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Introduction

This essay is concerned with the roles of research in indigenous universities and public laboratories in the processes through which countries behind the technological and economic frontier catch up. Given the purposes of the project of which this essay is a part, our focus will be on catch-up in industrial technology and practice. However, in much of our analysis, we recognize explicitly that the process of economic development involves building capabilities in a wide range of areas – agriculture, medicine and public health, the ability to manage transportation systems, maintain safe water supply, and many others as well as developing capabilities in industry. We will argue that, for several reasons, the role of indigenous public research in industrial catch-up is more important today than it was earlier in the 20th century. We also call attention to the fact that building an effective indigenous system of research is no easy task, while offering some guidelines that may be helpful.

However, before getting into these topics, we need to set the stage by considering the process of catch-up more generally, and in historical perspective. It is clear that the process of catch-up involves in an essential way learning about and learning to master ways of doing things that are used by the leading countries of the era. However, the term catch-up seems to connote that the catching up country simply copies, and this is misleading. While practice in advanced countries does usually serve as a model, what is achieved inevitably differs in certain ways from the template. In part this reflects that exact copying is almost impossible, and attempts to replicate at best get viably close. In part it reflects deliberate and often creative modifications aimed to tailor practice to national conditions.

Most of the writings on catch-up have presumed, explicitly or implicitly, that the key practices that need to be mastered are "technologies", in a rather conventional sense of that term, with the know-how involved of the sort that is learned by engineers, and physical and biological scientists, and often embodied in physical things like machines, and specialized materials of various sorts. Certainly a lot of the powerful practice of advanced countries that developing ones are trying to acquire is technology of this sort: product designs, complex production processes, the seeds and pesticides and procedures used in productive agriculture, modern medical practice including the use of pharmaceuticals and sophisticated medical equipment, the technological core of modern air traffic control systems, and the like.

However, a lot of the relevant practice cannot be easily characterized as technology in this narrow sense. 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. As indicated above, later in this essay we will focus on the set of national public institutions that do research and advanced training. All of these involve ways of doing things –practices –but technology in a narrow sense is not at their core.

Nelson and Sampat (2001) have proposed that it may be useful to think of the latter as "social" technologies, as contrasted with the "physical" technologies. Rather than being embodied in physical hardware and materials, social technologies are embodied in organizational forms, bodies of law, public policies, codes of good business and administrative practice, customs, norms.

The point of view that we will develop here is that, in this modern age, physical technologies may be much easier to learn and acquire than social technologies, if the capabilities for assimilation are present. However, the phrase "if the capabilities for assimilation are present" flags several important issues.

First of all, the effective operation of many physical technologies requires the implementation of various social technologies. Thus in the present context it may be far easier to import the machinery and acquire the engineering knowledge to produce modern automobiles or semiconductors than to set up an effective firm organization and management structure to operate the physical technology efficiently, or to set up an effective set of procedures for acquiring inputs, or for marketing.

Second, the broad institutional structure of a nation, and the operation of particular institutions like its education and financial systems, and its system of public research and advanced training, strongly affects both the incentives and the ability to take on board and operate modern industrial, agricultural, or medical practice. Successful economic development generally will require the reform of traditional systems and the setting up of more modern ones, broadly guided by perceptions of how those systems are structured and work in high income countries, but tailored to fit in with national conditions and culture. In the past some countries have been able to do this effectively, but success in this endeavor is far from a foregone conclusion.

We proposed above that an effective system of public research has become an increasingly important part of the institutional structure needed for catch-up. We will develop this argument, and some of its implications, shortly. But first we want to lay out some things that seem clear about successful catch-up experience in the past, and some features of the contemporary scene that are different from what they have been.

The catch-up process in historical perspective

The proposition that the economic development process of countries behind the frontier is basically that of "catch-up" seems so compelling that one might expect that study of the processes involved would be at the center of attention of the contemporary development economics community. But this is not the case.

Understanding differences across countries in their level of economic development and the reasons for economic backwardness was of course a central concern of many of the great classical economists, particularly Adam Smith. But these questions gradually moved to the periphery of the field.

The question came back into focus after World War II. That the development problem was a catch up problem was put forth explicitly in Alexander Gershenkron's "Economic Backwardness in Historical Perspective" (1951), which considered the policies and new institutions of the states of continental Europe during the mid- to late 19th century as they strove to catch up with the U.K. and reflected on the present day relevance of this experience. However, outside of the economic historians, few development economists paid attention to the processes of catch up per se, because most of prevailing economic growth theory saw the principal reason for low productivity and incomes as low levels of physical and human capital, as contrasted with inadequate access to or command over technologies and other practices used in high income countries. Relatedly, imitation of technologies, and practices more generally, in use in advanced countries generally was viewed as relatively easy, if there were no barriers like intellectual property rights, and the needed inputs, particularly physical and human capital, were available. However, learning to do what others already have done often is not easy. Japan was successful at this at the start of the twentieth century, Korea and Taiwan later in that century, and China is proving effective at that task today. But many countries have made hardly any progress.[1]

Moses Abramowitz' propositions about the institutional and political conditions needed for successful catch up (1986) clearly recognized these difficulties, and generated a small research tradition specifically on the factors conducive to catch-up. Some of this research has been quite illuminating. Scholars like Fagerberg and Godinho (2004), and Bernardes and Albuquerque (2003), have shown that in recent years countries that have caught up rapidly have tended to focus their higher education systems on engineering training, and have developed indigenous research efforts. There are several quite detailed studies of particular countries that have been successful in catching up that delve into the key processes and institutions involved (see for example Kim 1997, and 1999). There are a few studies that have examined how firms in developing countries have caught up in particular industries (e.g. Hobday, 1995). However, these kinds of studies have not been brought together in a systematic way.

Our reading of prior relevant research leads us to propose that, in the past, all successful cases of catch up have involved the following elements.

First, considerable cross-border flow of people, with a combination of citizens in the then backward country going to learn abroad and then returning, and people from the advanced country coming as advisors or, in some cases, to establish themselves in the developing country. Thus the core of British textile manufacturing methods was brought over to the new United States by British technicians, who stayed. Similarly, there was a significant flow of British technicians to northern Europe in the early 19th century, who came with the objective of setting up business on the continent (Landes, 1969; Pollard, 1981; Rosenberg, 1970). The development of Japanese industry in the late 19th and early 20th century was helped by technical advisors from abroad, as well as by Japanese returning home after studying Western methods (Odagiri and Goto, 1996). The Korean and Taiwanese electronics industries were developed largely by men who had studied, and often worked, in the United States. While early on the cross border flows were to a considerable degree the result of individuals' search for economic opportunities abroad, they have increasingly been part of activities carried out by various organizations.

During the 20th century companies came to play an increasing role in this cross national learning and teaching process. The new 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.

Over the last 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. University faculty in the successful developing countries has to a considerable degree been based on nationals who received their training abroad. We believe that this university mediated trans national conduit 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 important element in countries that successfully caught up with the leaders during the 19th and 20th centuries was active government support of the catch up process, involving various forms of protection and direct and indirect subsidy. The guiding policy argument has been the need of domestic industry in the industries of the day judged critical in the development process for some protection from advanced firms in the leading nations. Alexander Hamilton’s argument (1791) for infant industry protection in the new United States was virtually identical to that put forth decades later by Friederich List (1841) regarding Germany’s needs. The policies and new institutions used in Continental Europe to enable catch up with Britain are documented in Alexander Gershenkron’s famous essay. The same story also fits well with the case of Japan, and of Korea and Taiwan somewhat later. In many countries these policies engendered not successful catch up but a protected inefficient home industry. However, they also were the hallmark during the 20th century of all the countries that have achieved their goals of catching up.

These policies obviously angered companies in the leading countries, and their governments, particularly if the supported industry not only supplied its home market but began to invade the world market. While the case made after World War II for free trade was mostly concerned with eliminating protection and subsidy among the rich countries, and at that time there was sympathy for the argument that some infant industry protection was often useful in developing countries, the international treaties that have been made increasingly have been used against import protection and subsidy in countries seeking to catch up from far behind.

Our belief is that Hamilton and List were right that successful catch up in industries where international trade is considerable requires some kind of infant industry protection or other mode of support. The challenge is to find effective means under the new conditions.

Third, during the 19^{th} and early 20^{th} century, many developing countries operated with intellectual property rights regimes which did not restrict seriously the ability of their companies to in effect copy technologies used in the advanced countries. There are many examples where licensing agreements were involved, but we believe that for the most part these were vehicles through which 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.

Like infant industry protection and subsidy, conflicts tended to emerge largely when the catching up company began to encroach onto world markets, or even to export to the home market of the company with the patent rights. Increasing instances of this clearly were a major factor in inducing the treaty on Trade Related 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 increased tendency of companies in high income countries to enforce their intellectual property rights is having consequences regarding agricultural development, and the workings of the public health systems in developing countries, as well as regarding manufacturing development. Patented seed varieties are playing an increasingly important role in modern agriculture. And patented pharmaceuticals are key elements in the attack on a number of diseases that devastate poor countries.

The arena of intellectual property is almost sure to become one of considerable international conflict in the immediate future. Developing countries need to learn to be able to cope with this new problem.

Changing conditions: the increased importance of indigenous technological and scientific capabilities

As we have noted, the current and future development environment for countries trying to catch up is different from what it has been, in a number of respects. International treaties, particularly the WTO and TRIPS, have changed the environment for catch up in important ways. Firms in the advanced countries are likely to press hard for access to markets and in many cases the rights to establish branches abroad. Protection and subsidy of domestic industry is likely to be met by legal and other punitive action on the part of the advanced countries, and hence will have to be more subtle, involving support of sectoral infrastructure, training, and research. Firms in advanced countries also are likely to be far more aggressive and effective in protecting their intellectual property rights, and hence firms and governments in developing countries will have to develop new strategies for access on reasonable terms.

The new legal environment has come into place in a context where both business and finance are operating on a more global frame. Foreign direct investment has played a significant role in the catch up processes of some successful countries, and is likely to play an even greater role in the future than in the past. So too partnerships between firms in developing countries and companies that possess advanced know how. At the same time, firms in developing countries can aspire realistically to sell on a world market if their wares are good enough.

Less well noticed, scientific and technical communities in different countries also are now more connected than they used to be.[2] 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.

The implications for catch up can be profound. On the one hand, in technologies with strong scientific underpinnings, advanced training in the field has become a prerequisite for ability to understand and control; simple working experience no longer will suffice. This fact clearly challenges the capabilities for education and technical training in countries seeking to catch up, even if studying abroad can provide at least a temporary solution to the need for acquiring advanced knowledge in relevant fields. On the other hand, a strong science base significantly reduces the importance of operating apprenticeship abroad, or tutelage by foreign industrial experts. This is not to argue that advanced formal training in a field suffices for mastery. However, in many fields it provides a substantial basis for learning by doing. Moreover, having a domestic base of good scientists provides the basis for breaking into the international networks where new technologies are being hatched.

As a result of these changes, we believe that the development of indigenous capabilities in research and advanced training now are much more important in enabling catch-up than used to be the case, and their importance will grow. As noted at the start of this paper, our focus here will be on the role of research at universities and public laboratories. However, the roles of such research needs to be understood in terms of their operation within a broader National Innovation System.[3] 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, Kim 1997, 1999; Albuquerque 2003; and Viotti 2002, 2003). We propose that a suitably reoriented concept of a National Innovation System can be a useful tool for considering policies and institutions needed for effective catch-up in the new context.

In the first place, it calls attention to the fact that the process of catch up involves innovation in an essential way. The innovating that drives the process of course 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.

Second, the Innovation System concept focuses attention on the range of institutions that are involved in the process of innovation. In most industries the roles of business firms is central. However, there has been a tendency of many economists writing about innovation to write as if firms are the full story, neglecting other kinds of institutions that are involved in the processes that support and mold innovation in many modern industries. While in earlier eras such a narrow institutional focus may not have been unwarranted, our argument is that public research institutions are likely to play an important one in the twenty first century. Perez and Soete (1988), and Bell and Pavitt (1993), argued this point some time ago. But we think it fair to say that standard development economics still is mostly blind to the issues here, and the important functions that public institutions are likely to play.

In the first place, indigenous universities and public laboratories will play an increasingly important role as vehicles through which the technologies and organizational forms of the advanced countries come to be mastered in the developing ones. They will do so partially as an organizing structure for and partially a substitute for international people flows. Indigenous universities will play a key role as the source of students who take advanced training abroad, and as the home of faculty who have been trained abroad. And it is clear that domestic universities must do the bulk of the training of people who will go to industry and other economic activities needing well trained technical people.

While often overlooked, indigenous research at universities and other public institutions long has been an important element of catch-up in certain important fields for which knowledge originating from abroad was ill suited to national needs. This is especially so in agriculture and medicine. An important part of the reason is that in these areas 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 in manufacturing the 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 and 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 circumstances may have changed. In the new regime of stronger protection of intellectual property, it is going to be increasingly important that countries trying to catch up 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 a 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 and D capability becomes essential. To a considerable extent the R and D needs to go on in firms. However research in universities and public laboratories can play a strong supporting role.

A look at some selected cases in earlier experiences of catch-up

There has been no systematic study of which we are aware of the roles played by indigenous universities and public labs in earlier experiences of catch-up. What is available is a scattered collection of individual cases, described at different levels of detail. 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.

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 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 note that much of what was going on at the experimentation stations during this period involved refining, as well as testing, of 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 ration 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 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 seeds 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 production in these colonies, in the face of rapid increases 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 too, the growth of agricultural production has been since the 1970s shifting from a base in the expansion of cultivated land to one driven by increased yields, and the introduction of new crops and of new varieties of traditional ones. Public research had a strong hand in this transformation. The government created EMBRAPA in 1972 as a public sector corporation to coordinate the R&D activities in the field of agriculture carried out at a large variety of institutions across the country. The latter include 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 quite successful experiences. First, the public research was not particularly "high science." 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.

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.

Around the time of the Meiji restoration in 1868, absorbing knowledge of Western science and technology had become a crucial component of Japan's industrial development strategy. This goal was pursued through a variety of mechanisms. Crucial among them was the recruitment of foreign professionals to work as consultants and specialized technical personnel for a variety of industrial development projects. Japanese students of Western sciences and technology were likewise sent abroad to visit industrial firms and universities or other educational institutions. But the Japanese government also proceeded to establish educational institutions that could rapidly train indigenous students to serve the industrial development needs of the country. Newly founded universities and specialized schools were organized and staffed at first by large numbers of foreign professors. The early cohorts of students provided the specialist knowledge and skills necessary to staff the emerging bureaucracy overseeing public projects of various kinds, and in particular provided the new generation of professors for indigenous universities and advanced schools. In the early stages of Japan's catch-up experience, there was little emphasis on public research, except in so far as this was part of the training of scientists and engineers.

The task of educating scientists and engineers became the province of public academic institutions.[4] The teaching of natural sciences was promoted at the Tokyo University formed in 1877 by merging together a number of institutions devoted to Western learning. While the faculty of science hosted also a course in engineering, the Japanese government sponsored the development of a specialized institution, the Imperial College of Engineering, which was founded in 1873 with a faculty of eight British professors, offering instruction according to a four-year curriculum modeled after that of ETH in Zurich. The degree program included three 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). The College merged into the Tokyo University in 1886, where it became part of the Department of Engineering.

The year 1886 marked a reorganization of the Japanese educational system. The government decided to focus its financial efforts on just one national university, renamed the Imperial University of Tokyo, where research activities would be promoted. Until then, Tokyo University was a teaching institution without adequate laboratories and faculty support for the conduct of basic research. In 1885 new 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. The public system of higher education comprised also a large number of specialized training institutions, where instruction was in Japanese language. These were responsible for training a much larger number of students, most of whom found employment at private enterprises. In contrast, most graduates of the Imperial University (about two thirds in the 1890s) were recruited to public service positions (Amano, 1979).[5]

Historical accounts of Japan's industrial development indicate clearly that 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 a period of study and research abroad (Uchida, 1980; Yonekura, 1994). Already at this early stage in the development of Japan's academic system, professors and graduates contributed directly or indirectly to the development of new technologies, and the adaptation of existing ones.[6] In fact, it was a diffuse practice among professors to act as technical consultants for private business enterprises, and to maintain connections with their students as the latter took employment or founded industrial enterprises. During the First World War, when their access to foreign technology was substantially restricted, Japanese companies became increasingly dependent on the technological assistance by university professors. 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).

The widespread diffusion among academics of consulting for domestic businesses was partly the result of the limited financial support that the government provided for academic research during the period up to the end of the First World War. However, public support for research aimed at industrial development increased during the early twentieth 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. In addition to the formation of testing and R&D programs by private enterprises, the government provided financial support to 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 eleven members. The Laboratory was expanded in 1906, in the aftermath of the Russo-Japanese war, and then again in 1911. From a staff of eleven at inception, the Laboratory grew to more than thirty members in 1911 when new divisions were created for ceramics, dyeing and electrochemistry. 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, 1979). 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, 1979).

In addition to the Industrial Experiment Laboratory, other specialized public laboratories came into existence after World War I thanks to public and private funding (Hashimoto, 1999). In addition to providing greater support to public research activities, the Japanese government also supported the creation of private research laboratories, such as the Research Institute for Physics and Chemistry (Riken) established in 1917.[7] 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.[8]

The form of government support to the development of technological capabilities reflected of course characteristics of the industrial technologies of interest. Thus, the government promoted the development of iron and steel production primarily by financing and organizing the founding of 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 provided its support to organizing 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 of its Cooperative Research Divisions launched in 1926 as a mechanism for organizing collaborative research.[9]

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 2,000 Korean science and engineering graduates were living abroad in 1968 (Kim and Leslie, 1998). 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 thirty-one 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, D.H. et al., 1991), its contributions to the development of indigenous capabilities consisted 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 led to the creation of the Electronics and Telecommunications Research Institute (ETRI) in 1985.[10]

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 fifty 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 6,600 to 440,000, and the number of teaching faculty from 1,000 to almost 22,000 (Hsieh, 1989). Government 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.[11]

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 diffused the relevant know-how to a spin-off firms (United Microelectronics Corporation) through a demonstration factory and the transfer of 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.[12] In particular, the origins of Embraer, currently the world's fourth largest aircraft vendor, illustrate important aspects of the relationship 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.[13]

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 collocated in 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.

Recent studies of how industry draws 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, we think it 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 viewed as 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 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 nineteenth century largely responding to the demands from American industry (Nelson and Rosenberg, 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. Tulsa University, 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, was 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 (Klevorick et al., 1995; Cohen et al., 2002). The fields tend to be the engineering disciplines, and the applications-oriented sciences, as contrasted with the more basic sciences like physics, and mathematics. In addition to fields like electrical engineering, and pathology, the industry scientists clearly also tended to identify academic chemistry, and academic 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.

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 and 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.

Relatedly, the conventional wisdom has it that the principal contribution of university research to industrial innovation is to stimulate, trigger, new industrial R and D efforts aimed to take advantage of those breakthroughs. However, respondents in most industries reported that most of their R and 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 and D to solve problems effectively in projects so oriented, rather than to trigger new industrial R and D projects.

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.

The picture which 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 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.

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 and 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 twentieth 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.[14]

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 US 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 and 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 doesn't, 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. One important reason is the inevitable, and desirable, decentralization of decision-making. Effective research structures can't operate in the 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 doesn't.

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 doesn’t. An important objective of this paper is to help catalyze continuing analysis and cross country discussion of how to use public research programs as an effective support of industrial catch-up.

Notes

[1] The different views regarding the importance of learning processes and development of capabilities in economic catch up are well captured in the contrast between accumulation and assimilation theories of the growth of the Asian tigers (Kim and Nelson, 2000). The intellectual perils of neglecting the difficulties of learning what others have done, and the associated failures in earlier World Bank development strategies, have been highlighted by Easterly (2002).

[2] 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 1988-2001 period (National Science Board, 2004). Similar trends have been observed in the other countries.

[3] Christopher Freeman (1995) has proposed that Friederich 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.

[4] Private institutions in sciences and technical fields formed early on but due to the lack of financial support could not maintain scientific and engineering courses on a par with those offered by the public institutions.

[5] From all accounts, it appears that the government controlled the growth of the higher education system, including the activities of private institutions. As a result, the otherwise remarkable growth of the Japanese system of higher education did not really result in a trend toward mass higher education, at least until the 1960s. This may help explain why Japan did not experience during the early twentieth century a phenomenon of underemployment of graduates from academic institutions, a problem that surfaced clearly during more recent catch-up experiences.

[6] Odagiri (1999) provides a few instances of professors involved in the development of electrical equipment, pharmaceuticals, steel plants, and automobiles.

[7] This institute 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).

[8] The Research Institute named earlier (Riken) became the core research institute of a new zaibatsu whose subsidiaries operated in a large portfolio of business lines in metals, machinery, photographic equipment, and chemicals (Cusumano, 1989).

[9] 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.

[10] The significance of these projects for the chaebols' accumulation of capabilities in semiconductor technology has been evaluated differently by different scholars. 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 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.

[11] 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 (National Science Council, 1997).

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

[13] 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 twentieth century.

[14] 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.

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