen in 1825.

[iv] The number of doctorates increased from 851 during the 1820s to 1,727 in the 1860s (McClelland, 1980).

[v] Nelson and Rosenberg (1994) identify in the decentralization of the U.S. academic system a key reason for its success in contributing to the economic development of the country.

[vi] Nelson and Rosenberg (1994) document how U.S. universities distinguished themselves also in the twentieth century for the speed with which study programs are formed to support training and research in new fields of knowledge.

[vii] The differences in the approach to engineering typical of nineteenth century U.S. and French professors are illustrated by Kanakis's (1989) comparison of scientific work on essentially identical topics. Abstract mathematical formulation of engineering problems and solutions were typical of the French scientific literature, much as tables of data evinced from extensive laboratory testing were the hallmark of U.S. engineering work. Workshop and laboratory experience was considered an essential, if not dominant, component of the training of the engineers. Around 1900, the hours of laboratory and workshop experience included in the mechanical engineering program at Cornell exceeded hours of lecture by 25%.

[viii] Thus, Sylvanus Thayer spent four years at the Ecole Polytechnique (1813-1817) before becoming superintendent of the West Point Military Academy (Grattan-Guinness, 2004). The School of Mines at Columbia University was the creation of Thomas Egleston, a Yale graduate who studied at the Ecole des Mines in Paris. At its founding in 1864, several of the engineers and scientists serving on the faculty of the school had received their training in France or Germany.

[ix] As noted earlier, the approach to engineering education developed in the U.S. became the focus of a reform movement among German engineering professors, the anti-mathematicians (Gispen, 1989), who worked to restore the industrial relevance of the Hochschulen's technical education by adopting the empirical orientation of U.S. engineering schools. This shift in orientation was particularly visible among professors of mechanical engineering, the branch of engineering that had felt most deeply the effects of the academization movement.

[x] Salaries paid to foreign teachers were several times those provided to nationals, and accounted for one third of the Tokyo University budget in the late 1870s and even more during the following decade.

[xi] There were fifteen non-academic laboratories in 1885. Another fifteen were established before 1900. These laboratories included agricultural experiment stations, the Institute of Infectious Diseases, the Serological Institute, and in 1900 the Industrial Experiment Laboratory. Japan's minister of education at the time, Mori Arinori, intended these efforts to serve purely utilitarian goals, having little regard for people whose pursuit of knowledge was not useful to action.

[xii] Among the Germans who moved to Britain, consider the experience of August Wilhelm Hofmann, one of Liebig's students at Giessen. The founders of the Royal College of Chemistry failed to lure Liebig himself to a professorship in organic chemistry. Liebig recommended that the professorship be offered to Hofmann, whose research activities at the College proved valuable for the British dye industry until 1865, when he returned to Germany to head a new laboratory at the University of Berlin. There, he took an active role in establishing ongoing collaborations with German chemical firms and acted as lead consultant to AGFA (Murmann, 2003).

[xiii] Berlin's experimental station only began to be used for instructional purposes in 1892.

[xiv] Both Schlesinger and Wallichs were students of Alois Riedler. The former had considerable industry experience at the time of his appointment at the Technische Hochschule in Berlin, having been at the head of the design engineering department of Ludwig Loewe, one of the most innovative machine tool firms in Berlin.

[xv] The Haber-Bosch process technology was licensed by the Research Institute for Nitrogen Fixation (created in 1918), which later sold its rights to an association of chemical firms (Mikami, 1979).

[xvi] Amsden (1989)'s account of capability building at the Korean steel maker POSCO presents similar features.

[xvii] Amsden and Chu (2003) report that by 2000 more than 15,000 professionals had worked for ITRI, and 12,000 had gone on to hold positions in the high-tech sectors of the Taiwanese economy. Accordingly, a considerable fraction of the start up electronics firms that over time were formed in Taiwan Province of China featured ERSO-trained people within their staff.

[xviii] Similar initiative was taken later on in Korea.

[xix] Needless to say, these activities are usually not independent from one another in practice, nor are they as distinct conceptually. Particularly in the context of a developing economy, much of the work involved under the second heading is likely to have very minimal research content at first and focus instead on the dissemination of knowledge to economic actors. In this sense, universities and public research institutes constitute repositories of knowledge that is disseminated to third parties according to different modalities.

[xx] The same can be said for universities and engineering schools to the extent that engineering professors were often recruited from industry, that it became common for academic staff to consult with business firms and to spend training periods in industry.

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The graph on the cover, generated by means of fractal geometry model, simulates a pattern formed by three ring vortices playing catch up with one another (also called 'chaotic leapfrogging').

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