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Background Paper Series

The Role of Knowledge-Based "Public Goods" in Economic "Catch-Up": Lessons from History

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Industrial Development Report 2005 Background Paper Series

The Role of Knowledge-based "public goods"

In economic "catchup":

Lessons from History

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Office of the Director-General

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

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Contents

Introduction

Much of the debate of the past 20 years over economic development policy for low- and middle-income economies has operated in an evidentiary vacuum. The focus of development policy in such institutions as the World Bank during the 1970s and 1980s on investment-led growth, criticized by Easterly (2003), was replaced by the "Washington Consensus" of the 1990s that encouraged economic liberalization and market-opening strategies. Yet neither strategy has enjoyed great success, and neither strategy seems to comport well with the evidence compiled during the past 100+ years on the institutional and policy strategies associated with successful economic "catchup" and development. For example, the remarkable economic transformation of such economies as the Republic of Korea and Taiwan Province of China since 1960 incorporates some elements of both the "investment-led growth" and "Washington Consensus" frameworks, but adheres fully to neither one and includes other important policies and institutions. Nor does the experience in economic "catchup" of Germany and the United States in the late 19th century closely adhere to the prescriptive tenets of either view.

One area in which this historical evidence seems to disagree most sharply with current orthodoxy concerns the contributions to economic development of investments, largely from public sources, in institutions and activities related to the creation, transfer, application, and dissemination of knowledge. With the exception of the World Bank's study of *Knowledge for Development* (1999), the design and role of a "knowledge-based infrastructure" for economic catchup has received surprisingly little attention in the literature on economic development.[1]

As Nelson (2003) points out, this inattention to the role of institutions in knowledge creation and exploitation reflects the narrow conceptualization of knowledge (and technology) that pervades much of economics. Economists have tended to treat knowledge as either a "public good" (in the case of fundamental research) or a "book of blueprints" (in the case of technology), and have not developed a nuanced view of the complex processes through which knowledge (both fundamental and applied) is created, emulated, imitated, and transferred. Similarly, the "blueprints" characterization of technology fails to comprehend the knowledge-intensive nature of the technology transfer and adaptation processes. A similarly simplistic view of the nature and structure of institutions has limited much of the economic analysis of these issues, although this oversight has been remedied to some extent in more recent work.[2]

This inattention to the role of institutions and the knowledge-intensive nature of many aspects of technology transfer and application has coincided with declining or stagnant levels of public investment in public R&D in many developing economies. In such areas as sub-Saharan Africa, these declines in public investment have been influenced by political turmoil or public health crises, in addition to the heavy government debts that resulted from the extensive loan programs of multilateral economic development organizations such as the World Bank. In other cases, a lack of supporting complementary policies has contributed to insufficient demand for the services of such institutions, and many of the components of national "knowledge infrastructures" have performed poorly. But flat or shrinking public investments also reflects a belief that such components of national "knowledge infrastructures" as national agricultural research and extension programs no longer are important in the face of higher levels of investment in innovation by private firms and/or substantial investments in international agricultural research institutions such as those included in the Consultative Group on International Agricultural Research (CGIAR). This view of the role of such national programs, like the conceptualization of knowledge transfer that underpins it, is misguided.

This paper presents a survey of the role of the "knowledge infrastructure" in economic catchup and development, drawing on historical studies of U.S., German, and East Asian experience. The paper discusses case studies of the role of higher education in these economies, the role of public R&D investment in the development of the South Korean and Taiwanese semiconductor components industries, the development of the U.S. public agricultural research and extension system, and the role of public investments in the development of the Internet in the United States. I rely on these case studies to discuss some guidelines for the design of the institutional components of national "knowledge infrastructures" and contrast these guidelines with what we observe in many developing economies.

The paper seeks to develop some general "design principles" for public R&D policy and the institutions that it supports, but it is important not to overstate these principles. Indeed, one of the most important conclusions from any such historical survey is the critical importance of context. Economic, technological, and political circumstances change over time and differ across nations, and institutions designed for one national setting will not necessarily prove suitable elsewhere. Public investments designed for one economic era may be poorly suited to its successor. Indeed, one of the most important principles for institutional design in this field is the need for both institutions and policies to be flexible and adaptive, capable of adjusting to changing circumstances. Such flexibility is rare in even the most capably administered organizations in the industrial economies, and its absence is no reason to condemn the lack of "capacity" in a developing economy. Nevertheless, it is essential that policy and institutional design incorporate the need for flexibility and adaptiveness.

Immediately below, I discuss the extent to which the "new economic order" of the WTO and related policies has changed the policy goals and requirements for economic catchup. This overview is followed by the case studies. The final sections consider some implications for policy in developing economies.

One of the most important of these implications can be stated succinctly: The future may not resemble the past, but it assuredly is not a future in which government support for R&D will no longer be required in developed or developing economies. Indeed, such public investments are an indispensable complement to the export-oriented policies that are at the heart of the Washington Consensus. For example, national agricultural research systems have a key role in the development of higher-value agricultural exports that can conform to the increasingly complex phytosanitary regulations associated with such high-income markets as the European Union, the United States, and Japan (See Naik, 2004; Kiggunda, 2004; Finger and Schuler, 2000). Yet little support for adaptation to these requirements currently is available from either national developing-economy governments or the WTO and related multilateral agencies.

Given the evidence of abundant needs for public R&D investment as a complement to market-oriented development strategies, the (limited) evidence of declines in such investment is distressing. Unfortunately, the availability of data typically is correlated with GDP per capita, and reliable time series on domestic R&D investment (rarely disaggregated into public and private R&D investment) are not available for most low-income developing economies. Nonetheless, as I note below, the limited evidence on public financing for agricultural R&D, an important focus for public R&D expenditures in high-income as well as middle-income developing economies, indicates that such funding has declined in sub-Saharan Africa since the 1970s (Pardey et al., 1997). Other evidence (Morales, 1998) points to declines in public agricultural R&D investment in Latin America during the same time period. Merely reversing funding cutbacks is insufficient; the failures of institutional design that have led to poor performance must also be addressed. But these problems call for reform rather than disinvestment.

R&D investment trends in developing economies

Data on R&D spending in developing economies are scarce, and time series data are especially scarce. Figures 1 and 2 contain data from UNESCO, which in turn are based on reports from member states, on R&D/GDP ratios for selected Latin American and Asian economies for the 1996-2001 period. These data cover few low-income developing economies (virtually no sub-Saharan African nations are included), and may be suspect for even the countries included in the Figures. In addition, of course, these data do not distinguish between public and private R&D investment. Nonetheless, the Figures highlight significant differences between levels and trends in R&D spending in the late 20th century between these two regions.

In Latin America, the R&D/GDP ratio exceeds 1% only for Brazil, and only for 2001 in that nation. With the exception of Brazil, the trends in Figure 1 are essentially flat for the late 1990s—the failure of Chile's R&D/GDP ratio to grow during this period is particularly striking, in view of this nation's relative success with economic liberalization and macroeconomic stabilization during the period. No economy other than Brazil exhibits an R&D/GDP ratio above .6% for the period. Other data, however, suggest that absolute levels of inflation-adjusted R&D spending grew during 1990-96 in Costa Rica, Brazil, and Mexico, while declining in Venezuela, Chile, and Argentina during the period (National Science Foundation, 2000).

Middle-income Asian economies present a significant contrast to Latin America, as R&D/GDP ratios grow significantly for all of the five nations represented in Figure 2. By the end of the 1996-2001 period, the R&D/GDP ratio exceeds 2.5% for the Republic of Korea and is above 2% for Taiwan; by comparison, the R&D/GDP ratio for Spain in 2001 was .96% and that for Portugal was .83%. R&D/GDP for China is above 1% by 2001, and exceeds .75% for India. Only Malaysia in 1996-98 lies in a region similar to that of the Latin American economies depicted in Figure 1, and it is likely that more recent data would reveal growth in this nation's R&D/GDP ratio.

A second important element of contrast between the R&D investment patterns in most Latin American economies and the most rapidly growing East Asian economies (Taiwan, the Republic of Korea, and Singapore) is the larger share of national R&D investment accounted for by private firms in these Asian economies. Government accounts for roughly 70% of national R&D investment in most Latin American economies, considerably higher than the share of government in national R&D spending in these three fast-growing East Asian economies, which display government R&D shares of 40% or less.

Figure 1
R&D/GDP ratio, selected Latin American economies, 1996-2001

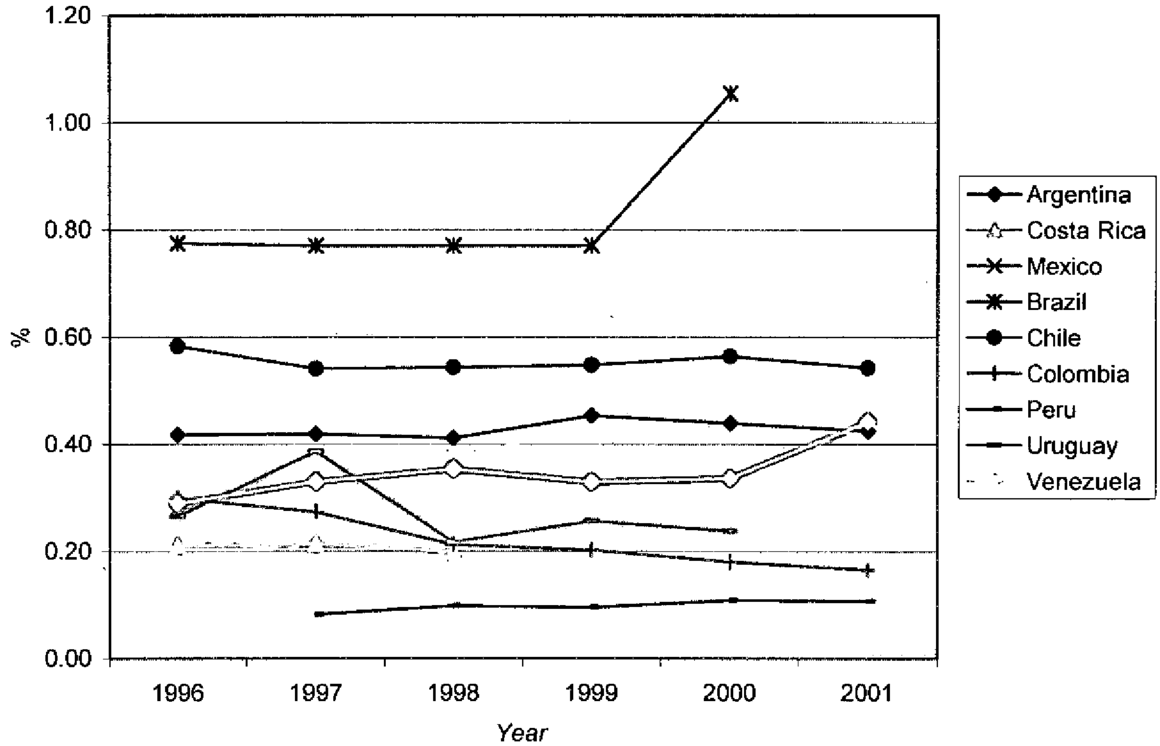
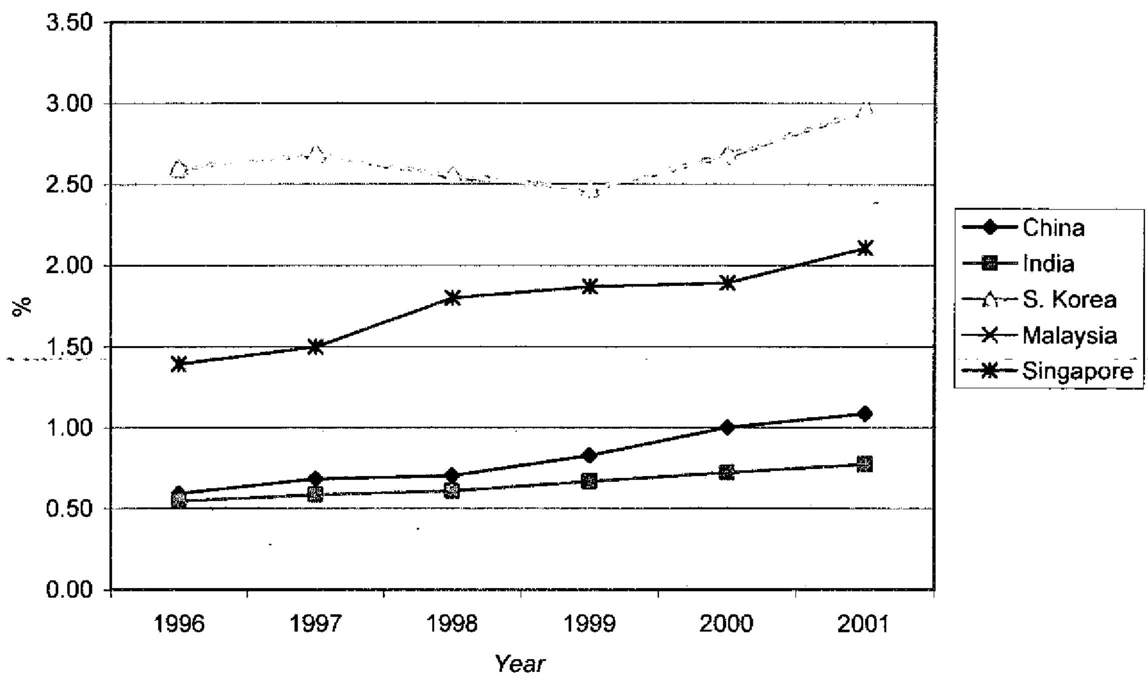


Figure 2
R&D/GDP ratio, selected Asian economies, 1996-2001



Economic 'catchup' in the 21^{st}-century global economy

Economic "catchup" typically is defined as a process through which national economies that are behind the economic and technological frontier defined by one or more advanced economies succeed in narrowing the gap (typically measured in terms of labor or "multi-factor" productivity) between themselves and these "leading" economies. As Nelson (2003), Fagerberg and Godinho (2004) and numerous other scholars have pointed out (most notably, Gerschenkron, 1962), the process of economic catchup consists of much more than imitation of the industrial technologies, policies, and institutions observed in the leading economies. The process of inward transfer and "imitation" of industrial technologies from the leading economies involves considerable adaptation of these technologies to a different economic environment, and in a number of instances, entirely new technologies are developed in the "lagging" economy (e.g., the "Toyota production system" in Japan's automotive industry).

Economic catchup also involves considerable modification by follower nations of the economic policies and institutions of the leaders. Both the United States and Germany used tariffs to protect domestic producers during much of their economic "catchup" with Great Britain, a nation that through most of the 19^{th} and earlier 20^{th} centuries adhered to free trade. Similarly, the institutional innovation highlighted by Gerschenkron in German economic "catchup" was the development of the large industrial banks that financed and invested in many of the German firms in such "new industries" as chemicals. A similar mix of institutional, economic, and policy imitation and innovation is clear in the economic "catchup" of Taiwan Province of China and the Republic of Korea.

Economic "catchup" thus has always involved some adaptation of leader nations' policies and institutions to a different set of circumstances in the follower nation, along with other forms of institutional, policy, or technological innovation. Nevertheless, the economic environment of the 21^{st} century arguably has shifted in ways that require more far-reaching institutional innovations on the part of would-be "catchup" nations in the contemporary global economy. Nelson (2003) and others have argued, for example, that the global trade regime overseen by the World Trade Organization (WTO), most notably the strengthening of international intellectual property rights incorporated in the TRIPS agreement that is one part of the WTO's foundations, may limit the prospects for "reverse engineering" and other forms of imitation of advanced-nation industrial technologies by would-be follower nations. If such inward technology transfer becomes more difficult or limited, developing nations will have to invest more heavily in institutions and policies that can support the creation of new technologies. Similarly, the tariff provisions of the WTO agreement may limit the scope for pursuit by "catchup" nations of the industrial protection that historically played a role in U.S., German, Japanese, South Korean, and Taiwanese economic catchup.

Although the environment faced by developing nations assuredly has changed from that of the Cold War "catchup" economies such as the Republic of Korea and Taiwan Province of China (I treat post-1945 Japan in the current discussion as an example of rapid economic reconstruction rather than catchup), concerns over the limited availability of industrial technologies may be overstated. Many scholars argue that with the exception of pharmaceuticals and chemicals, formal patent protection poses a relatively weak obstacle to the types of reverse engineering and imitation that many East Asian engineers and firms pursued during the 1960s and 1970s. And the tariff provisions of the WTO do not preclude the establishment by nations of relatively high tariffs on industrial imports, although these tariffs are "bound" and cannot be raised further (Noland and Pack, 2003). Indeed, many of the protectionist policies of such postwar "catchup" nations as the Republic of Korea, as well as Japan, relied on government control over foreign-currency exchange rates and reserves, in addition to formal tariffs.

However distortionary and ill-advised, such exchange-rate policies are not precluded by the WTO agreement.

Moreover, in at least one key area, the WTO agreement establishes the possibility (as yet unrealized) for significant improvements in the prospects for developing economies' agricultural exports. This potential has not yet been realized, thanks to the failure of the high-income signatories to live up to the spirit as well as the letter of their obligations under the agricultural portions of the WTO agreement. Nonetheless, expansion of agricultural exports may offer a novel avenue for 21st-century economic "catchup." Realization of this possibility, however, requires a renovation in the national agricultural R&D systems of many of the low-income economies, in addition to a commitment by high-income economies to liberalize their agricultural markets. Public investments in such "generic" domestic research programs as those included in the national agricultural research systems of many developing and most high-income economies are not restricted by WTO regulations.

The export of higher-value agricultural products also requires far-reaching improvements in the logistics, customs, and transportation infrastructure of many low-income developing economies, as well as substantial investments in technical assistance (including considerable support for technology development, adaptation, and diffusion) by low-income economies. The costs of conformity to the phytosanitary regulations that high-income nations impose (often with the intention of protecting their domestic producers) on agricultural imports (particularly for fresh produce and/or processed agricultural products) are substantial. Finger and Schuler (2000) reported that the costs of upgrading domestic agricultural processing practices in Argentina (for exports of plants and animal products) and Hungary (solely in the area of improvements in slaughterhouse sanitation) amounted to $80 million and $40 million respectively, The average cost of $60 million exceeds the total annual agricultural research budget for 1991 of any sub-Saharan African nation, with the exceptions of South Africa, Nigeria, and Kenya (Pardey et al., 1997).[3]

There is little doubt that the policies and institutions required for economic "catchup" in the 21st century will differ in a number of respects from the "catchup" policies of previous eras. Indeed, one of the most important guidelines for such policies is the importance of tailoring them to the needs and circumstances of the current and prospective environment, rather than imitating some "model" of "best practice" that may have little relevance to current circumstances. Unfortunately, our knowledge of both current circumstances and the requirements for adapting historically successful policies to such circumstances is limited. The case studies below are intended to offer exemplary, rather than comprehensive, evidence on some of these issues.

Knowledge infrastructure for research and education: The role(s) of universities in economic catch-up

Introduction

Universities are widely cited as a critical institutional actor in national innovation systems (see Nelson, 1993; Edquist, 2004, Mowery and Sampat, 2004, and numerous other works). As Edquist (2004) notes, the precise definition of "national innovation systems" remains somewhat hazy, but most of the large literature on the topic defines them as the institutions and actors that affect the creation, development, and diffusion of innovations. The literature on national innovation systems emphasizes the importance of strong linkages among these institutions in improving national innovative and competitive performance, and this emphasis applies in particular to universities within national innovation systems.[4] The "national" innovation systems of the industrial economies appear more and more interdependent, reflecting rapid growth during the post-1945 period in cross-border flows of capital, goods, people, and knowledge. Yet the university systems of these economies retain strong "national" characteristics, reflecting significant contrasts among national university systems in structure and the influence of historical evolution on contemporary structure and policy.

The economically important "outputs" of university research differ over time and across industries.[5] They include, among others: scientific and technological information[6] (which can increase the efficiency of applied R&D in industry by guiding research towards more fruitful departures), equipment and instrumentation[7] (used by firms in their production processes or their research), skills or human capital (embodied in students and faculty members), [8] networks of scientific and technological capabilities (which facilitate the diffusion of new knowledge), and prototypes for new products and processes.[9]

The relative importance of training and research differs considerably among the university systems of OECD member nations. These differences reflect cross-national differences in industry structure, especially the importance of such "high-technology" industries as electronics or information technology that are research-intensive and (at least since the end of the Cold War) rely heavily on private-sector sources for R&D finance. In addition, of course, the role of nonuniversity public research institutions differs among these economies, and is reflected in the contrasts in universities as performers of publicly funded R&D. These structural contrasts are the result of a lengthy, path-dependent process of historical development, in which institutional evolution interacts with industrial growth and change.

These path-dependent historical processes are revealed in a comparison of the roles of national university systems in the processes of "economic catchup" in the United States and Germany in the late 19th and early 20th centuries, Japan in the 20th century, and the recently industrialized nations of the Republic of Korea and Taiwan Province of China since 1960. The contributions of each nation's university system to training, education, and other innovation-related activities differ considerably, as does the evolution of the structure of each nation's system of higher education. This brief summary highlights the significant contrasts in the roles of knowledge-based "public goods" associated with the processes of economic catchup, as opposed to the creation or maintenance of technological leadership in a global economy.

Universities in economic catchup in the 19th and early 20th centuries: Germany, the United States, and Japan, 1870-1940

Consistent with the above characterization, the roles of universities differed in the processes of economic "catchup" associated with the growth of the German, U.S., and Japanese economies in the late 19th and 20th centuries. All three of these nations experienced rapid industrial development during this period, and both Germany and the United States developed strong competitive capabilities in such key industries of the "Second Industrial Revolution" as chemicals and electrical equipment, closing the gap between their domestic knowledge-based industries and those of the economic leader of the mid-19th century, Great Britain. Although Japan's economy did not challenge British (or German or U.S.) leadership in these industries before 1940, Japan nonetheless experienced an economic transformation between 1868 and 1940 that arguably was even more dramatic than those of the United States or Great Britain, inasmuch as its formerly isolated, agricultural economy rapidly industrialized and penetrated world markets in such sectors as textiles.

The domestic higher education system of each of these nations was key to their economic catchup. But the contributions of each nation's universities to economic catchup differed substantially, and each nation drew on the higher education systems of other nations in developing a domestic pool of scientists and engineers. Broadly speaking, the growth of Germany's chemicals industry followed the development of strong research capabilities in German universities during the 19^{th} century, and a similar pattern is apparent in the development of the German electrical equipment industry. The same cannot be said of either Japan or the United States, however, where domestic universities' contributions to training of scientists and engineers outstripped their contributions to research throughout this period. In the case of Japan, university contributions to training remained more significant than academic research excellence through much of the post-1945 period, although university faculty were important technical consultants for many large Japanese industrial firms. Indeed, the weakness of scientific research in Japan's national universities reflected the legacy of the structure established in the late 19^{th} century.

Germany (more precisely, Prussia, in advance of the formation of the German state in 1870) was where the modern research university, focused on the promotion of research in a discipline-based organizational structure, originated. This reform occurred in the wake of Prussian defeat by Napoleon in the early 19^{th} century, and in the early decades following these reforms, Germany universities moved to the forefront in scientific research in chemistry. Indeed, the production of advanced degreeholders in chemistry by German universities outstripped the capacity of the nation's embryonic chemicals industry to absorb them, and many of the technical personnel in the mid-19^{th}-century British chemicals industry (including such giants as Justus Liebig) were German citizens who had trained in their nation's universities.

The rapid expansion in Germany's network of research and technical universities during the second half of the 19^{th} century thus was critically important to the growth of industrial research, particularly in the chemicals industry. German universities produced a large pool of scientifically trained researchers (many of whom sought employment in France and Germany during the 1860s), university faculty advised established firms, and university laboratories provided a site for industrial researchers to conduct scientific experiments in the early stages of the creation of in-house research laboratories.

Within the German research universities of the 19^{th} century, faculty research was central to the training of advanced degreeholders. In addition, the German polytechnic institutes that had been founded during the 1830s by the various German principalities were by the 1870s transformed into technical universities that played a central role in training engineers and technicians for the chemicals and electrical equipment industries. By the 1870s, according to Murmann (1998), Germany had nearly 30 university and technical university departments in organic chemistry, and seven major centers of organic chemistry research and teaching. And many of these technically trained personnel moved into senior management positions within German industry, further strengthening the links between corporate strategy and industrial research.

The contrast between Germany and Great Britain in the role of universities is especially striking.[10] British universities received far less public funding, supported less technical education, and were less closely linked with industrial research (especially in such industries as chemicals) than was true in Germany by the 1880s. British university enrollment increased by 20% between 1900 and 1913, far less than the 60% increase in German university enrollment during the same period. Enrollment at the "redbrick" British universities (largely founded during the 19^{th} century, this group excludes the ancient English universities of Oxford and Cambridge) grew from roughly 6400 to 9000 during 1893-1911, but only 1000 of the students enrolled in these universities as of 1911 were engineering students, while 1700 were pursuing degrees in the sciences (Haber, 1971, p. 51). By contrast, the German technical universities alone enrolled 11,000 students in engineering and scientific degree programs by 1911. British government funding of higher education amounted to roughly £26,000 in 1899, while the Prussian government alone allocated £476,000 to support higher education. By 1911, these respective amounts stood at £123,000 and £700,000 (Haber, 1971, p. 45 and p. 51).

The German universities were funded largely from public sources. Lobbying by chemicals industry organizations, the election to legislative bodies (e.g., the Prussian Parliament) of leading figures from the chemicals industry,[11] and the creation of industry-academic collaborative organizations for the support of applied research all played a role in expanded public funding for academic research in chemistry, culminating in the establishment of the Kaiser Wilhelm Institute for Chemistry in 1911.

The U.S. research university appeared in its modern form first at Johns Hopkins University in 1877, which was privately financed and modeled on the German structure. Although the Morrill Act of 1862 led to the establishment of new public universities, the quality and quantity of research within this system was modest until the late 19th century. Nevertheless, enrollment in the U.S. higher education system, characterized by wide diversity in institutional type (public or private, secular or religious, etc.), size, and quality, grew even more rapidly than did German university enrollment:

> Education statistics for the entire U.S. show the explosive growth of the American system of higher education after 1862. Starting at a lower enrollment level than Germany, the increase in the United States is even higher than in Germany for the same period.
>
> Because U.S. degree statistics for the period before World War I are already broken down by subject, it is possible to gain a quantitative picture about the growth of individual disciplines. The yearly number of U.S. bachelor's degrees in all fields and in chemistry increased by over 400% in the period from 1890 until 1914 (7,228 to 31,540 and 631 to 2573 respectively). During the same period, the yearly number of doctorates in chemistry increased by about the same percentage from 28 to 107... (Murmann, 2003b, p. 18)

The pursuit of research was recognized as an important professional activity within both U.S. industry and higher education only in the late 19th century, and research in both venues was influenced by the example (and in the case of U.S. industry, by the competitive pressure) of German industry and academia. The reliance of many U.S. universities on state government funding, the modest scope of this funding, and the rapid expansion of their training activities all supported the growth of formal and informal linkages between industry and university research. U.S. universities formed a focal point for the external technology monitoring activities of many U.S. industrial research laboratories before 1940, and at least some of these university-industry linkages involved the development and commercialization of new technologies and products.

Both the curriculum and research within U.S. higher education were more closely geared to commercial opportunities than was true in many European systems of higher education. Swann (1988) describes the extensive relationships between academic researchers, in both public and private educational institutions, and U.S. ethical drug firms that developed after World War I.[12] Hounshell and Smith (1988, pp. 290-292) document a similar trend for the Du Pont Company, which funded graduate fellowships at 25 universities during the 1920s and expanded its program during the 1930s to include support for postdoctoral researchers. During the 1920s, colleges and universities to which the firm provided funds for graduate research fellowships also asked Du Pont for suggestions for research, and in 1938 a leading Du Pont researcher left the firm to head the chemical engineering department at the University of Delaware (Hounshell and Smith, 1988 p. 295).

Training by public universities of scientists and engineers for employment in industrial research also linked U.S. universities and industry during this period. The Ph.D.'s trained in public universities were important participants in the expansion of industrial research employment during this period (Thackray, 1982, p. 211).[13] The size of this trained manpower pool was as important as its quality; although the situation was improving in the decade before 1940, Cohen (1976) noted that virtually all "serious" U.S. scientists completed their studies at European universities. Thackray et al. (1985) argue that American chemistry research during this period attracted attention (in the form of citations in other scientific papers) as much because of its quantity as its quality.[14]

The Japanese university system emerged as one element of the wide-ranging reforms associated with the Meiji Restoration of 1868. "Persuaded" (more accurately, coerced) by Commodore Perry's naval expedition to (re)open its economy and society to foreign trade and influence, Japan's political leadership became concerned over the nation's economic backwardness, and launched a large-scale effort at inward transfer of technologies, ranging from mining to textiles. Part of this effort involved the creation of a national university system that was modeled on that of Prussia, widely seen as the world leader of the time. Foreign scholars and university administrators from Prussia, Great Britain, and the United States all played prominent roles in the reform of the Japanese university system. The Engineering Department of what became Tokyo University, founded in 1886, produced graduates who founded many of the major manufacturing firms of pre-1940 Japan (Odagiri and Goto, 1993).

The major contributions of Japanese universities to the economic transformation of Japan during the Meiji Era was training of skilled personnel for technical and managerial positions in the government agencies and firms that were created as part of the wide-ranging reforms of the period. Faculty also provided consulting services to newly founded firms in such industries as electrical equipment. University-based research made important contributions to the inward absorption and dissemination of advanced scientific and engineering knowledge from foreign sources that characterized Japan's catch-up activities during the period. During and after World War I, when Japan's economy experienced rapid industrial growth in the face of curtailed supplies of advanced equipment and materials of all sorts, additional universities were established, and a number of public research institutes in fields ranging from electronics and chemistry to silk production were established.

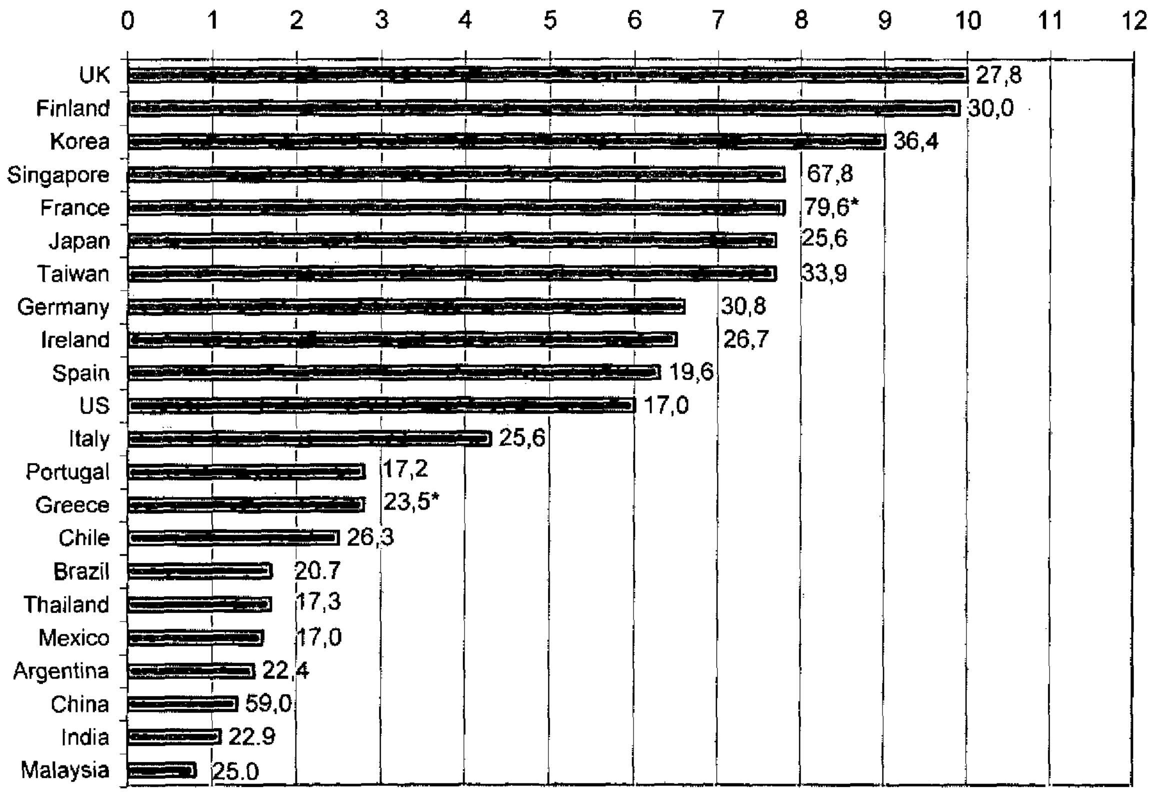
Through much of the post-1945 period of reconstruction and economic catchup, the contributions of Japanese universities to training remained far more significant than their research performance. In part, this reflected the centralized control of the leading Japanese research universities by the Ministry of Education, which included reliance on formula rather than competitive funding of academic research. In addition, the extensive network of government research laboratories absorbed a substantial share of public R&D funding. By the 1990s, policymakers expressed great concern over the (perceived) lack of linkage between university and industrial research in Japan, as well as the (perceived) weakness of the system in advancing basic research. Although some initiatives have been undertaken to improve patent-based technology transfer from universities to industry, much of the basic structure of Japan's public research universities has changed little from that of 19^{th}-century Prussia, the original model for this inward transfer of technology.

Universities in economic catchup: Taiwan Province of China and the Republic of Korea, 1960-2000

By 1999, both Taiwan Province of China and the Republic of Korea ranked ahead of many other East Asian economies as well as most other OECD economies in the share of the

24-year-old population with first degrees in science and engineering (Figure 3).[15] Both nations' domestic university systems made significant contributions to the training of a technical workforce for the rapidly growing knowledge-intensive industrial sector in each economy. But the research contributions of the South Korean and Taiwanese university systems to the remarkable development of industry in each economy were modest.

Figure 3
Ratio of First University Degrees in Natural Sciences and Engineering to 24-year-olds in the population, 1999 (%).



Although Japanese colonial administration left Taiwan Province of China with relatively high levels of primary educational attainment in the earliest phases of independent economic development, the Republic of Korea had much lower levels of primary school attainment within its population,[16] and secondary and tertiary educational attainment levels in both economies were low in the early 1950s. Both nations experienced rapid growth in university enrollments during the 1950s, leading to the high levels of scientific and technical educational attainment at the end of the 1990s noted above. The number of South Korean students enrolled in universities (excluding junior colleges) grew from roughly 8,000 in 1945 to slightly more than 38,000 in 1953, nearly 91,000 in 1960 (6.4% of the relevant population cohort) and more than one million (exceeding 25% of the relevant cohort) in 1990. The number of universities in the Republic of Korea grew from 69 in 1966 to 100 in 1985 (Kim, 1993). Equally significant, however, was enrollment growth in junior colleges (2-year institutions), which increased from 4,900 in 1960 to nearly 507,000 by 1994. At least 70% of this junior-college population was enrolled in technical programs by the 1980s and 1990s (Kim, 1997). Enrollment growth rates in Taiwanese universities and vocational training institutes during this period also were rapid, and as of the early 1990s, 55% of students were enrolled in vocational institutes and 45% of enrolled students were in academic universities. The South Korean and

Taiwanese higher education systems both include a mix of publicly and privately funded universities and colleges.

This enormous growth in university enrollments placed some stress on labor markets for scientists and engineers in both nations. Unemployment among college graduates was especially serious in the Republic of Korea in the 1960s. A substantial fraction of college graduates in both nations pursued advanced degrees abroad and failed to return, creating a significant "brain drain" problem. The Republic of Korea's publicly funded research institutes provided a partial solution to the nation's college graduate unemployment problem, but a much more significant solution emerged with the rapid growth of South Korean industry in the 1970s and 1980s. Similarly, growth in Taiwan Province of China's high-technology industrial sector (notably, the Hsinchu Science Park) served to attract many Taiwanese émigrés with advanced degrees back to the nation of their birth. The experience of both nations' growth in university education highlights the failure of an increased supply of trained personnel to create its own demand. The growth in demand for higher education and the growth of industry are intertwined—it is simplistic to argue that one is a necessary and logical precondition for the other.

Despite their remarkable achievements in training graduates, particularly in technical fields, the South Korean and Taiwanese higher education systems have yet to develop strong scientific and technical research capabilities. In this respect, they resemble U.S. universities before 1940 and, perhaps, Japanese universities. Taiwan Province of China's public universities in particular are hampered by some elements of the Japanese system on which they were modeled, characterized by strong central-government control of policies and little autonomy to develop research collaborations with industry or other institutional innovations. Public funding of research in the Republic of Korea's universities lags behind funding of research in public laboratories; according to Kim (1993), expenditures from all sources on university R&D in 1987 amounted to only 5.4% of total national R&D expenditures, despite the fact that South Korean universities accounted for more than 33% of the nation's R&D manpower and more than 78% of its Ph.D. degreeholders.

The late Linsu Kim, one of the most insightful scholars of South Korean industrialization, argued in 1993 that the rapid growth of university enrollments in the Republic of Korea had significantly outstripped growth in financial support for education and research in both the public and private universities, noting that "...the student-professor ratio has retrogressed from 22.6 in 1966 to 35.8 in 1985, making all universities primarily undergraduate teaching-oriented rather than research oriented. Thus, the 'publish or perish' principle is not applied." (p. 371). This statement highlights the failure to develop the type of strong complementarities between teaching and research in the Republic of Korea's university system that have proven to be effective for both activities in other national higher education systems, notably that of the United States.

Taiwan Province of China's higher education system has also been criticized for its modest research capabilities. Given the concern of high-level policymakers in both nations over competitiveness in the "knowledge-based economy," where research-teaching complementarities appear to enhance the economic contributions of higher education, it is likely that public R&D funding for higher education will increase. But the design of such programs for public support of academic research raises important issues. The Japanese experience suggests that increases in research funding that are not accompanied by greater emphasis on competitive allocation of public research funds will have limited effects on the overall quality of the academic research enterprise.

Implications for developing economies

The discussion above suggests that economic catchup through the past 125 years has been linked with expansion (typically, measured in terms of the share of the 18-24 year-old population enrolled in tertiary education) in domestic higher education. But the temporal structure of this linkage varies somewhat among "catching-up" economies. The early stages of growth in enrollments in higher education (including technical institutes) and increased research in Germany appear to have preceded the growth of the knowledge-intensive industries in which German firms performed well in the late 19th century. Although the 1862 Morrill Act laid the foundations for growth in publicly funded higher education in the United States, expansion and restructuring of the U.S. higher education system occurred during the late 19th century in parallel with growth in such industries as electrical equipment and chemicals. The reform of Japanese higher education occurred in parallel with the early development of such export-oriented Meiji period industries as textiles. In the Republic of Korea and Taiwan Province of China, however, the initial expansion of higher education preceded significant growth in major export industries, producing significant unemployment among degreeholders and exacerbating "brain drain." The roles of higher education in training and research also vary among these economies during the period of economic catchup. Nonetheless, increased training of skilled manpower in universities, technical institutes, and other tertiary-education institutions appears to have been closely linked with the economic transformation of all of these 5 nations.

Unfortunately, this historical summary also suggests that labor-market imbalances for technical degreeholders in the wake of expanded public investments in higher education are not unusual, and may persist for a number of years. There are no easy solutions to these problems, although policies to support inward investment in developing economies for such "outsourcing" activities as call centers, engineering support, and basic software coding may ease adjustment. But such inward investment also requires high-quality infrastructure in areas such as electrical power and international telecommunications, in addition to well-trained technical graduates. Other policies to address such unemployment may include steps to ease outward (and, ideally, temporary) emigration of technical degreeholders, something that proved to be economically valuable for Taiwan Province of China, Germany, and the Republic of Korea. Nevertheless, the possibility of such labor-market imbalances may well spark political criticism of expansion in higher education, and it is important that any such expansion contribute to reductions in socioeconomic inequality rather than enhancing it.

The importance of tertiary education in these instances of successful economic catchup is one of several bases for concern over recent trends in tertiary education in the developing economies. As recent reports from World Bank have pointed out, the gap between the United States and developing economies in tertiary-education enrollment rates has widened during 1980-1995 from 50% to 72%, and enrollment rates in such regions as East Asia range from 2% to more than 50%.[17] According to the World Bank (2002b, p. 49), public spending on tertiary education as a share of total spending on public education declined during the 1990-2002 period in Bangladesh, China, Ghana, Guinea, Nepal, Oman, and the Philippines, among other countries. By comparison with most industrial-economy national higher education systems, developing-economy universities in particular perform a smaller share of public financed R&D (this appears to be true as well in the Republic of Korea and Taiwan Province of China) and the share of their students enrolled in advanced-degree programs (MA, MS, PhD) is smaller.

In addition, the institutional differentiation that characterizes the higher-education systems discussed in this section (including those of the Republic of Korea and Taiwan Province of China) is lacking in most developing-economy systems of tertiary education—nonuniversity institutions, such as community colleges, polytechnics, and other two-year training institutions account for a smaller share of students enrolled in tertiary education. This relatively low level of institutional differentiation contributes to low responsiveness of many of these nations' tertiary education systems to changes in labor markets and demand for different types of degrees. The combined effects of student fees and (limited) financial assistance programs in many developing-economy systems of higher education work to limit access to higher education and thereby reinforce, rather than eroding, social and economic inequality within these nations.

The tertiary education systems of many developing economies thus suffer from structural and financial problems that are mutually reinforcing. A lack of funding, as well as a lack of competitive funding for student education and training, limit the possibilities for entry by new types of institutions of the sort that could increase the differentiation and responsiveness of these nations' tertiary education systems to labor market forces. Similarly, limited funding for academic research, and (in most cases) the absence of competitive processes for allocating the bulk of these limited academic research funds, weaken or preclude the inter-institutional competition that has proven to be a very powerful force in upgrading the research capacity of some national university systems, such as that of the United States.

The challenges facing developing-economy systems of higher education are forbidding. Increased funding is a necessary but not a sufficient condition for improving the contributions of these systems to economic catchup. The focus of many analyses of the social returns to public investments in education on a "human capital" model that highlights increases in earnings often overlooks the important externalities created by expanded tertiary education, and therefore often favor increased investment in primary and secondary education (Birdsall, 1997).

Any increases in funding for post-secondary education should be combined with institutional reforms that will enhance access to tertiary education by all members of these societies, increase opportunities for the foundation and operation of new types of tertiary-education institutions, and enhance autonomy and competition among academic research centers. In this area as well as others, the fundamental design principle of separating the source of funding from the performer of the activities being supported (training, research) is highly desirable, albeit demanding in its requirements for sophisticated administrative capabilities. Experimentation with new institutional structures for tertiary training and education, as well as increased decentralization within domestic tertiary-education systems, also can improve performance and the economic contributions of tertiary education. Such institutional innovation must nevertheless be accompanied by effective monitoring and evaluation of performance and outcomes.

Knowledge infrastructure for the semiconductor industry: Government research institutes in Taiwan Province of China and the Republic of Korea

A nation's level of economic development affects the role of its national innovation system in technology transfer and absorption. Kim and Dahlman (1992) argue that many of the "late-industrializers" of the postwar period, such as the Republic of Korea and Taiwan Province of China, initially exploited foreign sources of relatively mature technologies. Such technology could be transferred through channels that relied on 'arms length' transactions, such as licensing, turnkey plants, and capital goods imports. Domestic R&D investment was less important during the 1950s and 1960s in both economies, and domestic entrepreneurs demanded little by way of public R&D funding or other formal technology programs.

The national innovation systems of these economies nonetheless contributed a critical input, in the form of scientists and engineers. The Republic of Korea and Taiwan Province of China, along with other East Asian high-growth economies, are far ahead of other developing economies in the shares of the relevant populations enrolled in post-secondary educational programs in science and engineering (Figure 3). Some of this expansion in S&E-related higher education may well be an effect, rather than a cause, of rapid income growth (recall that South Korean college graduates in particular experienced high rates of unemployment in the 1950s—see Kim, 1993; 1997). Nonetheless, as the previous section noted, both the Republic of Korea and Taiwan Province of China had institutions and policies in place to support human capital formation well before their attainment of high rates of economic growth during the 1960s and 1970s.

In both the Republic of Korea and Taiwan Province of China, indigenous R&D institutions became more prominent in the inward transfer and application of technologies from external sources during the 1970s and 1980s. Interestingly, however, the Republic of Korea and Taiwan Province of China pursued different paths toward expanded domestic R&D investment. In Taiwan Province of China, increases in public R&D investments complemented growth in private-sector R&D spending. Although the Republic of Korea's government also increased its R&D investments during the 1960s and 1970s, their scale and importance in electronics were dwarfed by the investments of the large South Korean *chaebol*.

The contrasting roles of public and private R&D investment, as well as the strength or weakness of the linkages between public and private innovative activities in these two economies' semiconductor industries, reflect the different financial and industrial structures that had emerged in Taiwan Province of China and the Republic of Korea by the early 1970s. Although much of its heavy industry was controlled by state-owned firms during the 1950s, the Taiwanese economy underwent considerable financial liberalization (under pressure from U.S. economic advisers) during the 1960s, and most private industrial firms by then relied heavily on equity finance. One result of this was the creation of a large population of small firms in such sectors as consumer electronics.

This industrial structure contrasted sharply with that of the Republic of Korea, whose industrial-finance system was subject to tighter state control. Most sectors of South Korean industry were dominated by large, highly diversified firms (the *chaebol*), which had favorable access to state industrial-development funds.[18] These firms dominated such emergent high-technology sectors as consumer electronics and semiconductors. The combination of state subsidies for industrial activities (a practice that rewarded the lobbying activities of large firms) and highly diversified giant industrial firms in the Republic of Korea severely limited entry by new firms into such sectors as semiconductors.

These contrasting industrial structures meant that public R&D "knowledge infrastructure" investments played very different roles in Taiwan Province of China and the Republic of Korea. In the Republic of Korea, public R&D investments accounted for 75% of total national R&D in 1975, a share that declined to 16% by 1994 (Kim, 1997), even as the R&D/GNP ratio grew from .42% to 2.61%. The Taiwanese R&D/GNP ratio in 1995 was 1.8%, and public funds accounted for roughly 40% of total national R&D investment (Amsden, 2001).

Similar differences between the two nation's R&D systems are obvious from a summary of Taiwanese and South Korean patents issued by the United States Patent and Trademark Office (Amsden and Chu, 2003). The top 4 Taiwanese patenters in the United States during 1980-96 include 3 government or quasi-public agencies and one industrial firm (Taiwan Semiconductor Manufacturing Company, TSMC), which accounts for 89, slightly less than 8%, out of 1140 Taiwanese patents. South Korean patenting, however, is completely dominated by *chaebol*, which occupy all of that nation's top 4 spots (a total of 3839 patents). One result of these contrasting industrial and policy structures was a more prominent role for government institutions in the development of Taiwan Province of China's semiconductor industry. By contrast, South Korean firms were the key actors in the inward technology-transfer process that laid the foundations for that nation's semiconductor industry.

Taiwan Province of China: The Industrial Technology Research Institute and the Electronics Research Services Organization

Taiwan's Industrial Technology Research Institute (ITRI), founded in 1973, and its Electronics Research Services Organization (ERSO), founded in 1974, were important sources of new technology, trained manpower, and (eventually) new firms for the nation's domestic semiconductor industry. ERSO in particular played a key intermediary role in the initial efforts to transfer semiconductor process technologies from U.S. firms to Taiwan Province of China, relying on a technology-sharing agreement with RCA. Employees from ERSO and ITRI were transferred to RCA's U.S. semiconductor production facilities for training (a total of 295 ERSO staff were sent to RCA during the 1977-79 period), and an experimental production facility was established within ERSO in 1977. By 1979, with the completion of the RCA partnership, ERSO "spun off" a new firm, United Microelectronics Corporation (UMC), 40% of whose initial financing came from government sources and 60% from private funds. ERSO's deputy director was the first CEO of the firm and 14 ERSO employees were among UMC's first employees. ERSO also provided training for new employees of UMC (Chen et al., 2001). ERSO thus relied on new-firm formation and "privatization" for the dissemination within Taiwan Province of China of externally sourced technology, a strategy that was feasible only in a financial system with a substantial supply of equity financing for new enterprises.

This "spinoff" model was used extensively by ERSO and ITRI in subsequent years in the semiconductor and other industries. In 1982, ERSO spun out a semiconductor design firm, Syntek, much of whose senior management came from ERSO. A major ERSO project in very large-scale IC (VLSI) fabrication technology concluded in 1987 with the "spinoff" of Taiwan Semiconductor Manufacturing Company, which was jointly financed at the time of its foundation by the Taiwanese government and Philips of the Netherlands. TSMC, headed by a former senior executive from Texas Instruments, became a successful "foundry" fabrication firm in the semiconductor industry.

ERSO undertook other R&D projects in DRAMs, photomask fabrication, and related technologies in the semiconductor industry, relying in many of these projects on the "spinoff" model, in which a new firm was created and financed with some government assistance and eventually privatized. Government policy also played an important role in the concentration of TSMC, UMC, and other semiconductor and electronics firms in the Hsinchu Science Park, established in the early 1980s. Firms meeting the criteria for location in the Science Park received tax benefits and access to low-cost loans from public sources, and benefited (mostly through hiring graduates, and in some cases, faculty) as well from proximity to two leading Taiwanese technical universities, Chiao Tong and Tsinghua. Over time, these benefits were supplemented by those associated with co-location with other firms in a high-technology agglomeration.

In conclusion, it seems clear that public agencies and funding were important in the development of Taiwan Province of China's semiconductor industry, in contrast to the South Korean case discussed immediately below. Taiwanese universities played a modest role as sources of research in the industry's development, although they were of great importance (along with returning Taiwanese émigrés) in supplying high-quality scientific and engineering talent to the growing industry. Taiwanese government R&D institutes relied in the early years of the industry's development on collaboration with foreign firms and the use of "spinoffs" to support the creation of competitive domestic firms whose ultimate survival depended on their penetration of export markets. Although the growth of Taiwanese semiconductors is a case of "industry targeting" by government policy, these policies focused primarily on the creation of knowledge-based "public goods" and the supply of R&D. The importance of Taiwan Province of China's public R&D investments as a complement to the inward transfer of industrial technology underscores the knowledge-intensive nature of cross-border industrial technology transfer.

The Republic of Korea: The Korean Institute of Science and Technology and the Chaebol

The Republic of Korea's government established a number of government research institutes in the 1960s, beginning with the creation in 1966 of the Korean Institute of Science and Technology (KIST).[19] KIST in turn established a number of specialized research institutes in chemicals, shipbuilding, and electronics (the Korean Institute for Electronics Technology, founded in 1976). One motive for the establishment of KIST, according to Kim (1997), was the desire of policymakers to create an attractive environment for returning South Korean émigrés. Eighteen such "returnees" were recruited to KIST at its foundation, and by 1980 KIST employed 276 returned émigrés. In 1976, the Korean Advanced Institute for Science and Technology (KAIST) was founded as a graduate institute for training scientists and engineers, reflecting the weakness of South Korean universities in research in these fields.

Despite their importance as employers of South Korean scientists and engineers (especially in their early years, when alternative opportunities for domestic employment in technical professions were scarce), however, most accounts of the Republic of Korea's industrial development minimize the importance of these institutes in the nation's development of technological capabilities within industry:

> these institutes suffered from poor linkages with industry at least through the mid-1970s. In these institutes most of the overseas trained Korean researchers came from either academic fields or from R&D organizations of highly industrialized countries that undertook advanced research. Expertise was particularly lacking in manufacturing and the development of prototypes, which were in great demand in the early years. Furthermore, Korean researchers could not compete with foreign licensors in supplying detailed blueprints and other manufacturing know-how, as well as being unable to assist industry in solving the problems in the crucial initial stages...(Kim, 1993, p. 364)

Nevertheless, the role of these institutes as employers contributed to the availability of a substantial domestic pool of scientists and engineers with advanced training (one that was modestly enlarged by the return of émigrés with few alternatives for domestic employment) that was subsequently exploited by South Korean firms in their industrial development.

The key institutional actors in the inward transfer and exploitation of semiconductor manufacturing technology in the Republic of Korea were the *chaebol*. The KIET played an important role in training scientists and engineers, but like other government research institutes, it failed to develop good links with industry and fell behind the technological frontier.[20] Leading *chaebol* sought to enter the semiconductor industry after 1975 as part of the South Korean government's "Heavy and Chemical Industries" program that provided subsidies and low-cost loans to firms in the chemicals, shipbuilding, semiconductor, and steel industries. But even these giant firms were hamstrung by difficulties in obtaining access to semiconductor production technologies from foreign sources, and semiconductor-related investment grew slowly.

Only in 1982 was Samsung able to license the technology for a VLSI semiconductor product, the 64K DRAM, from a U.S. firm, Micron Technologies, that was experiencing financial difficulties. Samsung established R&D facilities in the Republic of Korea and in the Silicon Valley of California to develop the production technology, and was further aided by assistance from a team of Japanese semiconductor engineers with experience in constructing and starting up large-scale semiconductor production plants. Samsung introduced its 64K DRAM in early 1984, 40 months after the first (U.S.) firm had introduced the product and only 18 months after the introduction of this product by a Japanese firm. Hyundai worked with Texas Instruments and Vitelic to enter the production of 64K DRAMs two years after Samsung, and LG licensed technology from Advanced Micro Devices and Zilog.

In contrast to Taiwan Province of China, the inward transfer and exploitation of key technologies for the first VLSI products of the Republic of Korea's semiconductor industry relied on the capabilities of private firms, with little direct assistance from government R&D investments or facilities. The ultimate success of South Korean firms' entry into DRAMs in particular also owed a great deal to the U.S. – Japan Semiconductor Trade Agreement of 1986, which provided a "price floor" for DRAM components and enabled these entrant firms to reap substantial profits in their early years of production.

Despite widespread agreement on their minimal contributions to the technological development of the semiconductor industry, few accounts of the development of the Republic of Korea's public R&D infrastructure satisfactorily explain the reasons for their ineffectiveness. At least some of the reasons for this failure, however, reflect the unusual industrial structure that developed in the knowledge-intensive manufacturing industries of the Republic of Korea. In contrast to the situation in Taiwanese industry (or in U.S. agriculture), South Korean industrial firms invested heavily in intrafirm technological capabilities, and competed fiercely with one another in domestic and foreign markets. "Horizontal" collaboration among the *chaebol* in even "precompetitive" R&D therefore was difficult. Moreover, the South Korean financial and industrial structure precluded the "spinoff" strategies pursued with considerable success by Taiwan Province of China's public R&D institutes. Domestic dissemination of publicly developed technology through the creation of new firms was not a feasible option in this environment.

Their modest direct contributions to the South Korean semiconductor industry's development notwithstanding, the KIET and other government research institutes were important in training and employing many of the scientists and engineers that eventually were important to the development of the industry, as well as attracting émigré scientists and engineers back to their homeland. Even allowing for this important indirect contribution, however, it seems likely that the Republic of Korea may have overinvested in these government research facilities in the early stages of its economic development. Resources devoted to this component of the Republic of Korea's R&D infrastructure might better have been allocated to strengthening Korean research universities or other elements of the nation's innovation system.

Implications for developing economies

The contrasting roles of government research institutes in the Taiwanese and South Korean semiconductor industries underscore the importance of a good "fit" between a nation's industrial structure and the instruments of public R&D funding. Moreover, the fact that policy choices in public R&D investment strategies are contingent on a variety of other local factors makes it difficult to develop precise guidelines for policy in contemporary developing economies. The prominent role of ITRI and the less significant role of KIST and KIET reflected the contrasting structures of their respective client industries, which in turn resulted from the contrasting financial policies and industrial finance systems that emerged in the Republic of Korea and Taiwan Province of China. It seems clear that the Taiwanese public research infrastructure was more closely linked to Taiwan Province of China's embryonic semiconductor industry, and one key principle for public investment in a knowledge infrastructure is the importance of close linkages between publicly funded research and those seeking to apply this research. But in the Republic of Korea and Taiwan Province of China, the contrasting strength and nature of these linkages were themselves the result of very different industrial structures.

Although the enterprises were highly leveraged, the financial resources available to the *chaebol*, as well as the fierce competition among these firms that was encouraged by government policy, meant that collaborative R&D centered on public research laboratories was less attractive than the independent pursuit of parallel R&D efforts. However inefficient from the perspective of the social planner, the firm-centered R&D strategies associated with the Republic of Korea's "catchup" in the semiconductor industry was successful. Even the limited linkages between public research laboratories and the R&D activities of these firms may be seen as an outgrowth of this unusual industrial structure, rather than being attributable solely to ineffective policy. The limited contributions of these institutions consisted largely of training and repatriation of scientists and engineers, both functions that might have been performed equally effectively in universities. In this episode at least, the publicly funded knowledge infrastructure appears to have played a minor role.

Taiwan Province of China's successful "catchup" in semiconductors relied more heavily on public research facilities, which in turn developed innovative channels for the application and dissemination of the results of their R&D that were compatible with the nation's financial and industrial structure. As was the case in the Republic of Korea, ITRI and related research facilities filled an important role in training scientists and engineers in semiconductor technology, as well as providing attractive positions for returning émigrés. But it is unlikely that the ITRI "spinoff" policy for commercialization of its R&D would have proven feasible or effective in the Republic of Korea.

A striking element of similarity between the R&D strategies of the Republic of Korea and Taiwan Province of China in semiconductors concerns the limited role of university research, which was of little consequence in either nation. In part, this limited role of university research reflected the fact that neither nation had developed world-class scientific or engineering academic research capabilities by the 1980s. But it is important to recognize as well that U.S. university research also has made limited contributions to the development of the semiconductor industry. The limited contributions of university research reflect the fact that much of the innovative activity in the semiconductor industry involves process innovation, which in turn relies on access to highly capital-intensive experimental fabrication facilities that are beyond the means of most universities. University research in the United States and elsewhere in the industrial economies has been responsible for important advances in semiconductor-component design and design software, but an indigenous innovative capability in these areas was not essential to South Korean and Taiwanese catchup in semiconductors.

It is useful to consider the foundations for the success of the contrasting Taiwanese and South Korean strategies for entry into the semiconductor manufacturing industry. Both nations relied on the existence of a substantial pool of scientific and engineering talent, supplemented in both nations by the return of numerous emigrants. Indeed, cross-border flows of both talent and technology figured prominently in the development of the South Korean and Taiwanese semiconductor industries.

Both nations' strategies embodied elements of industrial "targeting," in the sense that direct and indirect measures were employed to develop domestic technological capabilities in semiconductor manufacturing. But the products that served as the vehicles for South Korean entry into semiconductor manufacturing (semiconductor memory chips) were products for which a well-established technological trajectory was clearly evident. In both the South Korean and Taiwanese case, public support focused on narrowing the gap with advanced industrial practice, rather than taking on the far riskier task of forecasting the direction in which the technological frontier would shift in the future. Moreover, the focus of the entry strategies of both Taiwan Province of China and the Republic of Korea on export markets meant that the results of these strategies would be tested against global competitors and success or failure revealed rapidly.

Although the human-capital requirements of similar strategies may limit their feasibility for contemporary developing economies, many of the elements of the South Korean and Taiwanese strategies do not appear to be prohibited by current WTO regulations. In both nations (especially in the Republic of Korea), public R&D expenditures supported "generic" rather than product-specific R&D activities. And both nations' inward technology transfer strategies relied on licensing agreements with foreign firms that appear to have covered both patented technology and some elements of "knowhow." In other words, these entry strategies appear to have conformed to current TRIPS provisions. Indeed, both the Republic of Korea and Taiwan Province of China benefited from the competitive structure of the global semiconductor industry that supported the existence of multiple sources of the industrial technologies necessary for entry. Finally, since the entry strategies of both nations were focused on export markets, reflecting the fact that neither the Taiwanese nor the Republic of Korean domestic market provided sufficient demand to support an import-substitution policy, tariff protection of domestic markets was not a central component of their semiconductor entry strategies. Although the "catchup" strategies of both Taiwan Province of China and the Republic of Korea in semiconductors may not be readily transferred to contemporary developing economies, many of the elements of these strategies are not in conflict with WTO membership.

Knowledge infrastructure for agriculture: The politics and economics of US agricultural research, 1890-1990

Introduction

Agriculture is an important source of employment and output in most developing economies, just as was the case in the 19th-century United States. Moreover, much of the knowledge relevant to improving agricultural technology, practice, and productivity displays the classic traits of nonexcludability and nonrivalrousness. For example, the development of product standards for agricultural products and inputs that support markets for agricultural commodities and improve the operation of markets for agricultural inputs such as fertilizer, is a public good—benefits are shared throughout the relevant sector, while the ability of investors in the research to capture the returns to their investment through limiting access to the results is very limited. Similarly, the returns to research investments in the "localization" and adaptation of new crop varieties to the idiosyncratic growing conditions of specific regions within a continent-sized economy such as that of the United States are diffuse, and the social returns to such activities exceed the capturable private returns.

This characteristic of "localized" agricultural research remains significant in today's global economy—national agricultural research systems continue to play an important role in adapting the results of research performed in the network of international crop research centers to specific climate, soil, and cultivation practices. Nevertheless, one of the hallmarks of the evolution of the U.S. agricultural research system is the shifting boundary between publicly and privately financed R&D activities.

As I note below, the U.S. agricultural research system evolved slowly, but by the mid-20th century included significant public investments in support for technology demonstration and adoption, known as "agricultural extension." Although highly knowledge-intensive, extension services arguably could be provided through market channels more easily than is true of much of the agricultural research supported by the public sector in the United States. But public investments in agricultural extension have two important benefits: (1) the extension activities of agricultural experiment stations and research facilities can serve as a significant channel for input from the users of new technologies to feed back into the evolving applied research agenda of these research facilities; and (2) the distributional consequences of extension activities, which erode some of the rents associated with early adoption for users (e.g., large farmers) that quickly exploit new technologies, reduce the economic inequality that otherwise may intensify as a result of innovation and adoption (Evenson, 1982). Finally, extension activities enable a more rapid take-up of new technologies and thereby may accelerate the realization of the productivity gains associated with innovation.

Historical overview of the development of public agricultural R&D in the United States

The emergence of the "modern" U.S. public agricultural R&D system spanned more than 50 years (the period between the 1862 passage of the Morrill Act and the 1914 Smith-Lever Act). The gradual pace of its evolution during that period was influenced by internal political tensions, notably between the southern states and those of the Northeast and Midwest. These tensions reflected both the baleful influence of slavery during the pre-Civil War period and the lingering effects in the postwar period of the very different pattern of landownership and cultivation practices in the South and the rest of the United States. But both the length period of time required for the system to assume its current form and the deep-rooted political disagreements that slowed this emergence underscore the complex politics of agricultural R&D policy in many contemporary developing economies.[21]

Technological advance in U.S. agriculture during the early 19th century resulted largely from the efforts of individuals, and focused mainly on mechanical technologies, reflecting the lack of scientific understanding of the chemical and biological processes underpinning plant and animal growth. Agricultural societies played an important role in importing new seed varieties from foreign sources, but found it difficult to capture sufficient revenues to support these activities. The U.S. Patent Office was the first federal agency to enter agricultural research, importing and distributing new seed varieties. In 1839, Congress appropriated funds for the Patent Office to collect and distribute plants and seeds, and to collect statistical information on U.S. agriculture. These functions were transferred to the newly established Department of Agriculture in 1862.

The Morrill Act of 1862 laid the foundations for the federal/state agricultural public R&D system in the United States. The Act was first introduced in the late 1850s, but was blocked by Southern congressmen and Senators who saw it as a threat to their region's slave-based plantation agriculture. Only after the secession of the Southern states and the outbreak of the U.S. Civil War was the Act passed. The Act granted federal lands to each state for the establishment of colleges devoted to teaching agricultural and engineering subjects, and thereby created some of the first research and teaching institutions in these fields in the United States.[22]

The next major step in the evolution of the U.S. agricultural research system occurred in 1887 with the passage of the Hatch Act. The Act's drafting and passage were influenced by developments during the 1850s and 1860s in European agricultural research, which experienced rapid progress with the development of agricultural chemistry in Germany (led by Justus Liebig) and the United Kingdom. Much of the research activity in both nations was centered in "experiment stations" that sought to apply new scientific advances to agricultural practice. The USDA had begun its own research program in the 1860s, focusing (among other things) on analyses of soils and fertilizer and the development of standards to prevent the adulteration of agricultural inputs, but the USDA program was modest in scope.

The Hatch Act provided federal financial support for agricultural experiment stations in each state, with management responsibility for these institutions delegated to state governments. Early versions of the Act allowed for greater federal oversight and stipulated that experiment stations should be affiliated with the land-grant colleges created by the Morrill Act, but opposition from Southern agricultural interests and supporters of states' rights limited the federal role to those of funding and (loose) oversight, as well as removing the requirement that the experiment stations be part of state colleges. The majority of the experiment stations created under the Hatch Act nevertheless were linked to land-grant colleges. The research institutions created by the Hatch Act drew on both federal and state funds, and in some cases performed research under the terms of privately funded contracts.

The last major component of the U.S. public agricultural R&D system was the agricultural "extension" system, designed to support the adoption of agricultural practices and technologies. The USDA had conducted such activities in the southern cotton-growing regions of the United States during the early 20th century, in response to the devastating boll weevil infestation that destroyed much of the cotton crop. The Smith-Lever Act of 1914 expanded and "nationalized" these activities, but relied on a complex funding formula that reflected disagreements between Northern and Southern politicians over the role of federal personnel in conducting these activities, as well as the links between extension activities and the land-grant colleges and universities. The resulting agricultural extension system incorporated state and federal funding and personnel, with considerable variety in organizational structure and linkages to academic agricultural research and teaching.

The productivity performance of U.S. agriculture during the past century has been remarkable, and much of this productivity growth is attributed to public investments in agricultural R&D and extension. Huffman and Evenson (1993) estimate that total factor productivity in U.S. agriculture during 1889-1990 grew at an average annual rate of 1.55%, enabling an increase in real agricultural output during this period of more than 550%, while real inputs grew during this entire period by only 15%. Focusing on the 1950-82 period, for which better data are available, Huffman and Evenson find that publicly funded research and extension in crops accounted for more than one-half of the fraction of growth during the period in total factor productivity growth that can be explained, and a higher fraction of this growth than is accounted for by privately funded R&D. These results are reversed, however, for livestock, where the relative contributions of publicly and privately funded research and extension are reversed.

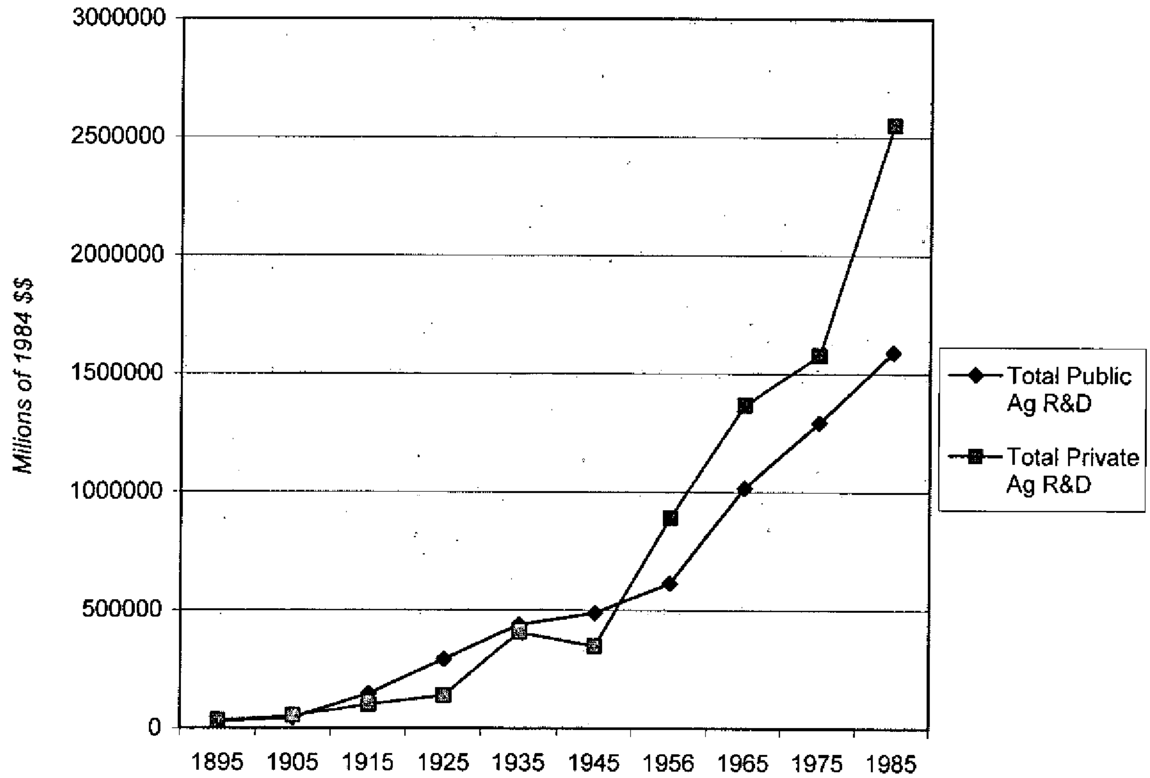
The estimated social rates of return on public investments in crop research for 1950-82 compiled by Huffman and Evenson are 47% for all research, more than 60% for fundamental research on crops, and slightly more than 40% for public investments in extension. The estimated social rates of return for overall public investments in livestock research and extension, however, are negligible (although the estimated social rate of return on fundamental research in this field exceeds 80%), highlighting one of the challenges faced by the "client-oriented" structure of the U.S. public agricultural research system (see below for further discussion).

Overall, these estimated rates of return on public R&D investments exceed those for most other fields of public R&D investment in the postwar United States, keeping in mind the great difficulties associated with such estimates. One other feature of these estimates is worth highlighting: Evenson (1982) notes the persistence of significant regional variation in agricultural productivity in specific crops, and argues that such regional variation reflects differences in the level of "local" R&D investments. The importance of these local investments for regional agricultural productivity reflects the costs and returns to investments in R&D associated with the inward transfer and adaptation of crop varieties and cultivation practices.[23]

Public and private investment in agricultural R&D, 1895-1985

Figures 2-4 display trends in U.S. agricultural R&D investment during the 1895-1985 period. Perhaps the most striking characteristic of the data depicted in Figure 4 is the sheer scale of the overall investment in agricultural R&D. According to these data, which were compiled by Huffman and Evenson (1993), the United States was investing more than $60 million (in 1984 dollars) in agricultural research by the end of the 19th century, an amount that grew sevenfold by 1925 in constant-dollar terms. By the mid-1950s, private and public R&D investment in agriculture amounted to more than $1.5 billion.

Figure 4
U.S. Public & Private Agricultural R&D Investment, 1895-1985



Second, the balance between private and public R&D investment has shifted over time. At the end of the 19th century (and according to Huffman and Evenson, on which this account relies, for most of the 19th century), private sources accounted for the majority of agricultural R&D investment. But in the aftermath of the Hatch Act of 1887 and the Smith-Lever Act of 1914, public funding grew significantly. By 1915, public funding outstripped private R&D funding by almost 50%, and public funding accounted for the majority of agricultural R&D investment through 1945 (Figure 4). Private investment in agricultural R&D grew more rapidly during the post-1945 period than public investment, however, and by 1985, privately financed agricultural R&D exceeded public investment by nearly 40%.

The final noteworthy feature of the U.S. agricultural research system is the prominent role of nonfederal public funds in supporting key activities, such as the state agricultural experiment stations and agricultural extension (Figures 5 and 6). Figure 5 displays the "nonfederal" share of funding for state agricultural experiment stations during 1895-1985. The bulk of this "nonfederal" share is accounted for by state funds, and this share has risen significantly since the early 20th century, from approximately 46% in 1905 to more than 70% by 1985. A similar trend is apparent in the state share of funding for agricultural extension activities during the 1915-1985 period (Figure 6).

Figure 5
Nonfederal share of funding for U.S. state agricultural experiment stations, 1895-1985

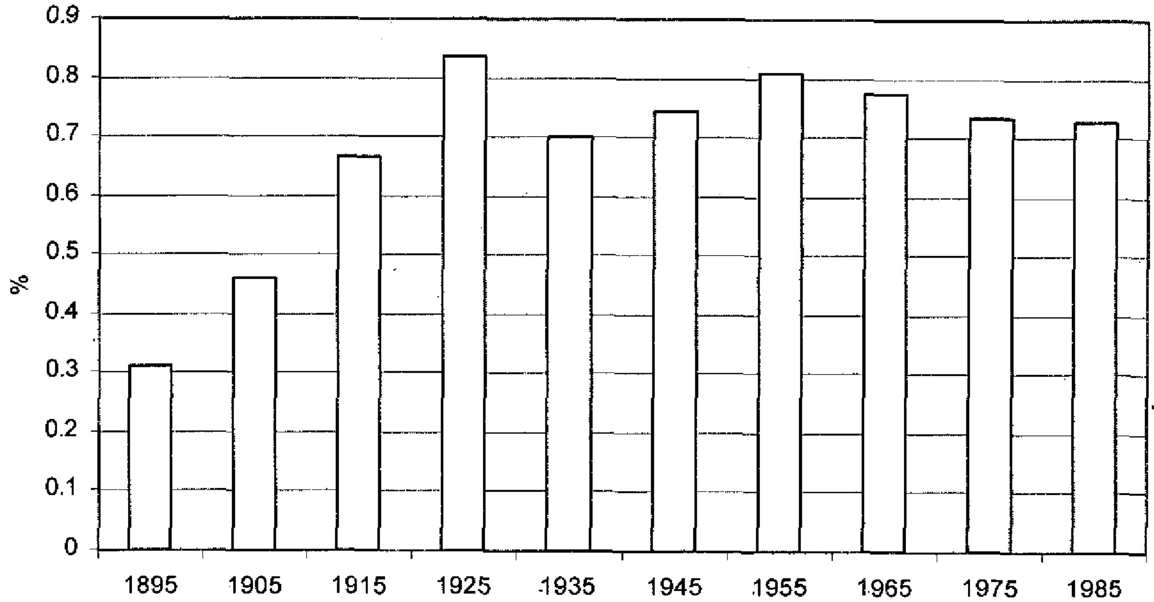
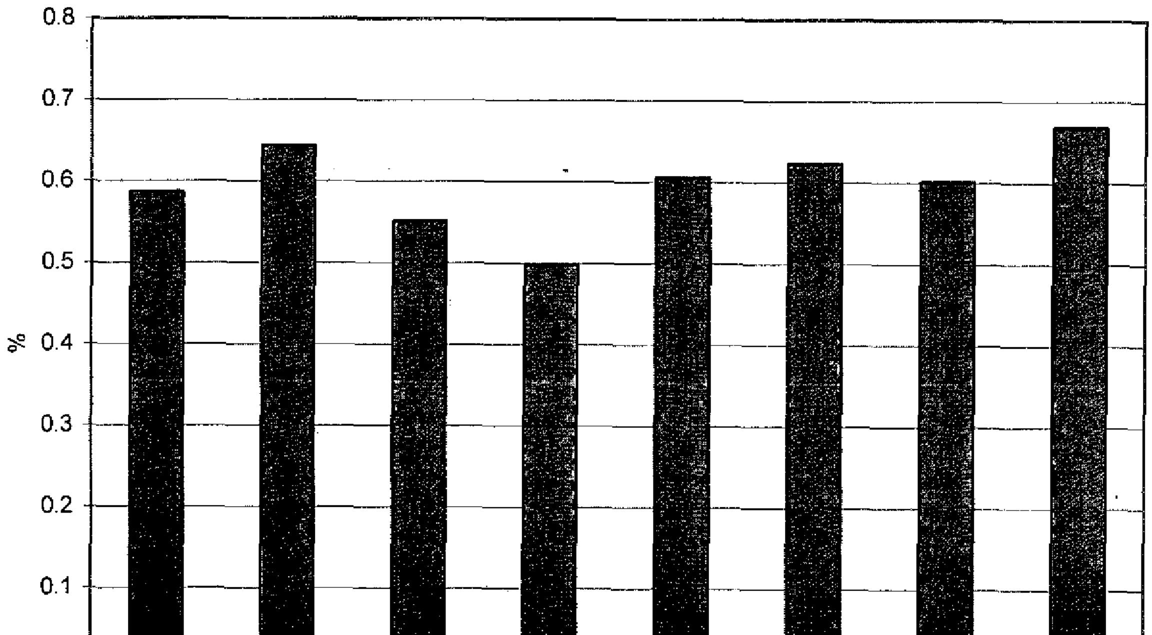


Figure 6
State share of U.S. agricultural extension funding, 1915-1985



The prominent role of state funding within the U.S. agricultural research system both reflects and reinforces the broad political support for public agricultural R&D investment. This funding structure also reinforces closer linkages between public research programs and local groups of users (farmers in various climate and crop regions) whose needs will vary substantially across states. At the same time, however, the decentralized structure of the resulting publicly financed R&D system, as well as its close links to important client groups, arguably has weakened the public sector's performance in fundamental research and has made the system less responsive to new scientific opportunities, issues that I briefly discuss below.

Policy challenges for the U.S. agricultural research system

The long history of the U.S. public research system in agriculture highlights the extent to which design choices in the structure of public R&D investments in a particular sector are enmeshed with deep-seated internal political tensions. It is not a coincidence, after all, that the first major legislative initiative for support of public investments in U.S. agricultural research was passed by the U.S. Congress only after the outbreak of civil war. Moreover, the legacy of the Southern plantation system of agriculture remained a potent force in the design of the U.S. public agricultural R&D system through at least the middle of the last century. Among other things, the decentralized structure of the public U.S. agricultural R&D system, the relatively weak oversight of federal agricultural R&D investments by the agency responsible for these expenditures, and the mix of state and federal government funds in the system, all reflect the sectional tensions that influenced the system's design.

These design decisions are reflected as well in recent criticism of the failure of the U.S. public agricultural R&D system to respond more effectively to the research opportunities created by the revolution in fundamental research in the life sciences (much of which was funded by the federal National Institutes of Health) since the 1950s. One reason for this failure is the structure of funding for public agricultural R&D, which emphasizes "formula" funding for state experiment stations and related institutions more heavily than competitive, peer-reviewed grants. Many U.S. land-grant universities maintain excellent research programs in fundamental sciences related to agriculture, relying in part on competitive research grants from the federal government and other institutions. But only in the 1980s, under Congressional pressure, did the USDA develop a significant program of "competitive research grants" for the state agricultural experiment stations. As of 1990, according to Huffman and Evenson (1993), competitive state experiment station grants administered by the USDA accounted for less than 10% of USDA funding of these experiment stations. This more modest role for peer review within the U.S. agricultural system is one aspect in which the system contrasts with the R&D funding systems operated by the National Institutes of Health or the National Science Foundation.

The emphasis on formula rather than competitive funding mechanisms within the public agricultural R&D system reflects the long history of this system—after all, the peer-reviewed system for allocating federal R&D funds in the United States emerged only in the 1950s, decades after the establishment of the public agricultural R&D system. But the durability of these mechanisms for funding public agricultural R&D also reflects the prominent role of users within the governance of this decentralized system. Indeed, the close links among public agricultural research, agricultural extension, and the user community contribute to a form of "capture" or "client orientation" that has important costs as well as benefits. As Evenson (1982) notes, the tendency for the state agricultural experiment stations to invest far more heavily in applied research (despite its lower estimated returns) reflects the interests of users:

> The strict peer review system by which research quality is judged and on which [academic] promotions are based has, in some ways served certain fields of science well. Nonetheless, it has been a practical reality that such systems do not allow much

weight to be placed on the economic value or relevance of the research contribution. Most scientific institutions do not have economic clients except very indirectly through federal public-support mechanisms. They tend to serve themselves. (p. 269).

This tendency for users to dominate the research agenda in public agricultural R&D also is reflected in the substantial investments of public funds, despite lack of evidence of much by way of social returns, in livestock research. At the same time, the "client orientation" of the U.S. public agricultural R&D system reveals itself in the relatively low levels of investment in research on sustainable agricultural practices.

The U.S. public agricultural research system illustrates the benefits and costs of decentralization and the creation of a set of politically powerful local interest groups supporting (perhaps, controlling) its research agenda. Nevertheless, the available data on the returns to public investments in U.S. agricultural R&D and extension indicate that these returns have been high, almost certainly higher than all but a few other federal R&D programs. Moreover, these programs have continued to yield high social payoffs in the face of substantial growth in privately funded agricultural R&D, especially in biotechnology. The data on economic payoffs to public investments in agricultural R&D highlight the complementary role that such public investments, in fundamental and applied research have played in the advancement of technology and economic performance in this sector.

Implications for developing economies

The long period of time required for the U.S. public agricultural research system to assume its current structure should give pause to policymakers seeking rapid transformation in the national agricultural research systems of developing economies. In the case of the United States in the 19th and early 20th centuries, as well as in many contemporary developing economies, agriculture remains an important source of employment, economic output, and political power. Decisions about agricultural research policy accordingly have significant political implications and can be a source of political and economic conflict.

In spite (or perhaps, because) of the political conflicts that surrounded its development, the U.S. agricultural research system relies on a number of different sources of financial support that create strong political and economic incentives for state-level agricultural research organizations to be closely linked to their agricultural constituencies. These close linkages are a source of strength for the system, since they make it more responsive to user needs and requirements. They also have been a source of weakness, focusing the research agenda on near-term rather than fundamental research issues. In response to these problems, a growing portion of the U.S. public agriculture research system's budget now is channeled through competitive grants. The evolution of this system highlights the importance of decentralized, diverse funding sources and provides some arguments for a mix of competitive and institutional funding, rather than exclusive reliance on one or the other funding mechanism. Another source of strength and user linkages for the U.S. public agricultural research system is the inclusion of agricultural extension within the responsibilities of many of the state-level agricultural research operations. This linkage enhances the provision of state-of-the-art technical advice to farmers, and proves a valuable channel through which user feedback can reach researchers.

Over the course of its lengthy development, the U.S. public agriculture research system has adapted to another fundamental change; the growth since the mid-20th century in private agricultural R&D funding and activity. Indeed, the changing mix of public and private funding in U.S. agricultural R&D over the 1860-1990 period highlights the complexity of the relationship between public and private R&D investment. Agricultural R&D investment during the mid-19th century was derived largely from private sources, but this balance had shifted decisively in favor of public financing by the 1920s. The balance shifted back to favor private funding during the 1950s and 1960s. In the face of change in the balance of public and private agricultural R&D investment, political support for public funding of agricultural research remains robust (recall Figure 4) and the public system has developed and maintained an effective complementary relationship with privately funded R&D. If there is an important role for public agricultural R&D in the United States, a high-income economy with one of the most robust private-sector agricultural R&D systems in the world, it is hard to see how one can argue against an equally if not more important role for publicly funded agricultural R&D in developing economies, which often provide far less attractive markets for private agricultural R&D investment.

Virtually all economic analyses of public investments in U.S. agricultural research find very high social returns to these investments, albeit much higher in plants than in animal research. The fact that these estimated returns remain high in the face of significant growth in both public and private agricultural R&D investment is due in large part to the importance of public R&D (as well as extension) in adapting crop varieties and farming practices to a diverse array of differentiated climatic and growing conditions. Similarly high estimates of social returns have been obtained from analyses of public agricultural R&D in developing economies such as India and in such research fields as improved rice varieties (Evenson et al., 1999; Evenson, 2003).

The importance of agricultural research for such "adaptation" cannot be overstated, and highlights the knowledge-intensive character of the knowledge transfer and adaptation processes in this sector. And the need for such research in developing economies with less highly developed agricultural R&D systems than that of India is great. Moreover, the work of Evenson et al. (2003), Ruttan (1992), and others shows that the growth of international collaboration in publicly funded agricultural R&D (e.g., through the CGIAR) does not remove the need for such localized R&D, which can be supported only through national agricultural R&D systems.

A number of other studies (Katz, 2004; Naik; 2004; Kiggunda, 2004) highlight the knowledge-intensive nature of the changes in agricultural practice and processing that are necessary in order to conform to the phytosanitary requirements imposed by high-income nations on imports of fresh produce and other high-margin agricultural products. These types of investments may yield high social returns, but the private returns associated with them often are difficult to capture, making them another important candidate for public support through national agricultural R&D systems.

In light of the enduring importance and high social returns to public investments in agricultural R&D at the national and local levels, slower growth or declines in public support for this activity in such areas as sub-Saharan Africa during the 1970s and 1980s are worrisome. As Pardey et al. (1997) note, the annual growth rate of public funding (from all sources—both domestic government funds and foreign aid, measured in 1985 dollars) for agricultural research in 19 sub-Saharan nations declined from 6.8% during 1961-71 to 2.6% in the 1970s and only 0.1% during the 1980s. Real expenditures per researcher have declined through the 1961-91 period. In addition, of course, political instability and armed conflict contributed to the collapse of national agricultural research systems in a number of these nations, such as Zaire, Uganda, Rwanda, and Somalia.

Data on public agricultural research investments in other developing economies are scarce,[24] but the limited data on national agricultural research systems in Latin American economies suggest that the adjustment crises of the 1980s and 1990s in this region also were associated with reductions in public spending:

> Between the early 1980s and the early 1990s, the average research budgets of public institutes for agricultural research were reduced by 13-15%; at the same time, the number of personnel increased by 22-27%. This resulted in a reduction of expenditure per researcher and sometimes even in reductions of the salaries of qualified personnel, together with lower operating budgets. Such difficulties have negatively affected the performance of public institutions dedicated to agricultural research. (Morales, 1998, p. 24)

The evidence on the importance and high returns to public investments in agricultural R&D make a reversal of these reductions in such investments an urgent priority. The U.S. case, as well as those of other developing economies, such as India, demonstrate that national agricultural R&D systems continue to play an important role as complements to both private R&D investment and to the international network of agricultural R&D organizations. It seems clear as well that increased funding of this important activity must be accompanied by structural reforms, to ensure stronger links between researchers and practitioners and to develop closer links between support for research and support for technology adoption. Separation of responsibility for allocating funds from responsibility for performing research (including the possibility of public funding for private R&D organizations) is a valuable design principle, although exclusive reliance on competitive allocation of funds for research and extension may not be advisable. But the "hollowing out" of the national public agricultural R&D systems of sub-Saharan and other low-income developing nations must be reversed.

The development of the Internet in the United States

Introduction

The Internet resembles many postwar innovations in information technology in that it was commercialized primarily in the United States. But the Internet differs from at least some other major postwar IT innovations in that some of the key inventions underpinning its (eventual) explosive diffusion first appeared in foreign economies. European as well as U.S. researchers produced many significant advances in computer networking. Nonetheless, U.S. firms and users proved adept at integrating these foreign inventions with a large array of related domestic technological advances to developing the major innovations of the Internet and the WorldWide Web.

Like other components of the postwar "information technology industrial complex," the Internet benefited from federal policies in defense-related and civilian R&D spending, regulation, and antitrust. Federal agencies such as the Department of Defense (DoD) and National Science Foundation (NSF) played a critical role in funding the development and diffusion of early versions of the technology. Federal spending on R&D and procurement was complemented by the R&D investments of large corporations and the many start-ups that quickly came to populate Internet-related industries. These small firms often drew on expertise developed in U.S. research universities or in large corporations and benefited from the regulatory and antitrust policies of federal agencies such as the Federal Communications Commission and the Justice Department.

Research on computer networking began in the 1960s, roughly 15 years after the advent of the computer itself.[25] Like many of the early academic and industrial efforts in computing technology, much of this networking research was funded by the U.S. Department of Defense. Although the Department of Defense sought to exploit a number of these new technologies in defense applications, the DoD supported "generic" research and the development of a substantial infrastructure in academia and industry for such research, on the assumption that a viable industry capable of supplying defense needs in computer technology would also require civilian markets (Langlois and Mowery, 1996).

During the early 1960s several researchers, including Leonard Kleinrock at MIT, Paul Baran of RAND, and Donald Davies at the National Physical Laboratories in the United Kingdom, developed various aspects of the theory of packet switching.[26] By the late 1960s, the theoretical work and early experiments of Baran, Kleinrock and others led the U.S. Department of Defense Advanced Research Projects Agency (DARPA) to fund the construction of a prototype network.[27] In December 1968, DARPA granted a contract to the Cambridge Massachusetts-based engineering firm of Bolt, Beranek and Newman[28] to build the first packet switch. The switch was called an Interface Message Processor (IMP), and linked computers at several major computing facilities over what is now called a wide-area network. A computer with a dedicated connection to this network was referred to as a "host." The resulting ARPANET is widely recognized as the earliest forerunner of the Internet. (NRC, 1999a Ch. 7). The initial DARPA network spanned the continent and connected three universities (UCLA, UCSB and Utah), a consulting firm (BBN), and a research institute (Stanford Research Institute). By 1975, as universities and other major defense research sites were linked to the network, ARPANET had grown to more than 100 nodes.

ARPANET was not the only prototype network constructed during the late 1960's and early 1970's. Donald Davies completed the construction of a data network at the National Physical Laboratories in the UK before the development of ARPANET, and a French network called CYCLADES was built in 1972. U.S. dominance thus did not result from a first-mover advantage in the invention or even the early development of a packet-switched network. The factor that does seem to separate ARPANET from these simultaneous projects was the sizeable scale (which reflected the size of the public investment in its deployment) and flexibility in its deployment, which resulted in a large prototype computer network that included a diverse array of institutions. Its size and inclusion of a diverse array of institutions as members, even in its earliest development, both appear to distinguish the ARPANET from its British and French counterparts.

The Role of Government-Sponsored Research

Public funds were used to develop many of the early inventions that fueled the development of the Internet in the United States. Although it is tempting to attribute U.S. leadership in computer networking to a "first-mover advantage" in government-funded basic research, the development of critical technologies such as HTTP/HTML outside the United States, and the early work of non-U.S. networking pioneers such as Donald Davies and Louis Pouzin cast some suspicion on this hypothesis. On the other hand, U.S. government agencies, such as the Department of Defense, appear to have been unique in their willingness to commit to funding a national network infrastructure and in their support of strong links between industry and academia.

Federal R&D spending, much of which was defense-related, played an important role in the creation of an entire complex of "new" postwar information technology industries (including semiconductors, computers, and computer software) in the United States. The origins of the Internet can be traced back to these efforts. Internet-related projects funded through the Department of Defense include Paul Baran's early work on packet switching, the ARPANET, and research on a variety of protocols, including TCP/IP. These public R&D investments in networking technology were preceded by a fifteen-year DoD investment in hardware and software technology that began with the earliest work on numerical computing. Federal R&D investments strengthened U.S. universities' research capabilities in computer science, bankrolled the early deployment of the ARPANET, facilitated the formation of university "spinoffs" like BBN and Sun, and trained a large cohort of technical experts who aided in the development, adoption, and commercialization of the Internet.

We lack the necessary data to estimate the total federal investment in Internet-related R&D. Even were such data available, the complex origins of the Internet's various components would make construction of such an estimate very difficult. Nevertheless, federal investments in the academic computer science research and training infrastructure that contributed to the Internet's development were substantial. According to a recent report from the National Research Council's Computer Science and Telecommunications Board, federal investments in computer science research increased fivefold during the 1976-95 period, from $180 million in 1976 to $960 million in 1995 in constant (1995) dollars. Federally funded basic research in computer science, roughly 70% of which was performed in U.S. universities, grew from $65 million in 1976 to $265 million in 1995 dollars (National Research Council, 1999a, p. 53).

Langlois and Mowery (1996) compiled data from a variety of sources that indicate that between 1956 and 1980 the cumulative NSF funding for research in "software and related areas" amounted to more than $310 million (1995 dollars). Most of this funding went to U.S. universities. Funding from DARPA's Information Processing Techniques Office (IPTO), which went to both universities and industry, averaged roughly $87 million annually (1995 dollars) between 1964 and 1980, before growing sharply to more than $198 million (1995 dollars) in 1984-85. Between 1986 and 1995, the NSF spent roughly $200 million to expand the NSFNET (Cerf, 2000). The investments of NSF and DARPA in almost certainly constituted a majority of Internet-related R&D funding, especially in academia. These federal R&D expenditures were sizeable and importantly, contributed to both research and training of skilled engineers and scientists.

In addition to their size, the structure of these substantial federal R&D investments enhanced their effectiveness. DARPA's research agenda and managerial style gave researchers considerable autonomy and the agency spread its investments among a group of academic "centers of excellence" (MIT, U.C. Berkeley, Stanford, Carnegie-Mellon, the University of Utah, and UCLA).[29] In its efforts to encourage exploration of a variety of technical approaches to research priorities, DARPA frequently funded similar projects in several different universities and private R&D laboratories. Moreover, the Department of Defense's procurement policy complemented DARPA's broad-based approach to R&D funding. Contracts were often awarded to small firms such as BBN, which received the contract to build the first IMP. This policy helped foster entry by new firms into the emerging Internet industry, supporting intense competition and rapid innovation.

The large scale of the U.S. defense-related programs in computer science research and networking distinguished them from those in the United Kingdom and France; but the contrasts extend beyond the scale of these R&D programs. Unlike their counterparts in the Soviet Union or the United Kingdom,[30] DoD information technology R&D programs, even before the establishment of DARPA, sought to establish a broad national research infrastructure in computer science that would be accessible to both civilian and defense-related firms and applications, and disseminated technical information to academic, industrial, and defense audiences.[31] Classified R&D was important, but a great deal of U.S. defense-related R&D consisted of long-term research that was conducted in universities, which by their nature are relatively open institutions.

Another factor in the success of federal R&D programs was their "technology-neutral" character. U.S. research programs avoided the early promotion of specific architectures, technologies, or suppliers, in contrast to efforts in other industrial economies, such as the French "Minitel" program, or celebrated postwar U.S. technology policy failures, such as the supersonic transport or the fast-breeder nuclear reactor (Nelson, 1984). The NSF, for example, focused on funding a variety of academic research projects, largely through grants to university-based computer scientists. NSF support, dating back to the late 1950s, literally laid the foundation for the formation and growth of many U.S. universities' computer science departments, a key component of the research and training infrastructure that supported the development and diffusion of the Internet. In addition to their research contributions, university computer science departments and CSNET formed the core of the early Internet.

The diversity of the federal Internet R&D portfolio reflected the fact that these federal R&D investments were not coordinated by any central agency (even within the Defense Department), but were distributed among several agencies with distinct yet overlapping agendas. NASA and the U.S. Department of Energy, for example, pursued their own networking initiatives in parallel with ARPANET during the 1970's, and DoD spending paralleled and occasionally duplicated NSF grants. In fact, the NSF's greatest single contribution to the diffusion of the Internet was the NSFNET program, which was initiated and carried out during a period of declining defense-related R&D investments in information technology. In an environment of technological uncertainty, this diversified and pluralistic program structure, however inefficient, appears to have been beneficial.

Other federal policies

The role of the federal government in the development and diffusion of the Internet was not limited to its financial support for R&D, but also worked through federal regulatory, antitrust, and intellectual property rights policies. The overall effect of these (largely uncoordinated) policies was to encourage rapid commercialization of Internet infrastructure, services and content by new, frequently small firms.

AT&T's failure to capture a large share of the computer networking market is a good illustration of the important role played by federal regulatory and antitrust policy. The Department of Justice's 1949 antitrust lawsuit against AT&T was settled by a 1956 consent decree that was modified in the 1982 conclusion to the federal antitrust suit against AT&T that was filed in 1974. The FCC hearings, "Computer I and II," (decided in 1971 and 1976 respectively) declared that computing lay outside the boundary of AT&T's regulated monopoly (Weinhaus and Oettinger, 1988). The 1956 consent decree and the FCC hearings imposed significant restrictions on AT&T's activities outside of telecommunications services. As a result, several of Bell Laboratories' major information technology innovations, including both Unix and the C programming language, were licensed on liberal terms and diffused extensively. Unix in particular was widely adopted within the academic community and played a major role in the diffusion of the computer-networking protocols (TCP/IP) that underpinned the Internet.

Federal telecommunications policy, particularly the introduction of competition in local markets following the 1984 break-up of AT&T, also affected the evolution of the Internet in the United States. The 1984 Modified Final Judgment stipulated that Regional Bell Operating Companies (RBOCs) would not be allowed into long distance until they established competitive local markets. This meant allowing Competitive Local Exchange Carriers (CLEC's) to connect to the network infrastructure on reasonable terms that would allow them to compete in various retail markets. The spread of local competition promoted the widespread availability of affordable leased lines that allowed commercial ISPs to connect their networks to IX points, long-haul carriers, and one another. The Telecommunications Act of 1996 reinforced competition in markets for broadband data communication.

State and federal regulations in the pricing of telecommunications services also aided the domestic diffusion of the Internet. State regulators have long enforced low, time-insensitive rates for local telecommunications service, in order to encourage the broadest possible access to local phone service. Regulators extended this time-insensitive pricing policy to Internet Service Providers (ISPs), the firms that managed the "server banks" that enabled users to connect to the Internet. Unmetered local access for residential telephone services encouraged the growth of the ISP industry in local markets and the widespread diffusion of the network among residential customers, who are less sensitive to the amount of time spent online than their counterparts in countries with metered pricing for local telephone service. By comparison with the United States, most countries were slower to institute deregulatory and other structural changes in telecommunications that appear to have promoted the diffusion of the Internet by encouraging competition in infrastructure markets and by lowering the price of Internet access (OECD, 1999a, 1999b).

U.S. intellectual property rights (IPR) policy also affected the evolution of the Internet, although the influence of IPR policy is less obvious and direct than that of antitrust policy or telecommunications deregulation. Many of the key technical advances embodied in the Internet (such as TCP/IP) were placed in the public domain from their inception. This relatively weak intellectual property rights regime reflected the network's academic origins, the Defense Department's support for placing research into the public domain, and the inability of proprietary standards to compete with the open TCP/IP standard. The resulting widespread diffusion of the Internet's core technological innovations facilitated entry by networking firms into hardware, software and services.

Implications for developing economies?

This brief history of the Internet's development arguably has limited "lessons" for the design of institutions and policies within developing economies to support innovation and technology adoption. Nevertheless, the Internet case illustrates the extent to which this central element of the "knowledge infrastructure" utilized throughout the global economy was itself the result of public investment and R&D support. Equally important is the way in which the form of public R&D investment, especially in the United States, influenced the "excludability" of many of the most important components of the Internet's architecture. For example, had the TCP/IP protocol been developed with private funds and/or protected by patents or copyright, the architecture of the Internet very likely would have been based on closed rather than open standards, with enormous implications for its emergence as a global "public good." The large investments of public funds by U.S. government agencies (largely defense-related agencies) also supported the deployment of early versions of the Internet, thereby accelerating its technical development and the development of Internet-related applications that ultimately enabled firms in the United States to exploit key inventions developed in other nations for the creation of the WorldWide Web.

The importance for the Internet's development in the United States of the other policies discussed in this case, including telecommunications regulation and antitrust policy, underscores another important point that is relevant to developing (as well as high-income) economies. The operation of national innovation systems is influenced by a broad array of policies, many of which fall outside of the categories usually considered to be of central importance for innovative performance. But these "peripheral" policies assuredly can frustrate or facilitate the goals of technology policy, and recognition of their effects is essential to the formulation and implementation of effective policies to enhance innovative performance.

The political context within which these substantial federal R&D investments occurred is important, and may limit some of the implications of this case for contemporary developing economies. The extensive investments in information technology R&D and in the deployment of such precursors of the Internet as the ARPANET were justified as important contributions to national defense. As the cases of agriculture and public health suggest, the postwar R&D

investment programs of most U.S. federal agencies have been related to their public missions, rather than justified politically in terms of their contributions to the broad advance of knowledge.

Nevertheless, the structure of the R&D programs and investments that produced the Internet does yield some important and relevant implications for the development of knowledge-based strategies for economic "catchup." These R&D programs were characterized by diversity in goals and performers, strong competition among funding agencies and research performers, and competition among the firms seeking to commercialize applications based on the Internet and the WorldWide Web. Clearly, the open architecture that resulted from public R&D investment contributed to this strong competitive environment. But the rapid development, deployment, and commercial exploitation of the Internet by U.S. public agencies and private firms owes much to the ways in which federal policy consistently favored competition at all levels of the technology creation, innovation, and commercialization processes.

Indeed, many of the important commercial applications of the Internet and related technologies (e.g., computer networking) were brought to market by new entrant firms, a characteristic that the development of the Internet in the United States shares with other high-technology postwar industries, such as semiconductors, computer hardware, and computer software. The prominent role of entrant firms underscores the importance of economic policies that reduce the costs of new-enterprise formation and operation within developing economies.

The scale of the public R&D programs that contributed to the creation of the Internet in the United States cannot be reproduced in most developing-economy contexts. Nevertheless, the success of the overall program structure, particularly its combination of diversity in R&D performers and competition in commercial applications, highlights the importance of competition within the "knowledge infrastructure" for enhancing overall performance. And far too many elements of the R&D systems of developing economies do not share this competitive structure, a characteristic that may contribute to disappointing performance in recent decades.

Conclusion

As this discussion makes clear, public investments in R&D have been a central component of the economic "catchup" strategies of nations for the past 125 years. The structure of these investments, as well as their goals and ultimate economic effects, have varied substantially, reflecting the contrasting economic conditions (both domestic and international) within which they were situated. But the most effective investments appear to have relied on strong links with user groups, competition among research funders, performers, and users, and (to the extent possible) decentralized structures. Importantly, excellence in fundamental research is desirable but not essential to success. The processes of economic "catchup," after all, involve the inward transfer, modification, and application of technologies in use in more advanced economies. These tasks demand considerable research, but may not require that researchers be able to extend the frontiers of science.

It seems indisputable that the environment faced by low-income economies seeking to catch up will differ significantly from that faced by the United States, Japan, and Germany in the late 19th and early 20th centuries, or that faced by the Republic of Korea and Taiwan Province of China during the 1970s and 1980s. But will such contrasts preclude the strategies employed by these nations in their earlier, successful efforts to close the gap with economic leaders? Most scholars who argue that the circumstances of economic catchup in the 21st century no longer resemble those of earlier periods assert that the transformed economic and political environment will increase the importance of public investments in R&D within low-income economies. In either case, the currently low and (in some nations) declining investments in public R&D are a cause for great concern. The market-opening policies advocated by the "Washington consensus" in many cases require complementary investments in knowledge to support the entry of domestic producers into export markets, to enable improvements in product quality, and to support the inward transfer and application of technologies from throughout the global economy.

At the same time, no expansion of investment in developing-economy public R&D programs can occur without significant improvements in the structure of these programs to make them more flexible, improve their linkages to domestic users, and to upgrade their quality. Separation of responsibility for funding of R&D from the performance of R&D is one desirable design principle, as is greater attention to monitoring research performance, outcomes, and impacts. Greater decentralization in the structure of such R&D programs is desirable, but may conflict with the need to create sufficient scale in individual programs or facilities to ensure viability. Ultimately, the principles for policy and program design must remain very general, reflecting the fact that the circumstances "on the ground" are the most important criterion for evaluating program structure. Moreover, since these circumstances themselves are constantly changing, program flexibility is essential, in order to support adaptation to change in the domestic and global economies.

Policy reform premises and principles

The policy implications of this discussion can be summarized in the following findings and recommendations:

1. Economic "catchup" since at least the late 19th century has involved significant public investments in knowledge-related capabilities and assets, as the discussion above of historical experience in the United States, Germany, Taiwan Province of China, and the Republic of Korea suggests. The historical discussion also highlights the importance of public support for both training of scientists and engineers and R&D. The efforts of contemporary developing economies to narrow the gap between their living standards and those of the high-income economies also will require such investments.

2. Economic "catchup" in the 21st century is if anything likely to place greater demands on the knowledge-related capabilities of developing economies, reflecting the faster growth of output and exports of knowledge-intensive products, the more prominent role of basic scientific knowledge in the innovation process, and the importance of stronger national "absorptive capacity" to exploit a much richer body of global scientific and technological knowledge.

3. Many of the policy alternatives for developing nations in strengthening their indigenous knowledge-related capabilities in such areas as tertiary education, domestic agricultural research, and generic research for industrial applications, are entirely compatible with current WTO provisions. Accession to the WTO does not preclude public investments in most of the essential elements of a domestic knowledge infrastructure.

4. The inward transfer, modification, exploitation, and domestic dissemination of scientific and technical knowledge derived from external sources are all knowledge-intensive activities, and indigenous investment in the creation and maintenance of knowledge-related capabilities is essential to the exploitation by developing economies of knowledge from public and private external sources.

5. Policies of market liberalization (reducing tariff barriers to imports, liberalizing inward foreign investment regulations, privatizing and/or deregulating domestic industries) must be complemented by public investment in knowledge-related capabilities. Market liberalization alone is insufficient, as is investment in R&D without the complementary macroeconomic and microeconomic policies to facilitate investments in the exploitation of knowledge.

6. The majority of contemporary empirical evidence on agricultural R&D investment suggests that (a) public investment in domestic agricultural research systems is an important complement to public and private agricultural investment at the international levels; and (b) the social returns to such indigenous investments in both high-income and some developing nations remain high.

7. Where they have occurred, reductions in public investment in such important components of developing-economy knowledge infrastructures as agricultural research should be reversed, albeit only in the context of reforms in the financing, staffing, and structure of such national agricultural R&D systems.

8. The precise structure of public programs for strengthening and maintaining indigenous knowledge-related capabilities must be tailored to the idiosyncrasies of a given national economy. Nevertheless, some general principles for structuring and reforming such programs can be derived from the historical experience of economic "catchup" in the 19^{th} and 20^{th} centuries.

9. Decentralization, autonomy, and close links to users are all important design principles for public R&D programs focused on industry or agriculture. At the same time, it is important to avoid "capture" of public R&D programs by a well-organized group of users.

10. Separating the functions of R&D funding from R&D performance is another general design principle that can facilitate structural reform of public R&D programs. But this "separation principle" must be accompanied by close monitoring by the R&D funding entity of the performance of the R&D performers. Such monitoring should include input from users, either in the form of evaluations or other evidence from users of willingness to pay for services (e.g., modest user fees for access to some forms of public R&D services).

11. Greater investments in evaluation capabilities must accompany investment in indigenous knowledge-related capabilities. Among other gaps in existing evaluation capabilities is a near-total lack of reliable data on R&D funding sources and performers in many if not most developing economies, including many middle-income developing economies.

12. Separation of responsibility for R&D funding from R&D performance also facilitates the introduction into public R&D systems of stronger competition for funding among different providers of R&D services. These competing providers may include both public and private entities.

13. Although competitive allocation of a substantial portion of public R&D funds is desirable, exclusive reliance on competitive funding may discourage the development of strong institutional capabilities. A mix of competitive and institutional funding is preferable.

14. Investment in domestic knowledge infrastructure will succeed only in the face of demand from users for the services provided by public R&D programs. Demand for

such services, particularly from industry, is likely to be greater when competitive pressure on domestic firms is more intense. Policies that reduce barriers to imports and restrictions on foreign investment (foreign firms often are important channels for inward technology transfer), as well as encouraging the formation and entry of new domestic firms, therefore are likely to strengthen the incentives of users to utilize domestic knowledge-related capabilities and to demand better performance from publicly supported R&D programs. Just as market liberalization is likely to fail without greater investments in domestic knowledge-related capabilities, these increased investments are insufficient by themselves to strengthen innovative capabilities in the absence of competitive pressure on firms to utilize their outputs.

15. The importance of competitive pressure on domestic firms also means that any policies of protection against industrial imports must incorporate strong inducements for domestic firms to export. Export performance is an important gauge of firm performance and an important source of competitive pressure. Pure "import-substitution" policies are likely to weaken competitive pressure on domestic firms and thereby weaken their incentives to pursue innovation.

16. Investment in and reform of public R&D programs must be accompanied by investments in a reformed system of tertiary education in many developing economies. Post-secondary education is a critically important source of technical and scientific skills, and universities under some circumstances are able to combine teaching and research activities in ways that enhance the payoffs to each activity. Steps to narrow the widening gap between developing economies and high-income economies in the levels of tertiary educational attainment, especially with respect to technical degrees, can contribute to economic "catchup."

17. The design principles for reform of developing-economy tertiary education systems are similar to many of those recommended for public R&D programs: decentralization, greater autonomy, stronger links to users (in this case, prospective employers of graduates) interinstitutional autonomy, and evaluation. The quality and responsiveness to labor-market signals of tertiary education must be enhanced. In addition, greater experimentation and innovation in the forms of tertiary education offered in many developing economies should be encouraged (e.g., expansion in two-year programs for post-secondary technical and vocational training). Reforms of tertiary educational policies also should incorporate steps (financial assistance for students, etc.) that widen access to tertiary education and reduce rather than exacerbating social inequality.

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Notes

[1] The extensive literature on "national innovation systems" (See Edquist, 2004) has focused primarily on innovation and economic performance in the industrial economies.

[2] The World Bank's 2002 report on *Building Institutions for Markets,* one example of this recent work, unfortunately devotes little attention to the role of institutions in technological innovation and adoption outside of agriculture.

[3] The WTO agreement's inclusion of international trade in services, and the associated liberalization of such trade, also could contribute to significant improvement of critical infrastructure weaknesses in many developing economies, including telecommunications, power generation and distribution, and financial services (See World Bank, 2002c). Realization of this potential, however, will be a considerable challenge, and will require pro-competitive supporting policies within these economies.

[4] Thus, Nelson's concluding chapter in his 1993 collection of studies of national innovation systems argues that "One important feature distinguishing countries that were sustaining competitive and innovative firms was education and training systems that provide these firms with a flow of people with the requisite knowledge and skills. For industries in which university-trained engineers and scientists were needed, this does not simply mean that the universities provide training in these fields, but also that they consciously train their students with an eye to industry needs." (1993, p. 511).

[5] This list draws from Rosenberg (1999), Cohen et al. (1998), and other sources.

[6] David, Mowery, and Steinmueller (1992) and Nelson (1992) discuss the economic importance of the "informational" outputs of university research.

[7] See Rosenberg's (1994) discussion of universities as a source of innovation in scientific instruments.

[8] Mowery and Rosenberg (1989) note that the conduct of scientific research and education within many research universities "…exploits a great complementarity between research and teaching. Under the appropriate set of circumstances, each may be performed better when they are done together." (p. 154).

[9] See Rosenberg (1999).

[10] See Murmann (1998, 2003a, 2003b) for a more detailed discussion.

[11] Murmann (2003a) highlights the important political role of the German chemicals industry in mobilizing and maintaining political support for expanded public funding of research within German universities and elsewhere.

[12] According to Swann (1988, p. 50), Squibb's support of university research fellowships expanded (in current dollars) from $18,400 in 1925 to more than $48,000 in 1930, and accounted for one-seventh of the firm's total R&D budget for the period. By 1943, according to Swann, university research fellowships amounting to more than $87,000 accounted for 11 percent of Eli Lilly and Company's R&D budget. Swann cites similarly ambitious university research programs sponsored by Merck and Upjohn.

[13] Hounshell and Smith (1988, p. 298) report that 46 of the 176 Ph.D.'s overseen by Carl Marvel, longtime professor in the University of Illinois chemistry department, went to work for one firm, Du Pont. According to Thackray (1982, p. 221), 65% of the 184 Ph.D.'s overseen by Professor Roger Adams of the University of Illinois during 1918-58 went directly into industrial employment. In 1940, 30 of the 46 Ph.D.'s produced by the University of Illinois chemistry department were first employed in industry.

[14] "...from comparative obscurity before World War I, American chemistry rose steadily in esteem to a position of international dominance. Almost half the citations in the Annual Reports [Annual Reports in Chemistry, described on the page as "a central British review journal"] in 1975 were to American publications. Similarly, almost half the citations to non-German-language literature in Chemische Berichte [the "central German chemical journal"] in 1975 went to American work. It is striking that this hegemony is the culmination of a fifty-year trend of increasing presence, and not merely the result of post-World War II developments. Second, it is clear that the increasing attention received in the two decades before World War II reflected the growing volume of American chemistry, rather than a changed assessment of its worth." (Thackray, et al., 1985, p. 157; emphasis in original).

[15] Both Bernardes and Albuquerque (2003) and Fagerberg and Godinho (2004, the source for Figure 3) emphasize the contributions of engineering manpower to knowledge-based economic development.

[16] Mazzoleni (2003) states that 40% of the Republic of Korea's workforce had no education and 53% had only a primary education as of 1945.

[17] "Despite the rapid growth of tertiary enrollments in most developing and transition economies over the past two decades, the enrollment gap between these economies and OECD countries has not diminished. In fact, the opposite has occurred…In 1980 the tertiary enrollment rate in the United States was 55 percent, whereas the average for developing countries was 5 percent. In 1995 the rates were 81 percent for the United States and 9 percent for developing countries…

"Of the other regions of the world, Latin America and the Middle East have the highest averages (1997 data), with 18 and 15 percent, respectively, and South Asia and Africa the lowest (7 and 4 percent, respectively). The East Asian average of 11 percent conceals wide differences, from less than 2 percent in Cambodia to almost 30 percent in the Philippines and 51 percent in Korea, which is on a par with the OECD average." (World Bank, 2002, pp. 46-47)

[18] According to Kim (1997), "By 1977, 93 percent of all commodities and 62 percent of all shipments were produced under monopoly, duopoly, or oligopoly conditions in which the top three producers accounted for more than 60 percent of market share. The ten largest *chaebols* accounted for 48.1 percent of GNP in 1980, making Korean industry even more highly concentrated than that of Taiwan or Japan." (p. 28).

[19] Kim asserts that "KIST spent a large proportion of the nation's total R&D expenditure in its early years." (1997, p. 48).

[20] "…the government R&D was not flexible and dynamic enough to adapt to rapidly changing technology in semiconductors. So by 1984, when the government decided to sell the facility to LG, it was virtually obsolete. Nevertheless, KIET made significant contributions to the industry by producing a large number of R&D engineers experienced in semiconductors who moved to the private sector and played important roles." (Kim, 1997, p. 152).

[21] "...it was not until the early1920s that it was possible to claim with some degree of confidence that a national agricultural research and extension system had been effectively institutionalized at both the federal and the state levels. It took 50 to 70 years of persistent effort to organize a productive agricultural research and advisory (extension) system in the United States. This seems an exceptionally long period when gauged by the impatient efforts of modern institution builders in the national and international aid agencies" (Ruttan, 1982, p. 77)..

[22] In fact, both Yale and Harvard Universities had established "scientific schools" by the 1850s, and Yale's program included a professorship in agricultural chemistry.

[23] "…regions with high levels of research intensity realize higher productivity gains. If research findings were easily transferred from one region to another, productivity growth would be similar among regions and not correlated with regional intensities. Obviously, it is not…" (Evenson, 1982, p. 265).

[24] "It is difficult to present an accurate picture of the current situation in funding for agricultural research. The last comprehensive studies on institutes for agricultural research were conducted around 1992 (e.g., Lindarte, 1995). Other information is partial, fragmentary and sometimes contradictory. Probably as a result of severe criticism of their resource administration and management, public institutes for agricultural research and other institutions are not willing to provide information on funding sources and use of funds." (Morales, 1998, p. 23).

[25] This early research was motivated primarily by the desire to promote sharing of the scarce computing resources located at a few research centers.

[26] Packet switching is fundamentally different from circuit switching, the technology that connects ordinary telephone calls. On a packet-switched network, information is broken up into a series of discrete "packets" that are sent individually, and reassembled into a complete message on the receiving end. A single circuit may carry packets from multiple connections, and the packets for a single communication may take different routes from source to destination.

[27] In contrast, Davies's efforts to enlist the support of the NPL and Britain's public telecommuncations agency, the General Post Office, for the construction of a similar network in the U.K. met with limited success and the prototype network that was eventually developed was far smaller than the early ARPANET (Abbate, 1999).

[28] Bolt, Beranek and Newman, an MIT "spinoff" founded in 1948, was an early example of the new firms that played an important role in the Internet's development. The firm was started by MIT Professors Bruce Bolt and Leo Beranek in partnership with a graduate student, Robert Newman. Populated as it was in its early years by a mixture of recent graduates, professorial consultants, and other technical employees with close links to MIT research, BBN is a good example of the "quasi-academic" environment within which many Internet-related innovations were developed. (Wildes and Lindgren, 1985)

[29] DARPA's early strategy in information technology R&D, beginning in the late 1950s, focused on the development of strong academic research institutions, rather than on peer-reviewed awards to individual investigators. Although DARPA research grants typically were made to individual researchers, this remarkably successful program did not adhere strictly to the norms of peer review that now are widely viewed as indispensable to research excellence (Langlois and Mowery, 1996).

[30] Goldstine, one of the leaders of the wartime project sponsored by the Army's Ballistics Research Laboratory at the University of Pennsylvania that resulted in the Eckert-Mauchly computer, notes that "A meeting was held in the fall of 1945 at the Ballistic Research Laboratory to consider the computing needs of that laboratory 'in the light of its post-war research program.' The minutes indicate a very great desire at this time on the part of the leaders there to make their work widely available. 'It was accordingly proposed that as soon as the ENIAC was successfully working, its logical and operational characteristics be completely declassified and sufficient be given to the machine...that those who are interested...will be allowed to know all details.'" (1972, p. 217). Goldstine is quoting the "Minutes, Meeting on Computing Methods and Devices at Ballistic research Laboratory, 15 October 1945 (note 14). Flamm (1988), pp. 224-226, makes a similar point with respect to military attitudes toward classification of computer technology.

[31] The Office of Naval Research organized seminars on automatic programming in 1951, 1954 and 1956 (Rees 1982, p. 120). Along with similar conferences sponsored by computer firms, universities, and the meetings of the fledgling Association for Computing Machinery (ACM), the ONR conferences circulated ideas within a developing community of practitioners who did not yet have journals or other formal channels of communication (Hopper 1981). The ONR also established an Institute for Numerical Analysis at UCLA (Rees 1982, p. 110-111), which made important contributions to the overall field of computer science.

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