Available online at www.sciencedirect.com
ScienceDirect
Research Policy 36 (2007) 1512–1528
research policy
www.elsevier.com/locate/respol

Public research institutions and economic catch-up

Roberto Mazzoleni [a,*], Richard R. Nelson [b]

[a] Department of Economics and Geography, Hofstra University, Hempstead, NY 11549, United States
[b] The Earth Institute, Columbia University, New York, NY 10025, United States

Received 23 October 2006; received in revised form 1 June 2007; accepted 18 June 2007
Available online 27 August 2007

Abstract

Public research institutions, often but not always connected with universities, have been in the past important elements of the structures supporting economic catch-up. Recent changes in the international economic environment, and the growing scientific basis for contemporary technologies, will make those institutions even more important in the future. Universities and public labs have contributed to the development of technological capabilities in different forms across countries and economic sectors. In contrast with current emphasis on university-based embryonic inventions and fundamental research, effective research programs have predominantly occurred in the application-oriented sciences and engineering, and have been oriented towards problem-solving, and the advancement of technologies of interest to a well-defined user-community.
© 2007 Elsevier B.V. All rights reserved.

Keywords: Catch-up; Public research; Indigenous technological capabilities

1. Introduction

An essential part of the economic development process of countries behind the technological and economic frontiers involves learning about and mastering ways of doing things that are in use in the leading countries of the era, that is "catching up." By catching up we do not mean simply copying. Practices in advanced economies do usually provide a model, but what catching up countries achieve inevitably differs in various and important ways from the existing templates. Partly this reflects the limits to the imitability of complex patterns of economic activity. Partly it is the result of deliberate efforts to modify and tailor technologies and practices to national conditions.

Universities and public research organizations are key institutions supporting this process of catching up. Our focus in this paper is on the role these institutions have played in countries that have in the past successfully caught up with the leaders in industrial technology and practice, and the roles these institutions will be called upon to play in countries still in the process of catching up.

Much of the orientation of this paper will be towards the role of public research institutions in enabling developing countries to learn about and come to master the kind of know-how possessed by engineers, and physical and biological scientists, and often embodied in physical things like machines, and specialized materials of various sorts. However, in virtually all fields of human practice, effective performance requires more than the acquisition of technological capabilities in a narrow sense of that term, what we might call "physical" technologies. Nelson and Sampat (2001) have proposed that it may be useful to think of effective performance as

* Corresponding author. Tel.: +1 516 4635593; fax: +1 516 4636519.
E-mail address: roberto.mazzoleni@hofstra.edu (R. Mazzoleni).

0048-7333/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.respol.2007.06.007

depending on the mastery of relevant "social" technologies, as well as the "physical" technologies involved. Social technologies are embodied in organizational forms, bodies of law, public policies, codes of good business and administrative practice, customs, norms. Our use of the term "institutions" refers broadly to structures embodying or molding social technologies.

Thus, complex production processes generally involve large teams of workers, with a division of labor, and a management and control system to generate effective coordination. Modern firms also need to have in place a system for hiring, rewarding, and occasionally releasing labor, and the capability to make the investments needed for effective operation and adjustment to changes in market opportunities and challenges. To operate effectively they must be supported by a system of education and training that gives them access to a labor supply with the needed skills, and a system of banks and other financial institutions that meets their financial needs. All of these involve ways of doing things – practices – but technology in a narrow sense is not at their core.

The public research institutions that are the focus of this paper are structures supporting important social technologies. Our argument is that the development of firm and country level capabilities in modern physical technologies today depends to a large extent on an effective system of public research and higher education. These have become an increasingly important part of the institutional structure needed for catch-up. We will develop this argument, and some of its implications, in the rest of the paper.

2. Common features of past experiences of successful catch-up

Differences across countries in the level of economic development were a central interest of Adam Smith, but these issues were not high on the intellectual agenda of later classical economists of the Anglo-American tradition. During the first half of the 20th Century first neoclassical economics, and later Keynesian economics, dominated the agenda, leaving little room for analysis of economic development.

Economic development came back into its own as a topic studied by economists after World War II. The range of approaches in the field was quite varied, but neoclassical growth theory provided the dominant point of view. Under that theory, investments in physical and human capital were the key to economic development. Achieving mastery of the technologies and other practices of advanced industrial nations was assumed to be an almost automatic byproduct of high investment rates, and a properly operating market system. The actual processes involved in catching up were little discussed.

Gerschenkron's famous work (1951), "Economic Development in Historical Perspective" is an exception. There he explicitly described the development problems of continental Europe during the second half of the 19th Century as that of catching up. Abramowitz' influential article (1986), "Catching up, Forging Ahead", and Falling Behind" has made the concept of catch-up part of the standard vocabulary of development economists, and stimulated a number of empirical studies that have probed in detail the key processes involved (see, for example, Hobday, 1995; Kim, 1997, 1999; Kim and Nelson, 2000). As a result of this work, and more general studies of economic history, it is clear that in the past successful cases of catch-up have displayed three common features.

First, all successful cases of accumulation of technological capabilities have relied extensively on cross-border flows of people. These flows reflected a combination of citizens from the then backward country going abroad to learn and then returning, and of citizens from the advanced countries establishing themselves or simply visiting in the developing countries as advisors, professors, or as technical personnel for local and foreign firms. Thus, British technicians played a central role in the diffusion of knowledge about their home country's manufacturing techniques when they migrated to the United States or continental Europe during the late 18th and early 19th Centuries (Landes, 1969; Pollard, 1981; Rosenberg, 1970). The recruitment of foreign technical advisors and the training of Japanese nationals abroad contributed greatly to the development of Japanese industry in the late 19th and early 20th Century (Odagiri and Goto, 1996). More recently, the progress of Korean and Taiwanese electronics industries was fundamentally helped by similar mechanisms of knowledge transfer, and the same is true in a range of other industries for China and India.

There is a common thread among these national experiences. However, we note that whereas early on the cross-border flows of people were the result of individuals' search for economic and professional opportunities abroad, more recently various types of organizations have created the setting for such movements. Business enterprises have become an increasingly important conduit.[1] But here we want to highlight that over the last

[1] During the 20th Century companies came to play an increasing role in this cross-national learning and teaching process. The new

quarter century an important part of the transnational flow of people in the catch-up process has involved university study abroad in the relevant fields of engineering and applied science. This has not only been a central mechanism for the training of new faculty for emerging indigenous universities, but also for indigenous firms to acquire access to advanced knowledge and skills in the relevant fields of science and engineering.

The perceived importance of this aspect of the cross-border flows of people lies behind the recent broadening of the focus of related policy debates from a discussion of the costs of a brain drain to the opportunities offered by the process of brain circulation. We believe that university-mediated transnational conduits of learning will be of particularly great importance during the 21st Century for countries seeking to catch-up. This certainly will be so regarding public health and medical care, as well as regarding manufacturing technology.

A second common feature of successful catch-up experiences of the 19th and 20th Centuries is the active government support of industrial development, involving various forms of protection, and direct and indirect subsidy. The guiding policy argument has been the need for some protection of domestic industry from advanced firms in the leading nations, at least in the industries of the day judged critical in the development process. This was in essence the argument put forth by Hamilton (1791) with respect to the United States, and decades later by List (1841), as he argued about Germany's development needs. It is a key part of Gerschenkron's (1951) essay advocating a catch-up perspective on economic development. And the successful catch-up experiences of Japan, Korea, and Taiwan, represent further instances of the key role of active government support to industrial development. While it is important to note that support policies in many countries engendered the growth of inefficient home industries, they were the hallmark of all the countries that have achieved their goals of catching up during the 20th Century.

Hostility to these policies among business firms and governments in the leading countries has been growing, particularly when the result of these forms of government support has been the creation of dangerous competitors in the international markets. It should be remembered that the case for free trade right after World War II was mostly concerned with eliminating trade barriers among the rich countries, while recognizing the potential usefulness of some protection for infant industries in developing countries. However, the international treaties that have been made since then have been opposed increasingly to import protection and subsidy in countries seeking to catch-up from far behind. If, as we believe, Hamilton and List were right that successful catch-up in industries where international trade is considerable requires some kind of support for infant industries, the challenge is to find effective means under the new conditions.

The third feature of successful catch-up experiences is that the countries involved operated with intellectual property rights regimes that did not restrict seriously the ability of their companies to in effect replicate technologies developed and used in the advanced countries. Even when licensing agreements were involved, these were for the most part vehicles through which the right to imitate or technology transfer was effected for a fee or other considerations, rather than instances of aggressive protection of intellectual property by the company in the advanced country.

Even with respect to this feature, conflicts over the degree of protection of intellectual property rights in developing countries emerged late in international trade negotiations, largely when catching up companies began to export to world markets, and especially to the home market of the companies holding patent rights on the relevant technologies. Increasing instances of this clearly were a major factor in inducing the treaty on Trade-Related Aspects of Intellectual Property Rights. But this treaty makes vulnerable to prosecution not just companies in developing countries that are exporting, but also companies that stay in their home markets.

The creation and enforcement of intellectual property rights across the developing world by companies from high-income countries has serious consequences in a wide range of domains, from agricultural development, to the workings of public health systems in developing countries, as well as manufacturing development. Many of the key technologies in these domains of economic activity are routinely the subject of intellectual property rights. Patented seed varieties play a crucial role in modern agriculture, and the use of patents is pervasive in a broad range of pharmaceuticals and biomedical technologies that represent key elements in the strategies designed to address various diseases that devastate poor countries. While conflict in the arena of intellectual property rights policy is likely to continue in the immediate

Japanese automobile and electrical equipment companies established close interactions with companies in the United States and Europe that served as their mentors. The development of Singapore was largely driven through the establishment branch operations by Western multinationals. Hobday (1995) has documented in detail how Korean and Taiwanese companies developed increasing competence working for American and Japanese electronics companies as Original Equipment Manufacturers.

future, at present developing countries need to learn to cope with this new problem.

3. Changing conditions and the increasing relevance of indigenous technological and scientific capabilities

We argue in this section that the acquisition of indigenous technological and scientific capabilities have become, and will continue to become, of ever greater importance for countries attempting to successfully catch-up with respect to key technologies. A number of changing conditions motivate our assertion, partly related to changes in the international economic relations and partly related to contemporary technologies' growing connections with scientific knowledge. As a result of these trends, we argue that the development of a public research infrastructure ought to be a central goal of policy, calling for a careful appreciation of its role in the context of a developing country's national system of innovation.

Two of the most important changes in the conditions for contemporary catch-up efforts have been flagged in the previous section. In a nutshell, recent international treaties, particularly the creation of the WTO and the TRIPS agreement included in the WTO treaty, have altered the context relevant to two of the common features of past experiences of catch-up we identified above. Developing countries today face significant limits in their ability to restrict foreign firms' access to domestic markets, and to protect or subsidize domestic firms. Support policies aimed at fostering indigenous industrial development will have to be subtler, and focus on supporting the development of sectoral infrastructures, training and research systems. To the extent that firms in advanced economies will choose to pursue and enforce their intellectual property rights in developing countries, firms and governments in the latter will have to develop strategies for access to technologies on reasonable terms different from outright imitation.

These restrictions on the policy space available to developing country governments have taken root (not coincidentally) at the same time that other trends have pushed or enabled business and finance to operate on a more global frame. Although foreign direct investment has played a significant role in the catch-up processes of some successful countries, its role is almost certain to become increasingly important. International alliances and partnerships have been proliferating, and will continue to provide important vehicles for firms in developing countries to access advanced know-how. Thus, while the space for government policies has been restricted, various aspects of the process of globalization have created new kinds of opportunities for firms in developing countries.[2]

Globalization has of course not been confined to the activities of business enterprises. Scientific and technical communities in different countries are also more connected now than they used to be.[3] This has come about at the same time that there have been major increases in the power of many fields of applications-oriented science, dedicated to achieving understanding of the principles that are operative in an area of practice, so as to provide a base for rigorous training of new professionals who will work in that field, and a scientific basis for efforts to move the technology forward. Included here are such older fields as chemical and electrical engineering, and modern fields such as computer science, biotechnology, and immunology. In recent years these fields of science have become increasingly open to those who have the training and connections to get into the relevant networks.

We believe that the trends highlighted above have profound implications for catch-up. Advanced training in the field has become a prerequisite for ability to understand and control those technologies with strong scientific underpinnings. Vice versa, these goals are much harder to attain on the basis of working experience only. In fact, a strong science base significantly reduces the importance of operating apprenticeship abroad, or tutelage by foreign industrial experts. While advanced formal training in a field will not suffice for mastery of specific technologies, it will often provide a substantial basis for learning by doing. Further, having a domestic base of good scientists provides the basis for breaking into the international networks where new technologies are being hatched.

Countries seeking to catch-up are confronted today with a more pressing need than used to be the case to develop indigenous technological capabilities.[4] While

[2] A glaring instance of these trends is offered by the evolution of the Indian pharmaceutical industry. We note though that the successful effort by leading Indian firms to enter foreign markets and to engage in various forms of collaboration with advanced economies' pharmaceutical companies resulted from a process of capability building that took place in a context marked by the conditions we identified in Section 2 of the paper.

[3] For example, the share of U.S. science and engineering articles that were the result of international collaborations increased from 10% to 23% over the years from 1988 to 2001 (National Science Board, 2004, pp. 5–47). Similar trends have been observed in the other countries.

[4] Empirical evidence and analysis consistent with this proposition are presented in Fagerberg and Godinho (2004) and Bernardes and Albuquerque (2003).

studying abroad can provide at least a temporary solution to the need for acquiring advanced knowledge in relevant fields (as it has often been the case in the past), educational and research activities at domestic universities and public laboratories will play a crucial role. The historical evidence that we will review in the next section suggests the importance of reflecting on the operation of these institutions within a broader National Innovation System.[5] Doing so calls attention to the fact that the process of catch-up involves innovation in an essential way.

The innovating that drives the process differs from the innovating that has been the central focus of research on technological advance in advanced economies. The new technologies, practices more generally, that are being taken on board, while new to the country catching up, generally are well established in countries at the frontier. And much of the innovation that is required is organizational and institutional. But what is going on in catch-up most certainly is innovation in the sense that there is a break from past familiar practice, considerable uncertainty about how to make the new practice work effectively, a need for sophisticated learning by doing and using, and a high risk of failure, as well as a major potential payoff from success. These aspects of catch-up tend to be denied or repressed in the standard economic development literature.

The National Innovation System concept focuses attention on the range of institutions that are involved in the process of innovation. While business firms play an undeniably crucial role, it is a flawed conception of innovation that which neglects other kinds of institutions involved in the processes that support and mold innovation in many modern industries. Among these, indigenous universities and public laboratories hold a special place.

As we will argue in the next section, they have been an important vehicle through which the technologies and organizational forms of the advanced countries have come to be mastered in the developing ones, partially as an organizing structure for and partially a substitute for international people flows. And while often overlooked, indigenous research at universities and other public institutions long has been an important element of catch-up in fields, such as agriculture and medicine, for which knowledge originating from abroad was ill suited to national needs. An important part of the reason for this is that in these fields developing countries often could not simply copy technology and practice in countries at the frontier, but needed to develop technologies suited to their own conditions. Soil and climate conditions tended to be different. The prevalent diseases were different. There is every reason to believe that the importance of having the capability to do effective research and development in these fields will be even greater in the future.

In contrast, while manufacturing technologies used in advanced countries may not have been optimal, at least they worked in the new setting with often modest modification, and they generally were available at no great expense. The experience of countries that have successfully caught up in manufacturing over the past half-century testifies to the importance of a nation's education system in providing a supply of trained engineers and applied scientists to manufacturing firms catching up. And an important part of the catch-up process has involved firms learning to do R&D on their own. However, while there are exceptions (electronics in Taiwan and Korea and aircraft in Brazil are examples), for the most part research per se in universities and national labs has not in the past played an important role in catch-up in manufacturing, beyond its role in the training function.

But this might not be the case under the new circumstances. In the new regime of stronger global protection of intellectual property, countries trying to catch-up will find it increasingly important to develop their capabilities to revise and tailor manufacturing technologies relatively early in the game. First of all, this can help companies to develop and employ technologies that avoid both direct infringement of intellectual property that is likely to be enforced aggressively and the need to compete for access to foreign technology through licensing arrangements. Second, over the longer run the development of an intellectual property rights portfolio by firms in developing countries can provide bargaining weight in the complex cross-licensing arrangements that mark many manufacturing industries.

More generally, achieving competence in many areas of manufacturing requires staying up with a moving target. Further, as the frontier is approached, the lines between sophisticated imitation and creative design of new products and processes becomes blurry. A strong R&D capability becomes essential. To a considerable

[5] Freeman (1995) has proposed that List had something like a National Innovation System in mind when, in the mid 19th Century, he was writing about what Germany needed to do to catch-up with Great Britain. While, the modern conception of a National Innovation System was developed to be useful in thinking about the key institutions involved in technological advance in countries at or close to the frontier (see, e.g. Nelson, 1993) recent research has reoriented the concept to provide guidance to countries significantly behind the frontier and striving to catch-up (see among others, Albuquerque, 2003; Kim, 1997, 1999; Viotti, 2002, 2003).

extent the R&D needs to go on in firms. However, research in universities and public laboratories can play a strong supporting role, and one that is likely to take on different connotations at different stages of the process of catching up.

4. The role of universities and public labs in earlier experiences of catch-up

The role played by indigenous universities and public labs in earlier experiences of catch-up has not been studied systematically, to our knowledge. But a scattered collection of individual cases, described at different levels of detail, is available that will be the basis for our review in this section. In order to bring some coherence to the present discussion, we will focus here on what is known about the roles of indigenous public research institutions in the successful catch-up experiences of Japan, in the late 19th and early 20th Century, and Korea and Taiwan later in the last century, supplemented by some instances from the Brazilian experience. Our particular interest is catch-up in industrial technology and practice, and here the studies on which we can draw are very piecemeal. There has been more systematic study of the role of indigenous public research in agricultural development in these countries, and while our focus is not there, we begin this section by summarizing briefly some research on this topic by agricultural economists.

4.1. Agricultural development

Very shortly after it came to power in 1868, the new Meiji government, which was committed to the rapid modernization of the Japanese economy, started efforts to improve Japanese agriculture. These efforts included both the establishment of agricultural experimentation stations, and agricultural colleges. At the beginnings of the efforts at agricultural modernization, Japanese experts and politicians had in mind the mechanized agriculture of the United States and (parts of) Great Britain as a model. However, as Hayami and Ruttan (1985) note, the very small size of the typical Japanese farm, more generally the very high ratio of farmers and agricultural workers to usable land, made American technology completely inappropriate for most of Japanese agriculture. As attempts at transplant made this fact evident, the orientation of the modernization efforts shifted.

It is interesting that the new orientation was largely toward identifying existing practices of Japanese farmers that were particularly effective. The new agricultural experimentation stations played a major role in this comparative analysis of practice, and in spreading the news regarding best practice to farmers. Teaching at the agricultural colleges became focused on best practice. Under this new regime, a considerable portion of the experimentation that identified better practice was actually conducted by individual Japanese farmers. However, the agricultural experimentation stations also were an important locus of experimentation, and for providing reliable information on the efficacy of different practices to farmers.

Hayami and Ruttan (1985) note that much of what was going on at the experimentation stations during this period involved refining, as well as testing, farmer innovations. During this period, the experimentation station system increasingly established local branches, which was particularly important because the efficacy of practice often was quite vocation specific.

During the 1880s and 1890s, there was increasing recognition in Japanese agricultural circles that, given the low ratio of land to people, improving the productivity of best practice Japanese agriculture largely meant increasing yields per unit of land, as contrasted with output per worker, as in the United States, and that there was a high premium on the discovery or creation of seeds and methods which effectively could employ high levels of fertilizer. The Japanese agricultural experimentation stations played a major and effective role in moving Japanese agriculture in this direction. Hayami and Ruttan (1985) propose that "the history of seed improvement in Japan is a history of developing varieties that were increasingly more fertilizer-responsive." The efforts at agricultural experimentation stations involved both systematic selection of existing seed lines, and increasingly the development of new seed lines through hybridization. Again, much of this work necessarily went on at a quite local basis.

Turning to the cases of Taiwan and Korea, it is interesting to note that the agricultural experimentation systems in these countries were begun during the 1920s and 1930s, under Japanese occupation. In both cases, the principal motive of the Japanese was to improve productivity of rice farming in these colonies, in the face of rapid growth in the demand for rice in increasingly affluent Japan, and diminishing returns to further applications of fertilizer that were occurring in Japanese agriculture, despite the largely successful research efforts just mentioned. In both Taiwan and Korea, the thrust of the efforts at the new experimentation stations involved crossbreeding of indigenous rice varieties, with fertilizer-responsive Japanese seed variety. And in both cases the result was significant increases in yields per acre.

In Brazil, the growth of agricultural production since the 1950s had slowly been shifting from a base in the expansion of cultivated land to one driven by increased yields.[6] Both processes, however, reflected the consequences of a considerable public effort at promoting research on new crops and new cultivars of old crops adapted to local soil and weather conditions. Strong public research programs had long been particularly active in the southern states, focusing on individual crops like coffee, cotton, cocoa, and later on, soybean (Ayer and Schuh, 1972; Dean, 1989), as exemplified by the activities of the Instituto Agronomico de Campinas. Established in 1887, this was the earliest agricultural research center in all of Latin America. The expansion of cultivated land in the interior states of Mato Grosso, Mato Grosso do Sul, and Goias, resulted from successful public research programs aimed at developing cultivars suitable for cultivation in the soils of these states' *cerrado*[7] (Pardey et al., 2004).

These programs were supported by a developing national infrastructure of agricultural research and extension services, that was brought under the coordinative umbrella of the National Department of Agricultural Research since 1938. This infrastructure became the operational basis for the restructuring of federal agricultural research that marked the birth of EMBRAPA in 1972 as a public sector corporation. EMBRAPA's coordination of R&D activities in the field of agriculture has been carried out through a network of institutions, including universities, private enterprises, and a number of national, regional, and state level research institutes. A great deal of the research carried out at regional or state centers focuses on local production systems and aims at adapting to local conditions the result of research conducted at national centers (Dahlman and Frischtak, 1993). It should be noted on the other hand that EMBRAPA is an important node in the linkages between the Brazilian system of agricultural innovation and foreign research centers, with whom it engages in cooperative research activities.

There are several things that we think noteworthy about these countries' quite successful experiences. First, important components of the public research were not particularly "high science."[8] Rather, it was pragmatically oriented and highly sensitive to the needs of the users, in this case the farming community. Second, and related, the public research operations had effective mechanisms for two-way communication with the farming community. They most emphatically did not operate as "ivory towers." Third, an important part of the effort involved tailoring technologies to local conditions. While this latter requirement is somewhat less important regarding industrial technology, we will argue that the importance of close, two-way interaction with potential users is just as important for making public research concerned with advancing technology as it is for agricultural research.

4.2. Industrial development

Universities and public research laboratories also appear to have been important institutional aspects of catch-up in at least a few industrial sectors in these countries. As mentioned above, knowledge of this phenomenon is far from systematic but presently scattered among various case studies. Again we want to sketch an outline of the emerging linkages between these institutions and industrial development in a few countries that have begun to catch-up with advanced economies since the late 19th Century.

After the Meiji restoration in 1868, absorbing Western scientific and technological knowledge became a key component of Japan's industrial development strategy. To this end, numerous delegations of Japanese were sent to study at foreign industrial firms, universities, and other educational institutions. Foreign professionals were recruited as consultants and specialized technical personnel for many industrial development projects. Foreigners played also an important role in staffing and organizing newly established academic institutions.

Early on, such institutions focused on the training of Japanese scientists and engineers, and research played a minimal role. It is important to recognize, however, that in order to perform the training function, the faculty had to themselves be quite versed in the technologies they were teaching about. Partly this was achieved through

[6] Graham et al. (1987) argue on the basis of data on agricultural output growth during the 1950–1980 period, that with the exceptions of coffee and cocoa "production increases over this period came largely through area expansion rather than through increases in yields" (p. 7).

[7] The *cerrado* is the Brazilian savanna, an eco-system that characterizes almost the entirety of Brazil's central plateau. Soil and weather conditions required extensive research focused on the development of suitable cultivars.

[8] We should note that this statement applies to agricultural research activities in both developed and developing countries. It does not imply that such activities were carried out to the exclusion of more fundamental scientific research, particularly in academic institutions. For a discussion related to Latin American context (see Velho and Velho, 1997).

bringing foreign professors to Japan.[9] But over time native Japanese came to make up the faculty at the Japanese universities, achieving their own training in the early days through study abroad, but then increasingly in the developing indigenous programs. And the technologically sophisticated faculty at the Japanese universities were involved in consulting, as well as teaching. Through both of these roles, the universities played key roles in the processes through which Japanese industry began to master western technologies, even though in the early days they did little research.

Government support of academic research increased after the reorganization carried out in 1886 that led to the establishment of the Imperial University of Tokyo. New research facilities were completed as the government strived to turn the Imperial University into a modern research university comparable to its counterparts in Western Europe or the U.S. While most graduates from the Imperial University (about two thirds in the 1890s) were still recruited to public service positions (Amano, 1979), many of the pioneers in industries like electrical equipment, chemicals, or iron and steel, received their training in the relevant fields of science and engineering at Japanese universities, often complemented by study and research abroad (Uchida, 1980; Yonekura, 1994). Professors too, contributed directly or indirectly to the development of new technologies, and the adaptation of existing ones (Odagiri, 1999), and more generally acted as technical consultants for private business enterprises. This practice became increasingly important when the outbreak of the First World War restricted further the Japanese companies' access to foreign technology.[10]

Likewise, public support for research aimed at industrial development increased during the early 20th Century in response to a variety of factors, including the 1899 reform of the patent law admitting foreign patent applicants and the growth of the government's industrial and military needs. The government financed the creation of research and testing laboratories either directly or through public enterprises. Already in 1900 an Industrial Experiment Laboratory was established to conduct testing and analyses on a contract basis for national firms, consisting of two divisions in industrial chemistry and chemical analysis staffed by 11 members. The Laboratory was expanded in 1906, in the aftermath of the Russo-Japanese war, and then again in 1911. This institution played an important role in developing techniques and processes that were adopted by chemical firms, including for example the synthesis of alizarin (a synthetic dyestuff), and techniques for the production of phosphorus and alkali (Uchida, 1980, pp. 164–166). In the late 1920s, the Industrial Experiment Laboratory provided Showa Fertilizer Co. with an adaptation of the Haber–Bosch process for the production of synthetic ammonia (Mikami, 1980). Other specialized public and private laboratories came into existence after World War I thanks to public and private funding (Hashimoto, 1999).[11] The research conducted at these laboratories led often times to the development of new technologies, patented both in Japan and abroad, frequently providing the basis for new products and processes adopted by business enterprises.

The government support to the development of technological capabilities took different forms depending on the characteristics of the industrial technologies of interest. In the iron and steel industry, for example, the government promoted the accumulation of technological capabilities by financing and organizing a large public enterprise, the Yawata Works, that became a center of technological learning for the whole Japanese industry. However, even before this firm established its own formal R&D program in 1916, the government supported the creation of the Iron and Steel Institute of Japan in 1915. This institute represented an industrial research center whose membership included representatives of private and public enterprises (both producers and users of iron and steel), as well as of higher education institutions. It diffused technological information among its members through publications, seminars, and the work

[9] For example, the Imperial College of Engineering was founded in 1873 with a faculty of eight British professors. This College adopted a 4-year curriculum modeled after that of ETH in Zurich. The degree program included 3 years of practical experience that students could acquire at laboratory facilities of the university or later on at an industrial laboratory operated by the Ministry of Industries (Bartholomew, 1989; Odagiri and Goto, 1993).

[10] Indeed, while industry need for technological capabilities provided a key rationale for government policies aimed at expanding academic enrollments in fields like applied chemistry, metallurgy, mining engineering, dissenting voices criticized the heavy load of consulting work performed by university professors for its negative effects on the quality of academic research and instruction (Bartholomew, 1989, pp. 228–230).

[11] Among the private laboratories, the Research Institute for Physics and Chemistry (Riken) was established in 1917 with the government's financial support. Riken was patterned after the German Physicalische Technische Reichsanstalt established in 1887, and its research mission encompassed both basic research in the fields of chemistry and physics and applied research aimed at industrial technology. This 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).

of its Cooperative Research Divisions launched in 1926 as a mechanism for organizing collaborative research.[12]

A number of features of the Japanese catch-up experience during the late 19th and early 20th Century can be found in the experience of the two countries whose economic performance during the post World War II years has been most remarkable, Korea and Taiwan. In both countries, the catch-up experience was marked by major investments in higher education, particularly the training of engineers. However, the growth of the educated labor force during the early stages of catch-up in both Korea and Taiwan outstripped the economy's ability to create jobs for graduates of the national universities, so that a phenomenon of unemployment or under employment began to surface and an outflow of college graduates from the countries. On the other hand, despite significant government support, academic institutions public and private struggled to satisfy the growing demand for higher education with high quality degree programs. As a result, the share of students studying abroad both at the college level and the graduate level increased considerably, contributing further to a general phenomenon of brain drain.

In Korea, early phases of development focused on the acquisition of technological capabilities in mature labor-intensive industries where skill requirements could be met through vocational education or on the job training. Thus, even if the Park government succeeded during the 1960s to increase enrollments in academic science and engineering programs, a matching demand for skilled labor only began to emerge a decade later. Moreover, the educational programs in science and engineering at Korean universities during the 1960s were insufficiently plugged into the realities and needs of industrial development. Rote learning and theoretical knowledge were emphasized in undergraduate and graduate programs that appeared to be geared to preparing students for admission to foreign universities and careers in academia. As a result, an estimated 2000 Korean science and engineering graduates were living abroad in 1968 (Kim and Leslie, 1998, p. 168). Similar problems plagued the expansion of the higher education sector in Taiwan. In an effort to meet both growing skill demands in industry and the public's aspiration for higher education, the government created a university level technical program that offered the prospect of an academic degree to students graduating from vocational high schools. But efforts at stemming the outflow of Taiwanese scientists and engineers met at first with limited success.

In hindsight, the repatriation of Koreans and Taiwanese with several years of education and professional research and training outside their home countries has been credited as providing the base of human capital that made it possible for national firms to develop in a short time adequate technological capabilities in a variety of industrial sectors. While the reverse brain drain that occurred over the last quarter century was driven by the growing demand for scientific and technological talent of private sector firms, early efforts to promote the return home of scientists and engineers were associated with the creation of public research organizations and academic institutions. Already in the late 1960s, awareness of the brain drain problem was an important factor behind the design of public policies whose primary goal was to foster the development of indigenous technological capabilities, and thus to reduce the dependence of national companies on foreign technology.

Consider the origins of the Korea Institute of Science and Technology (KIST). Its establishment in 1966 was the result of several years of negotiations between the Korean and the U.S. governments, during which plans were laid out for creating an organization charged with carrying out contract research for industry and government, along the lines of the Battelle Institute in the U.S. The contractual basis for the institute's activities was intended to ensure that the scientific objectives of its research be kept close to industrial development needs. Indeed, it was expected that after an initial period of government support, the laboratories would be able to finance their own activities through industry contracts. KIST's initial Staff was recruited among the ranks of Korean expatriate scientists and engineers. Thirty-two were appointed and trained in the operations of a contract research outfit at Battelle, which served as KIST's sister institution for the first few years of operation. Surveys and interviews of Korean firms were conducted ahead of the institute's establishment in order to identify the crucial technology areas. KIST was then organized in 31 independently managed laboratories focused on five broad technical areas (food technology, mechanical and chemical engineering, materials science, and electronics). KIST became centrally involved in research projects aimed at various industries, including shipbuilding, steel, chemicals, and industrial machinery (Kim and Leslie, 1998).

While KIST was responsible for the development of several patented technologies and able to generate royalty income from some of them (Lee et al., 1991), its contributions to the development of indigenous

[12] Yonekura (1994) argues that the activities of the institute, and of its research divisions, consisted mostly of the dissemination of the results of technological research carried out at Yawata Works.

capabilities consisted more often of collaborations in technology transfer projects with local and foreign firms, as well as of reverse engineering projects. Together with a rapidly growing array of other public research institutes, KIST played arguably an important role in training personnel for industrial research and in demonstrating the importance of R&D activities to private corporations.

In doing so, KIST together with other public research institutions and, later on, private enterprises strengthened the demand for scientific and engineering talent. Around the early 1970s, the graduates of the Korean universities did not adequately meet this demand for the reasons highlighted earlier. Such weakness prompted a U.S. based Korean scientist, Chung KunMo, to submit a proposal (supported by the Korean Ministry of Science and Technology) to the U.S. Agency for International Development for the creation of a specialized institution offering graduate level education in science and engineering focused on the emerging needs of industrial development. Upon recommendation of a committee headed by Frederick Terman (earlier president of Stanford University), USAID loaned the funds for creating the Korea Advanced Institute of Science (KAIS). The scope of KAIS's educational programs was narrow and focused on the needs of industrial firms like Samsung, Goldstar, and local affiliates of foreign companies, as they had been articulated in a series of interviews conducted by the Terman committee.

The establishment of KAIS created another inducement for Korean scientists and engineers living abroad to return to their home country. It has to be noted though that the research performed by KAIS's faculty was rather applied in nature, and closely related to the research projects undertaken by government research institutes like KIST. Indeed, the similarity in the orientation of training and research projects at these two institutions promoted their merger into the Korea Advanced Institute of Science and Technology (KAIST) in 1982.

An important area of research and instruction was the field of electronics, particularly semiconductor technology. During the 1960s, the growth of the Korean semiconductor industry was largely fueled by foreign direct investment focusing on old technologies and stages of the production process with high labor content. Indigenous research on semiconductors design and fabrication began in 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 a research department at KIST to create the Korea Institute of Electronics Technology (KIET), which carried out a number of projects aimed at the development of ICs for applications in consumer electronics and telecommunications. All of these projects featured the participation of the leading electronics firms, including Goldstar, Samsung, Daewoo, and Hyunday, whose evolving business interests and technological needs were probably also responsible for the reorganization of public research institutes that established the Electronics and Telecommunications Research Institute (ETRI) in 1985.[13]

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. These changes in the organization of public research infrastructure and research portfolio ought to be interpreted as an adaptation to the growth in the R&D investment carried out by private sector firms. Indeed, while the government accounted for more than 80% of national R&D funding in 1967 when KIST began operating, the private sector's share of national R&D surpassed 50% already in 1977 and exceeded 80% in 1988. But while these data suggest that Korea's effective move into high tech industry awaited the development of in-house R&D programs by Korea's large firms (chaebols), it would be misguided to neglect the role played by public research programs in promoting the development of indigenous technological capabilities and in bringing back from abroad a number of very talented researchers, and providing them with research experience.

The Taiwanese catching up experience during the past 50 years has been also characterized by the rapid growth of enrollments in higher education institutions. Since Taiwan's liberation from Japanese colonial rule, the Taiwanese government committed substantial public resources to education (as a fraction of GNP, education expenditure went from 1.73% of GNP in 1950 to 5.83% in 1985). The growth of the university system in Taiwan was remarkable by any indicator. Between 1950 and 1986, the number of higher education institutions went from 7 to 105, the number of enrolled students from about 6600 to 440,000, and the number of teaching faculty from 1000 to almost 22,000 (Hsieh, 1989). Gov-

[13] The significance of these projects for the chaebols' accumulation of capabilities in semiconductor technology has been evaluated differently by different scholars. Wade (1990a,b) argues that these research collaborations provided the chaebols with technological capabilities that, coupled with other forms of industry support by the government, enabled them 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.

ernment efforts promoted student enrollment in science and engineering programs, so that these fields accounted for about half of all students in the late 1980s (64% of Master level students and 48% of doctoral students).

A considerable number of Taiwanese students migrated to foreign higher education institutions. In 1962, about 20% of all Taiwanese university-enrolled students were abroad, with the U.S. universities accounting for half of them. The migration of students was particularly strong in the natural sciences: in 1966 one third of the students were pursuing their degrees in U.S. institutions (UNESCO, 1972). Even at the end of the 1970s, the share of non-returning students among those who went abroad to pursue postgraduate studies was greater than 20% in the natural sciences and engineering (Hou and Gee, 1993). But, much like we saw in Korea, the large numbers of foreign-trained Taiwanese proved instrumental to the later development of higher education institutions in the country and to staffing the emerging R&D institutes and laboratories in the public and private sector.[14]

Public research institutions played in Taiwan an even more important role than in Korea. Consider that as late as 1987, the private sector's share of national R&D funding was 80% in Korea but only 40% in Taiwan. Public investment in science and technology became an important aspect of Taiwan's industrial development policy since the late 1960s and promoted the creation of a number of research institutes during the following decade, including the Institute for the Information Industry (III) and the Industrial Technology Research Institute (ITRI). The latter was formally organized in 1973 with the consolidation of three existing public research laboratories (Union Industrial Research Laboratories, Mining Research & Service Organization, and Metal Industrial Research Institute).

ITRI soon included a new laboratory dedicated to research in electronics and semiconductors technology, the Electronics Industrial Research Center (later renamed Electronics Research and Services Organization, ERSO). ERSO became a key national institution for inward technology transfer, and for the accumulation of indigenous capabilities in industrial research. The typical *modus operandi* of ERSO's technical projects involved licensing a technology from foreign firms, creating a pilot plant to master the technology and provide training for local personnel. At the conclusion of the project, the technology would be transferred to a spin-off firm. Thus, for example, in 1976 ERSO acquired RCA's metal oxide semiconductor technology and transferred relevant know-how to a spin-off firm (United Microelectronics Corporation) through a demonstration factory and key engineering personnel (Amsden, 2001; Hobday, 1995).

Later on, in the 1980s, ERSO promoted the formation of private spin-off companies by contributing venture capital and technological assistance to researchers who intended to exploit technologies developed or acquired through ERSO (Hou and Gee, 1993). Instances of this pattern of technology transfer include specialized companies in various semiconductor-related technologies, such as Taiwan Semiconductor Manufacturing Corp. (a joint venture with Phillips for VLSI chips manufacture), Taiwan Mask Corporation (fabrication masks), and Vanguard International Semiconductor (DRAM manufacturing). But as the local industry developed, established firms became increasingly involved in licensing technologies from ERSO or from foreign firms. Government support to R&D at public research institute and universities played a rather important role in inducing a qualitative change in the inward transfer of technology taking place as a result of other kinds of activities, including foreign direct investment, joint ventures between local and foreign firms, and subcontracting relations with foreign firms.

An interesting contrast to the cases of Korea and Taiwan is provided by the Brazilian experience. Here too, policy makers have long recognized in words if not in fact the importance of indigenous scientific and technological capabilities toward national economic development. However, the record of accumulation of technological capabilities across the spectrum of industrial sectors in Brazil has been considerably less impressive than those of Korea, Taiwan or Japan. While the reasons for this fact are too complex to be discussed in this paper, we would like to draw attention to the fact that higher education and public research institutions did play an important role in the successful development of specific industrial sectors.[15] In particular, the origins of Embraer, currently the world's fourth largest aircraft vendor, illustrate important aspects of the relationship

[14] Hsieh (1989) reports that in the late 1980s a large majority of the faculty at leading academic institutions in Taiwan (including the Academia Sinica, National Taiwan University and National Tsing Hua University) held degrees from foreign academic institutions, most notably American ones. Following the establishment of the Hsinchu Science-based Industrial Park in 1980, large numbers of foreign-trained nationals returned home as founders or investors in more than one-half of the new firms based in the Park (NSC, 1997).

[15] The evolution of the Brazilian system of innovation is analyzed in Dahlman and Frischtak (1993), Schwartzman (1991), and Viotti (2002), among others.

between education, research and the development of technological capabilities.

The early phase of development of Brazil's aerospace industry centered in fact on the establishment in 1945 of the Centro Tecnologico da Aeronautica (CTA), a center coordinating the activities of an engineering school and a research institute. Overseas institutions provided both a model for the center and a share of the initial faculty and research personnel at CTA. The engineering school (Instituto Tecnologico da Aeronautica or ITA) was organized in cooperation with MIT, and during the early years of activity many professors came to ITA from MIT and other overseas institutions. Even more important, the cooperation between the two provided an opportunity for ITA students to spend periods of study and research abroad. The successful launch of various undergraduate degree programs and, later on, of a graduate engineering school were undoubtedly related to the creation of a demand for engineers at research institutes located at CTA, and particularly at Embraer, a government-controlled company established in 1969 to develop aircrafts based on Brazilian design and engineering.[16]

In turn, access to engineering talent from ITA and to the fruits of R&D activities conducted at the research institutes of CTA was a crucial determinant of Embraer's success, and later of the growth of a cluster of technologically sophisticated enterprises in the region of Sao Jose do Campos. As a result of the public investments in training and research carried out during the 1950s and 1960s, Embraer could quickly accumulate technological capabilities in aircraft design and manufacturing. To be sure, learning at Embraer also proceeded on the basis of joint development projects with and technical cooperation with foreign enterprises. Effectiveness in this learning process enabled Embraer to quickly move on to the conception and direction of aircraft development projects. Existing historical accounts lead us to argue that these developments would have not occurred in the absence of the two-pronged public investment in training and research carried out by the CTA.

5. How does industry draw on university research in the United States?

The capabilities and demands on the university research system in the United States obviously differ from the capabilities and demands on university research in developing countries. Nonetheless, it is useful to discuss briefly the U.S. experience for two reasons. First, it is clear that, for better or for worse, in the minds of many scientists and policy makers in developing countries the current U.S. system is a model of what a system of university research ought to be. These views often are associated with beliefs about how the current U.S. system is contributing to technological advance in industry that are quite distorted. We want to argue that these beliefs can pull the development of university research systems in developing countries in quite the wrong direction. In contrast, despite the obvious differences in context, we believe that a correct appreciation of the way the U.S. university research system is in fact contributing to industrial development can provide some useful lessons for developing countries.

Second, as successful developing countries move closer to the economic frontier, it is helpful to have an understanding of what an obviously productive, university research system in an advanced industrial nation looks like. As signaled above, our view is that the differences between a system of public research useful in catch-up, and a system useful for economies operating close to the frontiers, is not black and white, and that the latter can grow naturally out of the former.

While our focus in this section will be on the contemporary U.S. system, it is important to put that discussion in historical context. Many authors have argued that, in contrast with the university research systems in the countries of Continental Europe, and the United Kingdom, from its beginnings, research at American universities tended to have a quite practical orientation. Thus, the state and federal government-funded agricultural research system was put in place in response to demands from farmers. In its early years, despite enthusiasm on the part of scientists employed by the system (for the most part chemists) to establish a science-based agriculture, farmers were skeptical, and insisted that the bulk of the efforts on the experimentation stations be directed to identifying best method, and improving it further. Ultimately, the advocates of a science-based agriculture proved the productivity of developing a solid scientific understanding of the chemistry and biology of plant and animal growth, nutrition, insect and other diseases, etc. But up to the present time, testing of both prevailing and new practice, and reporting results to farmers, continues to be an important activity of public agricultural research. Agricultural research stations tend to be quite responsive to the development of new diseases and other problems facing farmers in their

[16] On the contrary, the lack of a demand for specialized engineers and metallurgists by either private or public enterprises in the iron and steel sector plagued the development of the Escola de Minas founded in 1875 well into the 20th Century.

region. Indeed, there are striking similarities between the university base agricultural research system that grew up in the United States, and the one we described earlier that grew up in Japan. And there is good reason to believe that they have been productive for the same reasons.

Similarly, the American engineering schools like RPI, MIT, and the many that affiliated with the land-grant universities, grew up in the 19th Century largely responding to the demands from American industry (Rosenberg and Nelson, 1994). Originally oriented largely to training young men to work in industry, many of the schools gradually took on a research and consulting role specifically oriented to industry in their region. Thus, Purdue University, located at a major rail hub, developed a strong program of research as well as training in the technologies relevant to railroad equipment. The University of Oklahoma, in the oil country, has had a major research program on the technologies relating to oil exploration and refining. Researchers associated with the University of Minnesota developed a major and successful program to enable taconite iron-ore mining to continue to be profitable in the state, in the face of the mining out of the richer lodes.

Until after World War II, American university research and advanced training in the fundamental sciences, like physics and organic chemistry, were not particularly strong. A significant fraction of American students seeking to get advanced training in these fields went to the United Kingdom, or Germany, up until the war. The situation regarding government funding of fundamental research, and the strength of American research universities in the basic fields, of course, changed dramatically after World War II. For the past half-century, American universities have been the home of the lion's share of the path breaking fundamental research going on. Our discussion above, however, calls attention to the fact that American universities have been strong and effective in applications-oriented research for even longer. And the argument we will develop now is that it is a mistake to see the principal contributions of American university research today as largely flowing directly from fundamental research.

Several recent studies have explored which fields of university research are most drawn on by scientists and engineers working in industry (Cohen et al., 2002; Klevorick et al., 1995). The fields tend to be the engineering disciplines, and the applications-oriented sciences, as contrasted with the more basic sciences like physics, and mathematics. However, in addition to fields like materials science, computer science, mechanical and electrical engineering, the industry scientists clearly also identified chemistry, and, in selected industrial sectors, biology. It is important to note that these "basic sciences," like those more specifically aimed to solve practical problems, in fact often involve research that is quite close to applications (Cohen et al., 2002, pp. 10–11).

Not surprisingly, the studies of the development of particular technologies that highlight an important university role tend to locate that role in engineering schools, or medical schools.

This is not to play down the importance of the strength of American universities in training and research in the fundamental sciences. Among other things, capabilities and activities here provide an essential support for effective training and research in the applications-oriented sciences. But the latter, not the former, provides the direct links with industrial innovation, even in industries, like those in the United States, generally operating at the frontier.

Another widespread misconception about the ways in which research at American universities has been contributing to industrial innovation is that university research is the principal source of embryonic inventions, which are taken up and commercialized by industry. There certainly are a number of important instances that are like that. Thus, university research gave birth to the modern computer. Some important pharmaceuticals have come directly out of university research, and some important medical devices.

However, responses from industrial scientists and engineers suggest strongly that this is not the principal kind of contribution that university research makes to industrial innovation. One study asked industry respondents to rate the relative importance of three different kinds of inputs of public research to industrial R&D: prototypes, general research findings, instruments and techniques. Virtually all industry respondents said the latter two kinds of research outputs were far more important to them than prototypes. Even in pharmaceuticals, and in electronic devices, where current conventional wisdom has that the university-created prototypes are highly important, the respondents reported that general research findings, and instruments and techniques created through research, were far more important to them (Cohen et al., 2002, p. 10).

Relatedly, the conventional wisdom has it that the principal contribution of university research to industrial innovation is to stimulate, trigger, new industrial R&D efforts aimed to take advantage of those breakthroughs. However, respondents in most industries reported that most of their R&D projects were initiated in response to perceptions of customer needs, or weaknesses in production processes. The principle use of university research results that they reported was in enabling industrial R&D to solve problems effectively in projects so oriented, rather than to trigger new industrial R&D projects (Cohen et al., 2002, p. 6).

The respondents' reports on the important channels through which university research results flow to and get used by industry reflect what kind of university research outputs get most used, and how they get used. Respondents in most industries reported that publications, information disseminated at meetings and conferences, informal interactions with university researchers, and consulting, were the most important conduits through which draws on university research results. Contrary to current conventional wisdom, most industries reported that patents played little role in technology transfer. Even in pharmaceuticals, where university patents were rated an important vehicle of technology transfer, publications, and meetings and conferences were rated as more important vehicles through which industry gained access to the results of university research (Cohen et al., 2002, pp. 14–18).

The picture that emerges is that of a university research system helpful to economic development in the United States because important parts of it work at being useful. This is a very different picture than one that proposes that positive effects on economic development flow naturally from the efforts of university researchers concentrating on simply advancing their science. This is not to say the latter is not important. But the U.S. university research system has been as effective as it has been in contributing to economic development because it is not an Ivory Tower.

We propose that the features of the U.S. system of innovation highlighted above appear to in fact characterize the effective interactions between the public research infrastructure and industry in developing countries. For the case of the state of Minas Gerais in Brazil, Rapini et al. (2006) present the results of a questionnaire survey of university–industry linkages that display striking similarities with the U.S. evidence discussed above. Besides finding that the engineering and applied sciences are the fields of academic research wherein most of the fruitful university–industry interactions have formed, the survey results in Rapini et al. (2006) and Povoa (2007) indicate that patents are generally of limited significance as a means for structuring technology transfers from university research and industry, and that such knowledge transfers only rarely consist of embryonic product concepts and prototypes.

6. Conclusions: the challenge of institutional design and development

An influential body of literature argues that government has no business establishing and supporting research programs aimed to help particular economic sectors. First of all, such programs run counter to international treaties regarding the rules of the game under the WTO. Second, in any case governments inevitably make bad judgments when they try to help particular sectors. However, while the ground rules under the WTO inhibit the subsidy of specific commercial products or firms, they do not constrain broad support of R&D and training tailored to meet a sector's needs. And, as the examples we gave showed clearly, such government-supported programs have been very effective in the several successful cases of economic catching up.

In the preceding two sections we looked briefly at a number of instances and structures of public research contributing effectively to economic progress. We looked at agricultural and industrial development in Japan in the early stages of Japan's successful catch-up experience, at Korea and Taiwan in the last decades of the 20th Century, and at the successful programs in Brazil to support agricultural development and aircraft design and production. We then considered several recent studies of just how university research in the United States has been contributing to technological advance in industry. We think these cases together provide an illuminating picture of the kinds of structures and conditions under which publicly supported research contributes importantly to economic development.

The research programs that effectively contributed to catch-up did not operate within "ivory towers." Rather, in every case they were oriented towards an actual or potential user-community. They were designed to help solve problems, and advance technology, relevant to a particular economic sector.

As some of the examples suggest strongly, a program of public research can be effective only in a context in which the user-community has strong incentives to improve their practices, and the capability to use what is coming out of the research program. They need to be willing and able to try new things, to learn. It is interesting and relevant, we think, that in many of the successful cases, public research was part of a broader structure aimed to improve productivity in a sector which included, as well, education and training programs for people going out to become members of the user-community. Thus, the agricultural research programs in Japan complemented programs to give Japanese farmers better training. The productivity of the programs of public research in electronics in Korea and Taiwan depended on the major investments that had been made in the training of engineers, who went out into industry, and provided industrial firms with the technical sophistication they needed in order to draw fruitfully from that research. And in turn, a client population, eager for research results that can help them, and capable of recognizing and using those results when they become available, can provide an effective and demanding source of priorities and support for a public research organization.

While there is much to the argument that national governments cannot effectively identify particular firms or narrowly defined commercial products to be supported, the historical evidence indicates that they have much less difficulty in identifying broad economic sectors and technologies where public research can be productive. Programs of support of agricultural research, or research on diseases endemic to a country, simply are not of the kind that can be accused of trying to "pick winners." The agricultural research programs we described were focused on the particular problems and opportunities of indigenous agriculture. And for countries significantly behind the technological frontiers, research programs to support the development of indigenous capabilities in manufacturing are able to focus on technologies used in more advanced countries. These are technologies that indigenous firms are going to have to master if they are to be effective operating in the field. Thus, the Korean and Taiwanese programs of public research in electronics, and Brazil's program in aviation technology, were designed to enable domestic capabilities to come closer to capabilities at the frontier.[17]

We note that the fields of research contributing more or less directly to problem-solving and innovation in the user sector were and are largely the applications-oriented sciences and engineering disciplines. This observation is not to denigrate the importance of the development of indigenous capabilities in the basic sciences. Capabilities here are clearly important for training purposes. Engineers, agricultural scientists, medical scientists, need to have solid training in physics, mathematics, chemistry, biology. And problem-solving research in the applied sciences and engineering disciplines often fruitfully draws on relatively recent research results in the more basic sciences. However, all the cases we have considered show the applications-oriented sciences and engineering as the fields of public research where there is direct interaction with problems and opportunities in agriculture, industry, and medicine.

We also note that many of the successful cases and structures that we have considered developed outside of the more traditional system of public research in higher education. Earlier we observed that in the contemporary U.S. system, most of the fields of research contributing importantly to innovation in industry usually are housed in engineering and medical schools, rather than in general arts and sciences. Most of the cases we described of successful public sector R&D in developing countries also were located outside of the mainline university structure, in dedicated applications-oriented laboratories. The extent of linkage between institutions supporting engineering, agricultural, and medical research and training, and the broader liberal arts university system, has differed from country to country. But in the cases described earlier, successful systems of publicly supported applications-oriented research and training had their own special structures.

These structures were conducive to two-way interaction between the research institution and the user-community. Those involved in the research programs generally were well informed about the nature of prevailing practice in the fields with which they were concerned, and the problems and constraints of practitioners. Crucially, there were a variety of mechanisms through which what was learned and developed in research was effectively disseminated to the user-community.

Successful public research programs of other countries can and should serve as broad guides for countries trying to establish their own programs, but as indictors of principles to follow, not as templates. There is first of all the problem that it is very difficult to identify just what features of another country's successful program were key to its success, and which ones were peripheral. Second, what works in one country setting is unlikely to work in the same way in another. Among the several examples our short case studies provide, the highly differing ways that Korea and Taiwan have gone about supporting, successfully, the development of indigenous electronics stands out. Programs of public research need to be free to learn what works and what does not, and they need to be designed in such a way as to evolve in response to emerging patterns of development of technological capabilities in the private sector.

While high-level policy can set a frame for the development of a successful program of public research, that frame must have a certain looseness regarding the details.

[17] Reference to the case of Brazilian aviation makes it imperative to observe that in several cases of successful catch-up, governments also played important roles in stimulating or creating a demand for indigenous capabilities in the relevant technologies.

One important reason is the inevitable, and desirable, decentralization of decision-making. Effective research structures cannot operate in a setting where what is done is determined by distant, high-level government officials, either directly, or through a highly detailed planning document. The technical expertise resides to a considerable extent with the scientists at the relevant research institute. And it is there that the detailed understanding of the problems and opportunities of sector being serviced needs to be developed. An effective research program needs to be able to reallocate resources, refocus efforts, as perceptions of problems and opportunities change. Similarly, the problems of information flow, interaction, and mutual influence, between a research institute and the economic sector with which it is concerned, need to be able to develop and change, on the basis of experience which indicates what works, and what does not.

But while detailed planning and monitoring by government ministers can hinder the effectiveness of a laboratory, there must be mechanisms in place to prevent a research institution from becoming an ivory tower, focusing on what interests the researchers, or the research director, even if such a program has little to do with the problems and opportunities of the economic sector whose development provides the basic rationale for the research. There needs to be some mechanism by which the user-community has a voice in long run evaluation of a research program.

At the same time, it is important not to have the program captured by prevailing economic interests, First of all, these tend strongly to push the program towards short run problem-solving, and the expense of research that can have greater payoff over the long run. Second, in many cases potentially the most important research will open up possibilities for new directions and enterprises in the sector in question, which may not be to the interest of existing firms or farmers.

We close by noting that today many countries are beginning to try to use public research as part of their broad strategies for industrial catch-up. There will be accumulating experience in this area, some successful, some not successful, that can help sharpen understanding of what works and what does not. An important objective of this paper is to help catalyze continuing analysis and across country discussion of how to use public research programs as an effective support of industrial catch-up.

Acknowledgements

We wish to thank Giovanni Dosi and four anonymous referees for useful comments on earlier versions of this paper. The research behind this paper was supported by the Mellon Foundation.

References

Abramowitz, M., 1986. Catching up, forging ahead, and falling behind. Journal of Economic History 46 (2), 385–406.

Albuquerque, E., 2003. Immature systems of innovation. In: Paper Prepared for the First Globelics Conference, Rio de Janeiro, Brazil.

Amano, I., 1979. Continuity and change in the structure of Japanese higher education. In: Cummings, W.K., Amano, I., Kitamura, K. (Eds.), Changes in the Japanese University. A Comparative Perspective. Praeger.

Amsden, A.H., 2001. The Rise of "The Rest". Challenges to the West from Late-Industrializing Economies. Oxford University Press, Oxford.

Ayer, H., Schuh, G.E., 1972. Social rates of return and other aspects of agricultural research: the case of cotton research in Sao Pãulo, Brazil. American Journal of Agricultural Economics 54 (4-1), 557–569.

Bartholomew, J.R., 1989. The Formation of Science in Japan. Yale University Press, New Haven.

Bernardes, A., Albuquerque, E., 2003. Cross-over, thresholds, and interactions between science and technology: lessons for less-developed countries. Research Policy 32 (5), 865–885.

Cohen, W.M., Nelson, R.R., Walsh, J.P., 2002. Links and impacts: the influence of public research on industrial R&D. Management Science 48 (1), 1–23.

Cusumano, M.A., 1989. Scientific industry": strategy, technology, and entrepreneurship in prewar Japan. In: Wray, W.D. (Ed.), Managing Industrial Enterprise. Harvard University Press, Cambridge, MA, pp. 269–316.

Dahlman, C., Frischtak, C., 1993. National systems supporting technical advance in industry: the Brazilian experience. In: Nelson, R.R. (Ed.), National Innovation Systems. Oxford University Press, New York, pp. 414–450.

Dean, W., 1989. The green wave of coffee: beginnings of tropical agricultural research in Brazil (1885–1900). The Hispanic American Historical Review 69 (1), 91–115.

Fagerberg, J., Godinho, M., 2004. Innovation and catch-up. In: Fagerberg, J., Mowery, D., Nelson, R. (Eds.), Handbook of Innovation. Oxford University Press, Oxford, pp. 514–542.

Freeman, C., 1995. The 'national system of innovation' in historical perspective. Cambridge Journal of Economics 19, 5–24.

Gerschenkron, A., 1951. Economic backwardness in historical perspective. In: Gerschenkron, A. (Ed.), Economic Development in Historical Perspective. Harvard University Press, Cambridge.

Graham, D., Gauthier, H., de Barros, J., 1987. Thirty years of agricultural growth in Brazil: crop performance, regional profile, and recent policy review. Economic Development and Cultural Change 36 (1), 1–34.

Hamilton, A., 1791. Report on Manufactures, reprinted in: The Reports of Alexander Hamilton. Harper Torch-back, New York, p. 1965.

Hashimoto, T., 1999. The hesitant relationship reconsidered: university–industry cooperation in postwar Japan. In: Branscomb, L.M., Kodama, F., Florida, R. (Eds.), Industrializing Knowledge. MIT Press, Boston.

Hayami, Y., Ruttan, V., 1985. Agricultural Development: An International Perspective. Johns Hopkins University Press, Baltimore.

Hobday, M., 1995. Innovation in East Asia: the Challenge to Japan. Edward Elgar, Aldershot.

Hou, C.M., Gee, S., 1993. National system supporting technical advance in industry: the case of Taiwan. In: Nelson, R.R. (Ed.), National Innovation Systems: A Comparative Analysis. Oxford University Press, New York, pp. 384–413.

Hsieh, H.S., 1989. University education and research in Taiwan. In: Altbach, P.G., et al. (Eds.), Scientific Development and Higher Education. The Case of Newly Industrializing Nations, Praeger Publishers, pp. 177–214.

Kim, D.-W., Leslie, S.W., 1998. Winning markets or winning nobel prizes? KAIST and the challenges of late industrialization. Osiris (2nd series) 13, 164–185.

Kim, L., 1997. Imitation to Innovation: The Dynamics of Korea's Technological Learning. Harvard Business School Press, Boston.

Kim, L., 1999. Learning and Innovation in Economic Development. Edward Elgar, Cheltenham.

Kim, L., Nelson, R.R., 2000. Technology, Learning, and Innovation. Cambridge University Press, Cambridge, UK.

Klevorick, A.K., Levin, R.C., Nelson, R.R., Winter, S.G., 1995. On the sources and significance of interindustry differences in technological opportunities. Research Policy 24, 185–205.

Landes, D.S., 1969. The Unbound Prometheus. Cambridge University Press, Cambridge, UK.

Lee, D.H., Bae, Z.-T., Lee, J., 1991. Performance and adaptive roles of the government-supported research institute in South Korea. World Development 19 (10), 1421–1440.

List, F., 1841. National Systems of Political Economy, English ed., 1904. Longman, London.

Mikami, A., 1980. Old and new Zaibatsu in the history of Japan's chemical industry: with special reference to the Sumitomo Chemical Co. and the Showa Denko Co. In: Okochi, A., Uchida, H. (Eds.), Development and Diffusion of Technology: Electrical and Chemical Industries (6th International Conference on Business History). University of Tokyo Press, Tokyo.

National Science Board, 2004. Science and Engineering Indicators 2004. National Science Foundation, Arlington, VA.

National Science Council, 1997. White Paper on Science and Technology. Executive Yuan, Republic of China, Taiwan (http://www.stic.gov.tw/stic/policy/scimeeting/E-whitepaper/index_e.htm).

Nelson, R.R. (Ed.), 1993. National Innovation Systems. Oxford University Press, Oxford.

Nelson, R.R., Sampat, B.N., 2001. Making sense of institutions as a factor shaping economic performance. Journal of Economic Behavior and Organization 44, 31–54.

Odagiri, H., 1999. University–industry collaboration in Japan: facts and interpretations. In: Branscomb, L.M., Kodama, F., Florida, R. (Eds.), Industrializing Knowledge. MIT Press, Boston.

Odagiri, H., Goto, A., 1993. The Japanese system of innovation: past, present, and future. In: Nelson, R.R. (Ed.), National Innovation Systems: A Comparative Analysis. Oxford University Press, Oxford, pp. 76–114.

Odagiri, H., Goto, A., 1996. Technology and Industrial Development in Japan. Clarendon Press, Oxford.

Pack, H., 2000. Research and development in the industrial development process. In: Kim, L., Nelson, R. (Eds.), Technology, Learning, & Innovation. Cambridge University Press, Cambridge, pp. 69–94.

Pardey, P., Alston, J., Chan-Kang, C., Magalhães, E., Vosti, S., 2004. Assessing and attributing the benefits of varietal improvement research in Brazil. Research Report 136. International Food Policy Research Institute, Washington, DC.

Pollard, S., 1981. Peaceful Conquest. Oxford University Press, Oxford.

Povoa, L., 2007. Technology transfer from universities and public research institutes to firms in Brazil: a survey. Unpublished manuscript.

Rapini, M., Albuquerque, E., Silva, L., de Souza, S., Righi, H., Cruz, W., 2006. Spots of interaction: an investigation on the relationship between firms and universities in Minas Gerais, Brazil. Discussion Paper TD 286, UFMG/Cedeplar, Belo Horizonte.

Rosenberg, N., 1970. Economic development and the transfer of technology: some historical perspectives. Technology and Culture 11 (4), 550–575.

Rosenberg, N., Nelson, R.R., 1994. American universities and technical advance in industry. Research Policy 23, 323–348.

Schwartzman, S., 1991. A Space for Science. Pennsylvania University Press, University Park, PA.

Uchida, H., 1980. Western big business and the adoption of new technology in Japan: the electrical equipment and chemical industries 1890–1920. In: Okochi, A., Uchida, H. (Eds.), Development and Diffusion of Technology: Electrical and Chemical Industries (6th International Conference on Business History). University of Tokyo Press, Tokyo.

UNESCO, 1972. Statistics of Students Abroad, 1962–1968. UNESCO, Geneva.

Velho, L., Velho, P., 1997. The emergence and institutionalization of agricultural science. Cadernos de Ciéncia & Tecnologia 14 (2), 205–223.

Viotti, E.B., 2002. National learning systems. Technological Forecasting and Cultural Change 69, 653–680.

Viotti, E.B., 2003. Technological learning systems, competition, and development. In: Paper Prepared for the First Globelics Conference, Rio de Janeiro, Brazil.

Wade, R., 1990a. Governing the Market. Princeton University Press, Princeton, NJ.

Wade, R., 1990b. Industrial policy in East Asia: does it lead or follow the market? In: Gereffi, G., Wyman, D.L. (Eds.), Manufacturing Miracles: Paths of Industrialization in Latin America and East Asia. Princeton University Press, Princeton, NJ, pp. 231–266.

Yonekura, S., 1994. The Japanese Iron and Steel Industry, 1850–1990: Continuity and Discontinuity. St. Martin's Press, New York.