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Do Foreign Companies Conduct R&D in Developing Countries?

A New Approach to Analyzing the Level of R&D, with an Analysis of Singapore

Alice H. Amsden
Ted Tschang
Akira Goto

March 2001

Multinational companies tend to conduct little research and development (R&D) outside their home base, especially in developing countries. Singapore represents an anomaly because its multinational firms are reputed to undertake locally not only R&D but applied and possibly even basic research.

This paper tries to create a system for determining the content level of R&D through the introduction of a new comprehensive taxonomy of R&D characteristics. Based on this system of characteristics, which was tested in firm-level interviews, the authors conclude that the type of R&D undertaken by multinational companies in Singapore does not typically qualify as belonging even to the applied research category: most R&D is still closely coupled with production.

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PREFACE

The ADB Institute aims to explore the most appropriate development paradigms for Asia composed of well-balanced combinations of the roles of markets, institutions, and governments in the post-crisis period.

Under this broad research project on development paradigms, the ADB Institute Working Paper Series will contribute to disseminating works-in-progress as a building block of the project and will invite comments and questions.

I trust that this series will provoke constructive discussions among policymakers as well as researchers about where Asian economies should go from the last crisis and current recovery.

Masaru Yoshitomi
Dean
ADB Institute

ABSTRACT

Multinational companies tend to conduct little research and development (R&D) outside their home base, especially in developing countries. Singapore represents an anomaly because its multinational firms are reputed to undertake locally not only R&D but applied and possibly even basic research. Nevertheless, short of hearsay or peering over the shoulder of a researcher, there is no systematic or objective way to determine from outside whether or not the classification of any given R&D effort is correct.

This paper tries to create a system for determining the content level of R&D. Given traditional R&D types (pure science, basic research, applied research, exploratory development or advanced development), it introduces a new comprehensive taxonomy of R&D characteristics, such that variations in a characteristic behave systematically according to R&D type. The characteristics we explore are: the search and objective of an R&D investment; its intended output; its time frame; the measures of performance to which it is subject; the techniques employed by its researchers; their skills and qualifications; and the overall size of an R&D investment. The empirical determination of these characteristics does not require any infringement of a laboratory's intellectual property.

Based on our system of characteristics, which we tested in firm-level interviews, we conclude that the type of R&D undertaken by multinational companies in Singapore does not typically qualify as belonging even to the applied research category; most R&D is still closely coupled with production. Moreover, whatever advanced research that is occurring in Singapore is typically government-induced and revolves around national laboratories as a staging area. In light of the government's role, we draw a general distinction between "spillovers," or R&D activity that is market-induced, and "extractions," or R&D activity that is profit-maximizing but government-induced.

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1. Introduction

Late-industrializing economies with diverse and long-established industrial bases differ among themselves in two key respects: the ownership of their leading manufacturing enterprises and the depth and breadth of their research and development (R&D). In countries where dominant business enterprises tend to be nationally controlled, as in the People's Republic of China (PRC); India; Republic of Korea; and Taipei,China, aggregate investments in R&D tend to be high (otherwise such enterprises could not survive). By contrast, low aggregate investments in R&D and a high incidence of foreign ownership (and majority foreign-controlled mergers and acquisitions) tend to coexist in Argentina, Brazil and Mexico (see Table 1). The sample of latecomers is too small to test this hypothesized relationship statistically, but for major countries in East Asia and Latin America the relationship that one observes (more national ownership, more R&D) conforms with two independent stylized facts. First, despite globalization, multinational firms continue to conduct little R&D outside their home base (12% on average for multinationals headquartered in countries that belong to the Organization for Economic Co-operation and Development [OECD]) (OECD, 1998).[1] Second, country-specific statistics from latecomers corroborate that only a small fraction of local R&D is accounted for by foreign firms. The lion's share is undertaken by national companies, private or public (Amsden, 2001).

Singapore is an exception—just as in other key respects it performs as an outlier among larger developing countries. Multinational firms in Singapore appear to undertake R&D. They account for more than 40% of Singapore's total R&D spending which, in turn, approximates nearly 2 percent of its gross national product (GNP). PRC and India, too, are anomalous insofar as some of their leading foreign firms undertake R&D in software. The nature of software R&D, however, is not strictly comparable to that of hardware-related industries.

These exceptions raise questions about the characteristics of R&D in general. To our knowledge, no systematic method exists to answer questions about the content of R&D, foreign or national, although there is no shortage of classificatory schemes that distinguish and define different research types. By convention, basic research involves the generation of radically new technologies; applied research involves the application of existing technologies, and so forth. But until such generic research types are associated with specific characteristics (for instance, the techniques used by researchers, the performance standards by which their

[1] See also Patel, P. and K. Pavitt (1995); Doremius, P. N., W. W. Keller, et al. (1998); and Patel, P. and M. Vega (1999).

work is evaluated), there is no way other than speculation to judge whether any given R&D effort conforms to the definition it claims or is somehow assigned to it.

To insure that any given research effort is accurately classified—what is labeled "applied," for instance, exhibits objective, transparent properties that are shared by all investments in R&D whose intent is "to apply existing technologies"—this paper tries to specify and enumerate the most important objective properties and/or activities of different research classes (types), as suggested by our work in Singapore. We believe the usefulness of such an exercise is twofold.

First, just as the general economic activities of mid-income countries lie in between those of the most economically advanced and underdeveloped countries, so too, their R&D activities appear to fall somewhere in between the extremes of basic research on the one hand and advanced development on the other hand. We wish to learn more about intermediate endeavors by way of understanding how they got as far as they did and what is needed to move them closer towards research that generates more intellectual property and higher returns. Second, understanding the properties of different research types enables the R&D efforts of mid-income countries to be benchmarked, which may be helpful to their policy makers and R&D managers. Ultimately, such an exercise may provide a framework for predicting where geographically a multinational firm is likely to locate different types of its R&D.

Existing classifications of R&D do, in fact, use an objective criterion—albeit a highly theoretical one—to distinguish between various research types. The criterion is time, or the length of the time period before research results are expected. Research is considered to lie close to the basic end of the spectrum if the time frame involved is relatively long, and close to the applied end of the spectrum if it is relatively short. A theoretical distinction with respect to time may serve to offset extremes—pure science (the search for intrinsic knowledge) on the one hand versus advanced development. But a time discriminator is fairly lame in differentiating R&D activities that lie somewhere in between these extremes, a high probability in late-industrializing economies. Moreover, with shorter product cycles, arguably the time allotted for all types of R&D has been truncated and tends to converge. Time horizons are also difficult to measure in practice (they may be long by default rather than by design). Researchers, therefore, are typically forced to conclude that R&D in a particular case is "basic," "applied" or some hybrid depending on what a manager subjectively tells them. Because of the need for confidentiality and protection of intellectual property, usually outsiders cannot delve into the substance of R&D to draw their own conclusions.

Taking as given any basic-applied classificatory scheme (we ourselves use a modified fivefold distinction developed by the US Department of Defense [DOD]), we attempt to specify beyond the time dimension, the objective and, ideally, measurable and quantifiable characteristics that are found within each research class. The characteristics we investigate concern: the search in the research; the goal of the R&D sponsor; the time frame expected; the anticipated output; the measures used to evaluate the output; the techniques employed; the qualifications and skills of the researchers; and the size of the research effort (see Table 3). In collecting information on these characteristics in a particular research setting (through interviews, questionnaires, etc.), the characterization of R&D can move beyond an insider's subjective opinion.

The information we gathered on R&D characteristics in Singapore's leading multinational firms suggests that local R&D activity is less advanced than at corporate headquarters. It rarely comprises basic research, or even applied research. Thus, Singapore may be anomalous among latecomers in that multinational firms perform R&D there, but the level is still relatively low. This matters for economic development with respect to a certain family of industries that is fast growing worldwide: one in which (a) R&D is high by world standards; (b) scale economies tend to be large; and/or (c) experienced, skilled researchers are in scarce supply. These industries (electrical and non-electrical machinery, transportation equipment and chemicals, including pharmaceuticals) are likely to be subject to "first mover" advantage. The first firms to make the requisite investments in management, manufacturing facilities and marketing get the largest market shares (and often keep them for long periods) (Chandler Jr., 1990). If, therefore, a multinational becomes the "first mover" in such an industry in an emerging economy, it may succeed in "crowding out" the entry of nationally owned firms. Given negligible overseas investment by multinationals in R&D, it is unlikely that local R&D in these dynamic industries will occur. Instead, to grow and become internationally competitive, the industries will have to rely for their new technologies and advanced skills on whatever a foreign direct investor chooses to transfer from other subsidiaries. In these most dynamic industries, the late-industrializing economy will thus be denied the possibility of ever earning "monopoly," "technological," or "entrepreneurial" rents (we use these terms interchangeably) due to its failure to acquire the skill base that is a prerequisite for such rents.

The overriding importance of skills in the global income distribution of a high-tech industry is illustrated by the case of hard disk drives (HDDs). In 1995, Southeast Asia (mostly Singapore) had virtually no nationally controlled HDD companies, but it accounted for as much as 64% of final global assembly and 44% of total global employment (see Table 2). Southeast Asia's wage bill, however, was only 13% of industry wages worldwide. Developed economies (Europe, Japan and the US), by contrast, controlled the ownership of the HDD industry's leading enterprises and were responsible for virtually all of its R&D. These economies accounted for less than one-third of both final assembly and total employment but captured more than three-fourths of the HDD industry's wage bill (Gourevitch, Bohn and MacKendrick, 2000).

Historically, the R&D undertaken by foreign firms in Singapore was manufacturing-driven. It arose from a firm's need to solve a process problem or to improve a product design in order to cut manufacturing costs. Such early R&D thus qualifies as a "spillover."[2] It represents a purely market-induced, autonomous response (in this case, to production-related problems). By contrast, the more skill-intensive R&D that multinationals currently undertake in Singapore (exploratory development and applied research) takes the form of something more deliberate than a spillover. We call such activity an "extraction," because it is a response to government policies. Subsidies plus the establishment of a national innovation system in Singapore—with a large number of well-funded and well-managed government-owned R&D labs as the jewel in the crown—created the resources, especially experienced personnel, that were a prerequisite for foreign firms to upgrade. In concluding this paper, therefore, we provide information for other countries on how Singapore induced foreign investors to conduct R&D.

[2] For the concept and empirical measurement of a spillover, see, among many others, Cohen, W.M. and D.A. Levinthal (1989); Aitken, B., G. Hanson, et al. (1997); Blomstrom and Kokko (1998); and Borensztein, E., J. de Gregorio, et al. (1998).

2. Classification of R&D

We can think of the classification of R&D as consisting of two aspects: the actual types of R&D categories; and the characteristics of those categories. Most countries, such as Australia, Japan, Singapore and the US, rely on the OECD "Frascati manual" for classifying their R&D investments and activities (OECD, 1993). The Frascati manual classifies research into three distinct types: basic, applied, and experimental development. Nevertheless, it does not characterize different types of R&D beyond a very limited number of selected characteristics, such as the caliber of R&D personnel (scientist versus technician, for example). It does not even differentiate types of R&D by time, although more theoretical approaches tend to do so. Furthermore, types of R&D and variations in selected characteristics are not systematically connected with one another, and the same disconnectedness tends to characterize country-specific codes of research occupations.

Some research centers in Japan use the Frascati classification (i.e., basic, applied, and developmental), but these classes are not disaggregated, nor are the characteristics of each class stipulated. All government agencies in the US use variants of the Office of Management and Budget's (OMB's) categorization (basic, applied and developmental research), which also corresponds to the Frascati definition. The most finely detailed break-down is probably that of the US DOD, which is the one we use in a modified form below (Wagner, 1998). Nevertheless, not even this breakdown comes equipped with a complementary analytical classification of what, in fact, characterizes each type of R&D activity.

Conceivably, the substance of a research effort can be evaluated by determining the definition to which it most closely adheres: basic is defined in the Frascati manual as experimental or theoretical work to acquire new knowledge without any particular application; applied is defined as original investigation but with a specific practical aim; and experimental development is defined as systematic work drawing on existing knowledge directed toward producing new products or services. A research project can be pigeon-holed depending on the definition to which it best conforms. Nevertheless, determining such conformance requires the researcher to learn the precise and specific details of any research effort. Even assuming adequate capabilities on the part of the researcher to process such details, most research labs withhold confidential and proprietary information. By contrast, divulging information on the generic characteristics of research does not trespass nearly so much, if at all, on intellectual property.

3. Foreign Ownership and R&D

Assuming all countries follow the protocol of the OECD's Frascati manual in calculating the share of R&D in national spending (OECD, 1993), then Singapore distinguishes itself among emerging economies for the high share in R&D accounted for by foreign firms. In Taipei,China (Taipei National Science Council, 1996) and Korea (Ministry of Science and Technology, Korea, 1998), the share of foreign expenditure in total national R&D spending has typically been less than 2%, although foreign direct investment as a share of manufacturing output in these countries also tends to be small by Singapore standards. In Argentina, Brazil, Chile and Mexico, the share of foreign expenditures in total R&D spending also runs at less than 2% (Alcorta and Peres, 1998). In these countries, however, not only is direct foreign investment as a share of manufacturing output large (even if not necessarily as large as in Singapore), but R&D as a share in GNP is minuscule (see Table 1 for R&D in the largest countries) (Amsden, 2001).

The share in Singapore in manufacturing value-added of foreign-owned firms (using 50% equity as a cut-off) was 72% in 1998 (Singapore, 1998, table 8). General expenditures on research and development (GERD) as a share of gross domestic product were supposedly 1.8% (compared with 2.8% in Korea and 1.8% in Taipei,China—see Table 1). The private sector's share of GERD in Singapore was reported to be 61.6% (Singapore National Science and Technology Board, 1998). Therefore, the share of the foreign private sector in GERD may be estimated to have been as much as 44%. This percentage would be even higher if only the electronics sector rather than total manufacturing were considered. The electronics sector in the 1990s accounted for the greater part of Singapore's R&D (about 60%, depending on the year), and foreign-owned firms accounted for as much as 85% of electronics output (Wong, Phang, et al., 1997).

Even the 44% figure for Singapore is anomalous by all accounts. For OECD countries, the foreign share in national R&D expenditures tends to be small (with the exception of Ireland, another small economy). Stated otherwise, the share of R&D undertaken by the OECD's multinational firms outside their home base averages no more than 12% of their total R&D, although the figure varies by country. It is around the average for the US, only approximately 2% for Japan, and higher than the average for many European countries. In cases where the foreign subsidiary of a multinational firm does undertake R&D, more often than not this subsidiary originated as an acquisition, implying that the subsidiary had an established and functioning R&D facility before it was acquired (OECD, 1998).

Given the anomaly of foreign-sponsored R&D in Singapore, our first task is to develop a methodology to evaluate it.

4. A General Taxonomy of R&D and Caveats

Following the schema of the US DOD, we take as our starting point five types of R&D: pure science (6.0), a category we add to the DOD's classification; basic research (6.1); applied research (6.2); exploratory development (6.3); and advanced development (6.4) (see Table 3).

The properties/activities that we use to characterize each research type are: the search and objective of R&D; its output; the performance measures to which it is subject; its time horizon; the techniques its researchers employ; the qualifications and skills of its researchers; and the overall size of its effort (see Table 3). These characteristics were suggested to us by our fieldwork in Singapore. Hence, they are generated empirically rather than theoretically.

A caveat is in order before proceeding, one that applies to type and characteristic of research alike. There are dependencies among different research efforts—between, for instance, basic and applied, or applied and exploratory, such that one presupposes the other. These dependencies, however, may or may not occur within a particular firm, since a firm can buy, use, or adopt technology that is old or developed outside, a frequent occurrence in late-industrializing economies.

Another caveat is that research efforts are not necessarily mutually exclusive. There may be overlaps or similarities between them, depending on the characteristic in question. In terms of hardware and even software in the same industry, they may be indistinguishable in a laboratory undertaking "basic research" and one undertaking "applied research;" to all appearances work in the two settings is identical. Nevertheless, sharp differences may lie in yet another characteristic, such as the use (and hence output) to which the hardware and software is put. If R&D types take place as stages within a firm, then given the iterative nature of R&D, there may be cycles back and forth between different stages, rather than a simple linear progression of R&D across stages. This iterative and messy nature of the beast may be one reason why applied research and exploratory development, or other neighboring types, are not easily differentiated. For example, the design of a new HDD head may involve modifying the basic science (applied research) and designing the component (exploratory development) simultaneously. Similarly, there is overlap between exploratory and advanced development insofar as prototypes for design or manufacture may be iterative or the same, depending on how mature the technology and/or product actually is.

For all these reasons, it is important to investigate as many characteristics of research as possible before concluding anything about a lab's stage of complexity.

5. Objective, Search, Output and Performance Measure

In the case of R&D laboratories at the world technological frontier in developed economies, the heart of the present R&D drama is typically the angst of how to make conceptual knowledge more market oriented, or how to move from the left in Table 3 towards the right (from pure science and basic research, 6.0 and 6.1, to more applied and developmental work). University and government labs are under pressure to meet performance standards and demonstrate "concrete" results. Corporate labs are under pressure to do a better job of handing over basic concepts for practical product application and manufacture.

In late-industrializing economies, by contrast, the angst has been in the opposite direction, of how to move from advanced or exploratory development (6.4 and 6.3), focused on manufacturability and the import substitution of parts and components, to the generation of at least a differentiated product through better product design. The Great Divide occurs between developmental work (6.3 and 6.4) and applied research (6.2). To be sure, the first government labs in emerging economies typically arose with the intent of performing basic or at minimum applied research, and appeared chronologically before central R&D activity began in even the largest private firms.[3] But early government labs were criticized for failing to generate either state-of-the-art or practical outcomes. Or they were criticized for being overly concerned with national security and defense, as in the PRC and India, or with genteel dabbling in the field of medicine, as in Latin America.[4] The R&D that first occurred at the firm level, in private companies, tended to occur in conjunction with manufacturing, the core competency of latecomer firms (for Japan, see Ozawa, 1974; and Goto, 1993). The struggle over time has thus been one of moving beyond R&D tightly coupled with solving manufacturing and prototyping problems to R&D oriented towards generating differentiated products that can earn technological rents in segmented markets.

In moving from advanced or exploratory development to applied research, R&D characteristics related to search, objective and output tend to be as radically distinct—if not more so—than in moving from basic to applied research. Advanced and exploratory development remain largely in the realm of engineering—they are oriented towards solving concrete problems at the heart of which is the physical construction of a prototype. Applied

[3] For Korea, see (Kim, 1997), and Latin America, (Alcorta and Peres, 1998).
[4] In 1972, only two organizations in Singapore undertook R&D: the National University of Singapore and a department within the Ministry of Defence. In 1997 that department was corporatized and spun off as a separate lab, the Defence Science Organization (DSO).

research, by contrast, enters the world of science—it requires the transformation, variation and reapplication of a known concept to an unknown end, which is more demanding analytically (see Table 3). In terms of characterization (as shown in detail later), it is probably easier to distinguish between 6.3 and 6.2 than 6.1 and 6.2. That is, the dividing line in R&D between generating a detailed product design or prototype in an engineered system (6.3) and creating a new differentiated product (6.2), is probably sharper than researching a new concept with the intent of creating a new product (6.1) and differentiating that product on paper (6.2).

The organizational differences between advanced or exploratory development (6.4 and 6.3) and applied research (6.2) may be appreciated in the R&D effort in Singapore of Sony. Sony's research also illustrates the historical role of import substitution in a latecomer's R&D. In 1987, Sony established a production facility in Singapore (Precision Engineering Centre, or SPEC) for components, optical pickup, magnetic head and other products. By 2000, 750 employees were involved in manufacturing, and sales equaling $350 million. A Singapore-based R&D center (CRD—Components R&D) was established in 1996 to localize advanced development as well as to support this manufacturing operation. In the case of an optical pickup component, for example, 60% of parts were of Japanese design and materials. Soon, 98% of parts and materials became localized. R&D was oriented toward producing prototypes for this localization effort; Singapore vendors tended to be weak in prototype production (as indicated in Table 3, the output of exploratory development is defined as "detailed product design or prototype"). CRD learned a lot from close interaction with R&D in Tokyo. An on-line system connected the two. The weakness of the center was that R&D was confined mainly to the manufacture of optical pick-up devices, so the scope for learning was limited.

Slowly this began to change. CRD was restructured and as of 1 April 2000, a new organization, Singapore Research Laboratory (SRL), was established as a separate entity from SPEC. The focus of SRL will be on developing new magnetic and optical technology. Sony engineers in Singapore will "transform, variate and re-apply a known concept for a new application." There will be a complementary shift toward IT-oriented business (pickup testers, optical components evaluation such as interferometer and in situ testing, as well as digital up-scaled servos [optical pickups/HDDs]). The upscaled activity of Sony's Singapore-based R&D will be integrated at one end with HQ and at the other with various Singapore research institutes, especially the Centre for Wireless Communications (CWC), which expects to collaborate with Sony on a large research project. Thus, in the case of Sony, the qualitative graduation to applied research from development involved the creation of an entirely new R&D lab, with new interfaces with external organizations.

The distinction between advanced and exploratory development, and applied research, may be appreciated in the transition of a nationally-owned firm (as distinct from a foreign-owned firm) from a "manufacturer" (OEM), to an "original design manufacturer" (ODM), to an "original brand manufacturer" (OBM).[5] As only the manufacturer of a product wholly designed by a foreign contractor (OEM), the nationally-owned firm is required to "reduce the costs and uncertainties of manufacturing." As an original designer, it must "produce a prototype of a fully engineered system." The basic design platform of the product to be manufactured (and the parts and components to be procured) is still provided by the foreign customer, but the integration and details of design (to lower manufacturing costs and

[5] For these distinctions in the information technology industry of Taipei,China, see (Amsden and Chu, forthcoming).

especially reduce “time to market”) are the responsibility of the subcontractor. In this respect, the subcontractor must invest in R&D that may be quite expensive in order to integrate all parts and components into a workable system, and each customer requires its own system. Some rudimentary applied research may also be undertaken in order to anticipate changes in the market, but no attempt is usually made to lead the market. As an original brand manufacturer, by contrast, the whole research effort (as well as marketing effort) has to enter a new realm. The firm in question has to develop its own technology. If it can buy or acquire the fruits of another organization's basic research (depending on the stage of the product cycle), then it must still "transform, variate and reapply a known concept to an unknown end." In terms of the examples in Table 4 (from the telecommunications and HDD industries), the R&D of the ODM supplier would be oriented towards implementing a communications algorithm on a circuit or in software, or developing a new head prototype. The R&D of the OBM supplier would have to move beyond this, into the invention of a wholly new product concept, or at least a variant of that concept that commands brand-name respect in the market.

In the case of leading edge electronics companies, from developed countries, that choose to lower their production costs and "time to market" through foreign direct investment rather than subcontracting (as in Hewlett-Packard Singapore, [HP]), the distinction is equally sharp between exploratory and advanced development, and applied research. HP is one of Singapore’s largest manufacturers and in 1999 employed 9,000 people: 3,000 in Agilent, which specializes in components, and 3,000 in other types of manufacturing. R&D was a spin-off from manufacturing. In 1993, however, the printing business became a corporate division under pressure from local managers and engineers, who wished for more independence from HP headquarters in Palo Alto, California. With divisionalization, and local responsibility for sales, an R&D facility became necessary. HP’s printer division in Singapore was reputed to be undertaking cutting edge research. In reality, “core technology for printers still comes from Palo Alto,” despite the fact that the ink jet division in HP is one of the most advanced and oldest. Nevertheless, with divisionalization, HP Singapore’s R&D moved into the most preliminary stage of applied research. It began to modify in a limited way the basic designs provided by Palo Alto in order to build and sell a differentiated product that was more cost effective and suited to the Asian market (a low-end, portable ink jet printer). Turning now to the characteristics of output and performance measures, generally 6.0 and 6.1 (pure science and basic research) are measured by some standard related to intellectual property (IP), whereas 6.3 and 6.4 (exploratory and advanced development) are measured strictly by market results. Applied research (6.2) falls somewhere in between; the desired output of R&D labs in latecomer countries tends to be a differentiated product with IP, the source of entrepreneurial rents. Examples might be packaging for integrated circuits, or a drug delivery system using special polymers.

How the expected output of an R&D project is measured may strongly influence whether research trends in the direction of 6.2 or 6.3. The influence of a measurement criterion on the level of research was evident in a project undertaken in Singapore by a major unidentifiable multinational (call it MUM1). The project also illustrates an inherent problem of government-induced R&D, discussed later. The Singapore Government approached MUM1 to do Big “R.” A consortium was set up with government labs and other private sector parties in order to enhance general research capabilities in Singapore. However, the project was a failure due to “a combination of the way it was set up and the way it was measured” (according to MUM1’s director in Singapore). The Singapore Government persisted in wanting Big "R," and so with heavier incentives, MUM1 established an emerging technologies center, focusing on developing Internet technologies.

Teams were formed to undertake research on distributed computing and routing technologies by means of building prototypes (something which the corporate labs in the US had little interest in doing). Prototyping appears to have led to the enhancement of the group's technical skills. Nevertheless, according to the director, "The project had some science, but very little, because this was not the main way the project was measured. For a multinational to do research in Singapore, it has to make good business sense. This is how the Economic Development Board (EDB) sells its incentive package to foreign firms. MUM1 has to justify its operations in Singapore to corporate headquarters depending on market results, which makes undertaking Big "R" (or even Little "R") problematic."

6. Techniques and Research Qualifications

Techniques refer to the body of tools and methodologies used by researchers to conduct R&D. One dimension to techniques is their newness—whether they already exist or have yet to be created. Another dimension is the amount of conceptualization that is required in their use. To appreciate both dimensions, it is necessary to couple technique with the nature of the work being undertaken (in terms of the objective, as discussed above, and the tasks to which a technique is applied).

Techniques can be scientific or engineering in nature, and the type of R&D may depend on the proportion of one to the other. Scientific techniques involve mathematical and science-based theories and tools, and methods such as experimentation (e.g., laboratory testing of a theory). Engineering also uses mathematics and other scientific formulae, but in applied ways, in order to solve specific problems, including the use of data to develop solutions to a given equation. Engineering design involves piecing together separate components into a working system, while satisfying many real world constraints. All types of R&D may involve "innovative" solutions, such as the use of interdisciplinary practices in research, i.e., the fusion of two concepts, or the reapplication of a technology or concept from one field of inquiry (say, mechanical engineering) to another field (say, materials science). In general, we can say that 6.0 and 6.1 use scientific techniques. Type 6.3 mainly uses engineering design techniques and 6.4 mainly uses manufacturing-related engineering techniques. Type 6.2 uses a higher proportion of science than either 6.3 or 6.4 because applied research involves extending basic scientific principles to new contexts or problem areas.

To differentiate techniques further: both 6.0 and 6.1 converge in their use of mathematics or science, such as the development of first principles in science along with the accompanying mathematical equations and their algebraic solutions. Further, 6.0 and 6.1 share methods of scientific inquiry such as experimentation and "testing theory." In 6.1, however, we are involved in achieving a specific product as the objective, while in 6.0 the scientific inquest for the sake of knowledge represents a more diffuse objective. Therefore, in the case of 6.1, to develop new products, we may limit ourselves to studying specific classes of materials, or variants of them, while in 6.0, new materials may be studied simply for their interesting properties. Despite this, research conducted in different settings (e.g., university versus corporate labs), or with different objectives (e.g., academic publication versus corporate profitability), could still theoretically result in the discovery of the same material, and involve identical techniques.

One major difference between 6.1 and 6.2 may lie in the degree to which known tools and methodologies are being used. According to William Lau, Research Director of

Singapore's Defence Science Organization, basic research means you don't know how to solve a problem insofar as "there is no existing framework" to rely upon and "no one understands the science." By contrast, 6.2 relies on "work done before, so a basket of tools is available, although a quantum improvement is still required to apply what is known." While there is not necessarily a difference between the two in terms of a researcher's capability, the degree of understanding of the applicability and known or unknown nature of the technique differentiates the two.

The difference in technique between 6.2 and 6.3 relates not only to the tools themselves but also to the nature of the work, as noted above. Applied research relies on theoretical work to extend or variate the scientific principles laid down in 6.0 or 6.1. By contrast, 6.3 focuses on developing the prototype product, which may involve the first "paper design" (or paperless design as it were these days)—putting the new engineered element or equation into a specific design integrated with other elements. This involves the design of systems, the underlying component design, and their integration. Oftentimes, these components are assembled from engineering data or information extracted from data repositories and "cook books." These sources essentially involve recipes for components and their application. Advanced development, 6.4, involves prototyping for manufacturing in which the optimization of both a design's manufacturability and its manufacturing process have to take place, and production problems have to be solved. Research types 6.3 and 6.4 may thus use automated tools (e.g., computer-aided design) in engineering or systems design. The engineering methods in 6.2 through 6.4 are typically known, although sometimes new tools have to be developed or employed from other fields in order to achieve a product-related objective.

6.1 Example of new HDD head design: 6.1 to 6.2

The Singapore Government-owned Data Storage Institute (DSI) developed capabilities for undertaking a mixture of 6.1 and 6.2 research. These activities encouraged the type 6.3 work that multinational companies in Singapore began to conduct to improve their bottom line. The DSI helped them to develop key components, e.g., new materials for HDD head designs. DSI actually worked on new materials—HDD heads and other components of data storage systems (i.e., 6.1 work), but some of this was, in fact, an extension of more fundamental research that had already been carried out elsewhere. In the case of new materials for HDD heads, these were discovered by a combination of mathematical prediction, scientific simulation, and experimental mixing (of materials) and evaluation. To extend the current properties of new materials was no easy task, but it was one that nonetheless still operated within the bounds of established fields and applications. The focus on fundamental research required working with advanced scientific theory and equipment. The point, however, is that most of the really advanced or long-term 6.1 work in this field, such as research on radically new properties of materials, or whole new means of data storage (e.g., holographic storage), tended to be conducted by cutting-edge corporate labs, such as IBM's Almaden facility in San Jose, or university materials science departments. These latter sources were involved in developing or using advanced scientific theory, techniques and equipment, which DSI was not doing.

6.2 Example of communications algorithm: 6.2 and 6.3

In the communications field, first scientific principles, i.e., basic equations, have to be developed using fundamental mathematical techniques and engineering theory. For 6.0 and 6.1, these techniques may not yet have been invented, whereas for 6.2, the concern may be further exploring these known techniques. Type 6.2 may involve similar reapplication of the seminal equations to new problems, or development of variants of these equations. To use the communications example in Table 4, we may be taking the basic algorithm (i.e., set of equations) and variating it to be compatible with different communication protocols or frequency spectrums used in different countries.

The STMicroelectronics R&D group in Singapore developed communications algorithms and product designs in a mixture of 6.2 and 6.3 research. While the corporate lab (Grenoble, France) focused on the development of new mathematical algorithms, the Singapore team focused on 6.2 work that variated these (i.e., it extended the basic algorithm to new applications required in the Asian region), and 6.3 work that implemented these as prototype firmware (i.e., software embedded in hardware). This latter step required mathematical abilities (to modify the algorithms), and engineering skills. But it did not involve fundamental research for original algorithm development or, for that matter, fundamental research into the basic composition of silicon, the core of the computer chips manufactured by STMicroelectronics, requiring a strong background in physics.

By way of concluding this section, we thus see how R&D characteristics related to search, objectives, output performance measures and technique involve a noticeable qualitative divide in moving to applied research from left or right in Table 3, or from pure science and basic research on the one hand and advanced and exploratory development on the other. In the realm of techniques, the latter movement especially tends to involve a transition, however subtle, from engineering (using known techniques for problem solving) to science (inventing new techniques for conceptualization).

In terms of research qualifications, another characteristic specified in Table 3, they derive from all the characteristics discussed thus far, including techniques. Generally, to the left of applied research in Table 3, a Ph.D. is required; to the right, it is not. Excluding Japanese staff, very few Ph.Ds appear to have been employed in the Singapore-based R&D efforts of NEC, Sony (at least before 2000), Toshiba and National Panasonic. This was in spite of the fact that the qualifications of their workforce (R&D and non-R&D) have tended to rise, as measured by numbers of managers and engineers. As seen in Table 5, the share in 1987 of engineers and managers in total employment rose from 15% to 23% (in 1999) in HP and from 14% to 29% (in 1998) in NEC. According to HP managers, less than 5% of R&D staff in Singapore had a Ph.D. (compared with over 70% in HP corporate labs). If HP Singapore employed more Ph.D.s, these managers alleged, they would get in each other's way. In the case of GeneLabs Diagnostic (GLD), one of Singapore's largest biotech startups, it employed upwards of 50 people in 1999 (GLD takes proteins developed in its US headquarters and makes them into a marketable diagnostic product—its research falls under the classification of exploratory development). Although GLD continued to undertake some product-related R&D activity, over time its overall R&D effort became even more production oriented. In line with this shift, the number of its Ph.D.s declined.

The dividing line between employing doctorates and non-doctorates was centered on applied research. Virtually all companies interviewed indicated that their upgrading in Singapore into applied research depended not just on the availability of Ph.D.s, but also on the availability of Ph.D.s with experience in research. As discussed later, government labs were instrumental in promoting more advanced R&D insofar as their own applied research efforts provided the trained Ph.D.-holders allegedly required for employment by the private sector to undertake more advanced R&D. In the case of government labs, Ph.D.s comprised 16% of professional employment in CWC. In the Institute for Microelectronic Engineering, Ph.D.s numbered around 100, about half of the total professional staff. In the Institute of Molecular and Cell Biology (reputed to conduct fundamental research), 80% of its 300 staff were scientists with Ph.D.s. Singapore's Defence Science Organization had a staff of 800 people, including 500 scientists and engineers, of whom 13% had Ph.D.s.

7. Size of Effort

The jewel in the crown of R&D in advanced economies is the corporate lab (or its equivalent in the public sector), whose focus is on basic research. This lab is large in size relative to other R&D efforts, sometimes employing as many as 1,500 or 2,000 full-time researchers (depending on the industry). The first reason for large absolute size is that to conduct basic research for a new product, multiple disciplines as well as integrative capabilities are required. For example, the corporate lab at STMicroelectronics, a manufacturer of semiconductors, employed more than 1,900 people in 2000 with diverse scientific backgrounds ranging from chemistry and biology to computer science and pure mathematics (R&D absorbed as much as 16% of STMicroelectronics' total global revenues). Second, the infrastructure to support multidisciplinary and integrative activity must be large (necessitating, say, libraries and data banks). If external infrastructure is considered, in the form of a national innovation system with universities and government research institutes that provide supporting services to corporate labs, then the total effort, internal and external, is larger still. Third, most corporate labs are involved in multiple research projects by way of reducing risk and hedging bets.

If the corporate lab is regarded as the hub of a wheel, then the size of its various spokes, responsible for research types other than basic, may be expected to be smaller, although to varying degrees. Depending on how a piece of knowledge is sliced, fundamental research (6.0) may involve few people and resources (an individual graduate student or a small team, as in IBM Japan). Basic research could be expected to dwarf applied research due to fewer disciplines, integrative functions and supporting infrastructure. Absolute size in the case of applied research in locales other than corporate headquarters would depend on the number of baskets into which a multinational firm distributed its eggs. In the case of Ericsson, for example, its cyber-labs for Internet research were divided between four locations: Berkeley, California; New York; Japan; and Singapore, rendering the size of each individual effort smaller than otherwise. The size of advanced and exploratory development tends to depend on the specific system and production effort in question.

Generally, the in-house R&D (circa 2000) of multinationals in Singapore was small: about 18 people in Sony; 37 in STMicroelectronics; 50 in Philips; 14 in IBM; 300 (including marketing staff) in HP; 50 in Toshiba (video products) and 60 in a Digital Consumer Technology Centre; 20 in NEC's new Mobile Communications Development effort; 20 in Digital's Asia-Pacific Research Laboratory (for Internet-related hardware and software development); and 40 in Panasonic (for assembly testing and packaging of integrated circuits), to cite a few examples. Seagate's design team in Singapore was reputed to employ 200 people. This was uncharacteristically large by local standards.

Measured by the number of researchers, then, even in Singapore the small size of most foreign corporate R&D activity conformed with the stereotype of little R&D being carried out by multinationals abroad. Besides being small, such in-house efforts remained tightly coupled with production or, at most, with the design of a prototype for a production system. The time horizon for results in Singapore was typically short, and outcomes were usually judged by measures related to profitability rather than intellectual property criteria. The techniques employed were more in the realm of engineering than science, and the qualifications of researchers fell short of a Ph.D. Moreover, the sharp discontinuity between applied research on the one hand, and exploratory or advanced development on the other hand, introduced a rigidity and path dependence that made it difficult for a given lab to shift from one type of research to another, as was observed in the case of Sony.

Two questions arise: wherein is the substantial foreign R&D activity in Singapore that is suggested by official statistics? And how does a developing country shift the emphasis in foreign R&D from developmental work to applied work?

The significance in Singapore of foreign R&D must be sought outside corporate boundaries—as defined by in-house labs. Instead, foreign R&D has flourished in joint projects undertaken with state-owned research institutes. There is evidence of applied research occurring in such collaborative efforts, or in government-owned labs acting independently. Some labs have even begun to invest in basic research. This "outside" activity would account for both Singapore's relatively high share of R&D in GNP (approximating 1.8%), and relatively high share of foreign private companies in R&D, despite the small size of such companies' internal R&D effort (measured by the number of researchers). The role played by government labs would also help to resolve a paradox: despite the initial production orientation of foreign firms' R&D, most such firms indicated their intention to continue undertaking R&D in Singapore despite moving their production overseas, to still lower wage countries.

It is to the question of how government laboratories extracted greater R&D activity from foreign firms that attention is now turned.

8. Extractions

The Singapore Government was dedicated to bridging the divide between development and applied research. Its role was striking in two ways: (1) the unanimity with which foreign firms stressed its importance in their decision making; and (2) the nature of the services and subsidies the Government provided to induce multinationals to choose Singapore as their locale for both production and advanced R&D.

Foreign companies were unanimous in emphasizing that they had invested in R&D in Singapore because of government support. This came not only in the form of services provided by government labs but also protection of intellectual property and financial incentives. According to officials in the National Science and Technology Board (NSTB), for every $1.00 invested in R&D by a multinational firm between 1991 and 1999, the Singapore Government invested roughly 30 cents. More than half of all research grants were dedicated to personnel training. The remainder was used for machinery procurement, etc. Although wages for researchers were lower in Singapore than abroad (see Table 6), this was rarely mentioned as a motive for local R&D. Instead, systematic government support was stated explicitly as being paramount.

According to STMicroelectronics, the Economic Development Board (EDB) and NSTB were "very aggressive" in promoting R&D. They provided "good incentives" and no worries about intellectual property (IP). Within the CWC, the government lab with which STMicroelectronics collaborated, there was a very clear compartmentalization of projects, which made ST feel comfortable knowing that its IP was safe from other CWC corporate partners. Proposals for government money could be streamlined and grants involved joint finance (ST's three research grants all had equal cost-sharing with the Government). The emphasis was on "developing personnel."

According to HP, its R&D in Singapore was "tightly interconnected" with government subsidies, tax benefits being only one of many. R&D began with a grant from EDB for bonding. Under an EDB initiative, HP joined a consortium with Texas Instruments and Canon to work on print heads. HP also conducted joint research with Kent Ridge Digital Labs, a Singapore government body concerned with researching information technology. In the case of Sony, its decision to start R&D in Singapore was a response to "government encouragement." Philips' R&D in Singapore began with a risk grant from EDB. Philips worked with government labs because there were "no government claims on IP." Toshiba stressed that Singapore had the necessary infrastructure for R&D, the quality of its engineers was better than in other parts of Southeast Asia, and the Singapore Government provides "generous" financial incentives. "Government support was one of the major reasons why Toshiba stayed in Singapore." Similarly, one of the reasons why Matsushita was staying in Singapore was "very strong government support." Matsushita, with its local R&D facility, MasTec, founded in 1979, formed a consortium to improve process technology with the government-owned Gintic Institute of Manufacturing Technology. Matsushita also received government support for training and technology transfer, and sometimes used university equipment. Thus, if Singapore is anomalous among latecomers in the degree to which its foreign firms invest in R&D, then this anomaly appears to be closely connected with a high and effective degree of government promotion.

Government support to R&D appears to have been successful because it addressed the real operating problems that foreign firms in a latecomer country typically encountered. Subsidies addressed their shortage of skilled labor. Services addressed their design-cum-manufacturing problems associated with mature although incrementally improving products. The resolution of these problems, while challenging, was of little theoretical interest to researchers in corporate labs in developed economies. Nor could such problems be resolved by existing R&D that was oriented towards solving immediate manufacturing headaches (6.3 and 6.4 in Table 3). Instead, such problems were tackled in joint projects with government institutes. In the process, these institutes created a bridgehead into applied research.

The deliberate construction of this bridgehead was necessary, and did not evolve naturally, because R&D of foreign firms in Singapore was firmly rooted historically in solving the most immediate design-cum-manufacturing problems. STMicroelectronics had one of the largest semiconductor manufacturing capacities in Singapore (its Ang Mo Kio lab alone employed 1,600 people in 1999). The Vice-President of Sales and Marketing for Southeast Asia invested in local R&D "out of his own pocket so that he wouldn't have to go to European labs every time he had a request to solve the problem of a client. There was a need to develop information in Asia." With mass production and the manufacture of thousands of each type of product, manufacturing-cum-design errors were unacceptable. As in the cases of IBM and HP, STMicroelectronics' R&D in Singapore was organized as part of sales and marketing; it was not an independent staff function.

In Philips, R&D in the form of a Centre for Industrial Technology (formerly Centre for Technology [CFT]), "grew out of manufacturing." Philips established CFTs throughout the world because to produce goods efficiently, "a company has to look at how a product is designed." The CFT at Philips headquarters (Eindhoven) was responsible for advanced production; CFT Sunnyvale (California) is development oriented; CFT Singapore is "production oriented." In 1999, Philips' R&D was still supporting production in Singapore, mainly household irons. In the case of Toshiba, it at one time produced low-end TVs, VCRs and projectors in Singapore. An R&D center was established with two functions: to design the outside box and software for vintage TVs and VCRs, and to support the company's manufacturing operations throughout Southeast Asia (except the PRC, which was supported from Japan). With respect to Matsushita (Panasonic), in 1998 it had eight manufacturing facilities in Singapore, employing a total of 12,158 people (198 Japanese). Matsushita's MasTec produced automatic insertion machines, dyeing molds, assembly systems and computer integrated manufacturing (CIM) software. It also undertook R&D to support the Matsushita group in Singapore in enhancing production engineering capabilities. Oculex Asia Pharmaceuticals Ptd Ltd, a new biotech start-up in 1996, makes drug delivery systems. Basic research is undertaken at the US headquarters. R&D in Singapore consists of insuring that a product is workable commercially, i.e., that it can be made consistently, is a stable product with a good shelf life and that there are quality assurance (QA) test procedures, in place to ensure compliance with government-mandated practices.

Given the manufacturing background of Singapore's R&D, its next evolutionary stage was also manufacturing-based. Manufacturing problems that companies could not resolve within the context of their exploratory or advanced development procedures, they began to address in their alliances with government labs. The most obvious case was Gintic, whose staff of 400 engineers was devoted exclusively to solving the process problems of clients. Examples of joint projects with 200 multinationals included development of a high-precision computer numerical controlled machine (CNC) grinding system, a dynamic optimization and scheduling system for the semiconductor test manufacturing industry, a new precision jet cutting technology and high-speed milling techniques for hard materials.

A manufacturing base was evident in government labs ranging from the DSI, which serviced the HDD industry with a full-time staff of 200 scientists and engineers, and CWC, which serviced the telecommunications industry with a staff of 160. According to the director of DSI, "HDD manufacturers must reduce their number of parts to lower their costs, and their industry is brutally competitive. Hence, HDD design is sensitive to head positioning tolerances, reducing heat and noise generation, improving the servo mechanism, etc. These are all manufacturing issues that are not addressed in the US or Japan because corporate research focuses on more fundamental questions." In the case of DSI's clients that manufactured components, "they are concerned with yields. Their R&D must be done close to manufacturing because process obsolescence is fast and the transfer of knowledge is relatively slow. A company like Sony may have pioneered the technology of magnetic recording and hard disk drives, but it was behind in manufacturing skills."

When DSI first knocked on the door of all these companies to offer them support, it got no response. Then, after it raised its own capabilities, it knocked on the door again. "Companies would have to hire 20 people specialized in servo mechanisms, for example, to do R&D. Instead, they come to DSI, which already employs such specialists." Thus, DSI hoped to entice companies to come to Singapore to leverage on its technologies. These companies were expected to choose to locate their manufacturing in Singapore because they could obtain the research services necessary to manufacture higher value-added products efficiently.[6]

[6] In 1999, HDD manufacturer Western Digital moved out of Singapore, and Seagate laid off more than 1,000 staff as a result of "productivity enhancements" (DP Information Network Ltd., 2000). DSI, therefore, felt the pressure to increase the value of its services.

Joint projects between multinational firms and the Center for Wireless Communication (CWC) were production-driven insofar as they related to integration. The semiconductor (IC) division of a multinational company was typically precluded by the owner of an IC design, the handset division of the same multinational, from selling an IC outside corporate boundaries. To extend the scope of its market, the IC division, with little knowledge of design, came to CWC for help in changing designs and integrating them into a new system that could be sold to other companies.

The research objective of the multinationals that collaborated with government labs, usually fell under the category of exploratory development—the goal was a "manufacturing solution" (a prototype of sorts). Moreover, the measure of performance to which this objective was tied was typically "market results" rather than the creation of intellectual property. Indeed, the Singapore Government sold foreign firms on the idea of doing more local R&D by criteria related to the bottom line. This meant that within a corporate accounting system (such as that of MUM1 noted earlier), operations in Singapore had to justify themselves by showing a profit. Arguably, this mitigated against investment in more basic research, where market results were less certain and harder to achieve.

Nevertheless, for a variety of reasons, joint government-multinational projects in Singapore aiming to solve immediate manufacturing problems tended to extend beyond 6.3 and 6.4 into applied research (6.2). For one, research efforts were not necessarily mutually exclusive, as noted earlier. There tended to be "technological spillovers" between them. To solve certain manufacturing problems may require applied research, in terms of the qualifications of staff and techniques employed. For instance, the yield problem of component suppliers to the HDD industry took the form of the "spotting" of materials. The solution to this problem required knowledge of the materials science sub-specialty of grain science.

Other reasons for a production-driven project extending into applied research depended on human initiative. One thing led to another in the sense that a production-driven research project could create a close working relationship among partners. This relationship could then be exploited further in the form of collaboration on joint projects to develop intellectual property ("to transform, variate and re-apply a known concept for a new application," as specified in Table 3). In the case of CWC, the services it sold to multinationals did not generate much income, but they did generate a knowledge of how multinationals functioned. Networking, in turn, sometimes produced results. For example, Europe's big push into telecommunications led to the Advanced Communications Technology and Services (ACTS) project, a consortium of 16 European organizations and only one non-European organization, CWC from Singapore.

In the case of the BioProcessing Technology Centre (BTC), which was founded in 1990 by the EDB under a Biotech Competence Enhancement Program, it was responsible for the third and fourth steps of the bio-pharmaceutical industry's value chain (the first two steps were the responsibility of the Institute of Molecular and Cell Biology): process development and production. BTC's mandate (it employed 80 people) was to meet the process development needs of the local biotech industry in Singapore. In so doing, it established incubator labs to attract start-ups to locate in Singapore and spun off one company that was slated to undertake applied research, Genset Singapore Biotechnology Pte. Ltd., a joint venture with Genset (France).

Government labs operated on two parallel tracks: they provided services to multinationals to keep them in Singapore; and they undertook independent research to promote their own objectives. Their own research was measured by the government (NSTB under the Ministry of Trade and Industry) according to multiple performance criteria, including the generation of intellectual property and the spin-off of nationally owned firms. Sometimes the two measures were in conflict with one another. Encouragement appears to have been greatest for research in pursuit of "an original commercial outcome." Overall, such performance standards disciplined government laboratories and presented a strong incentive for them to undertake applied and, where necessary, basic research.

The undertaking of such research involved the labs in strong collaboration with Singapore universities. Doctoral students worked in government labs as part of their training, and labs benefited by accessing the latest theoretical knowledge from Ph.D. students. As indicated in Table 7, higher education accounted for roughly one third of the public sector's R&D budget in the late 1990s. In the case of CWC, for example, its "Strategic Research Division," which was designed to undertake basic research, employed only 16-17 full-time staff. But that staff was augmented with about 100 students (roughly 45% were Singaporeans), half of whom were post-doctorates. The symbiotic relationship between Singapore's labs and universities, a strength of its national innovation system, had the effect of increasing the supply of experienced researchers. The larger this pool of experienced personnel, the greater the likelihood that foreign firms would upscale their local R&D.

As a very small economy (with a population of about 3.2 million), Singapore suffered from a shortage of high-level research personnel. As indicated by our interviews, this manifested itself in high turnover. In addition to a tight labor market, turnover was high because of the limited opportunities for skilled personnel to acquire advanced research capabilities (and presumably because turnover was high, the incentive of private firms to invest in advanced skills was small). Turnover was also high in Singapore despite in-house training. According to one major unidentifiable multinational that appeared to be typical of other foreign firms (call it MUM2), "to satisfy employees' aspirations for self-education," training included off-the-job technical education in Japan as well as Japanese language instruction, with a bond or service contract as occasion demanded. Additionally, a plan was put into place to reduce the number of expatriates working in Singapore and to replace them with local staff. To satisfy the "value of appearances," an attempt was also made to create "an office environment appropriate to R&D." The problem was that whereas training to reach peak performance required about one year for a software engineer and three years for a hardware engineer, "some trainees quit before they reached this level."

To alleviate Singapore's skills shortage, the Government adopted liberal immigration laws. Policy towards foreign workers was guided by two major principles: (1) encouraging the deployment of foreign workers to high value-adding economic activities; and (2) promoting skills upgrading to raise productivity and lower overall dependency. Key measures affecting foreign labor supply included: (1) offering incentives such as double tax deduction to encourage companies to look beyond local recruitment; (2) promoting scholarships to attract overseas students; and (3) exercising flexibility in granting employment passes to those with the relevant skills but no formal qualifications. The Government allowed virtually free immigration in the case of professionals with the highest talents (Singapore Ministry of Trade and Industry, 1998). In 1995, it was estimated that about 300,000 foreign workers were employed in the economy at large. In that year, the total number of workers in the manufacturing sector alone was 375,538 (Wong, Phang, et al., 1997). Thus, the share of foreign workers in total employment was high.

In addition to liberal immigration laws to alleviate the shortage of highly skilled personnel in R&D, the Government expanded the university system, encouraged foreign business schools to open branches in Singapore with generous land grants, and promoted training within its own national labs. One major purpose of such labs was to create the experienced labor demanded by the private sector to upscale. As noted earlier, more than half of all the Government grants to industry were earmarked for personnel training.

By way of summary, from the mouths of corporate executives a unified voice emerges about the role of government promotion of R&D in Singapore. By all accounts, that role was decisive in encouraging a greater amount and higher level of R&D than would otherwise have occurred. By world standards, therefore, the atypical level of R&D among foreign firms in Singapore may be regarded less as a market-induced "spillover" than as a government-induced "extraction." Besides outright grants and subsidies to the private sector for undertaking R&D, the Government invested heavily in formal higher education. It also attempted to increase the supply of experienced talent through the operations of its own laboratories and ideally, their private-sector spin-offs. These labs were incubators for talent and solutions to production problems that were otherwise difficult to resolve. In the course of solving these problems, R&D made the leap from development (exploratory and advanced) to research (applied and sometimes even basic).

9. Conclusion

We started with the proposition that Singapore was anomalous among latecomers insofar as its industry was dominated by direct foreign investment but its total R&D and the share of its foreign firms in the R&D total were high. We then investigated the nature of foreign R&D in Singapore: Was it state of the art? Was it merely production-related? We soon recognized that there was no existing framework to analyze the characteristics of different types of research in order to make such a judgment objectively. That is, given conventional classifications of R&D types (basic versus applied, for example), and the confidentiality of private R&D with respect to substantive content, there was no way of verifying whether actual R&D warranted the classification it had been assigned (usually by an inside manager), even granted standard R&D definitions (the Frascati manual of the OECD was the most authoritative source). Objective characteristics associated with different R&D types had to be specified first to determine the nature of R&D in a latecomer country. Such a characterization became a major goal of our paper. The eight characteristics of R&D that we specified are: the "search" behind the research; the objective of the research agent; the expected output; the performance measures by which output is evaluated; the time horizon involved; the techniques employed; the qualifications of the researchers; and the size of the research effort.

Given these characteristics (others await investigation), the empirical data we collected in firm-level interviews led us to observe that there is a large discontinuity between exploratory and advanced development on the one hand and applied research on the other (types 6.3 and 6.4 versus type 6.2 in Table 3). Moreover, with only a few exceptions, most private sector R&D within foreign firms in Singapore was rooted in exploratory and advanced development, the R&D types most oriented towards immediate market results rather than the creation of long-term intellectual property. Nevertheless, the transition from production-related R&D to applied research was beginning in Singapore as a consequence of pro-active government policies and the operation of government-owned institutes and labs. The applied research being undertaken tended to be government-extracted, taking the form of joint public-private collaborations to solve production problems that corporate labs overseas were uninterested in tackling. We concluded, therefore, that Singapore was anomalous among latecomers in the degree to which foreign firms performed R&D due to the systematic role of government.

The government's role in extracting advanced R&D from foreign firms also appears to be large in PRC, where foreign R&D activity has begun to grow.[7] Moreover, state intervention to promote science and technology in general, including R&D, is legal under the laws of the World Trade Organization. Therefore, state promotion of R&D in latecomer countries is likely to be large, making it all the more important to understand better how that role can be made more effective. In the case of software, which has possibly become the most important industry to attract foreign R&D in latecomers, government policy must be customized. The classification of R&D, by both type and characteristic, will probably have to be revised.

[7] "The Chinese government has been favoring technological transfers and R&D functions when it screens applications submitted by foreign companies to set up plants in the country." Moreover, the geographical area in which foreign firms are establishing R&D centers—dubbed the "Silicon Valley of China"—is already home to some 70 state-funded research institutions and universities, including the Chinese Academy of Sciences, Beijing University and Tsinghua University (Toga, 2001).

Table 1
Corporate Ownership and R&D Activity

Country	M&A Foreign Majority Ownership (%), 1990-1997	FDI/GFCF Average (%) 1986-1991	FDI/GFCF Average (%) 1992-1996	R&D (% GNP) c. 1995
Predominant National Ownership				
Korea, Rep. of	na	1.3	0.8	2.8
Taipei,China	15	3.6	2.4	1.8
PRC	4	2.9	13.8	0.6
India	8	0.3	1.6	0.8
Predominant Foreign Ownership				
Argentina	59	5.6	8.1	0.4
Brazil	73	1.6	3.5	0.6
Mexico	36	8.3	12.1	0.0-0.3

FDI = foreign direct investment
GFCF = gross fixed capital formation
GNP = gross national product
M&A = mergers and acquisitions
na = not available
R&D = research and development

Source: Adapted from Amsden (2001).

Table 2
<u>The Global Hard Disk Drive (HDD) Industry, 1995</u>

(%)

All firms	US/Japan/Europe	Southeast Asia	Other
Nationality of HDD firm*	97.8	0	2.2
Location of final assembly	30.1	64.2	5.7
Employment in value chain**	32.3	44.0	23.6
Wages paid in value chain	77.7	12.9	9.4

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* Ownership is defined in terms of equity control.
** The major production stages in the hard disk drive industry are, in ascending order of technological complexity: (1) head subassembly; (2) final assembly; (3) disk media manufacture; (4) head fabrication; (5) semiconductor fabrication; (6) equipment design manufacture; and (7) R&D. Employment in US, Japan and Europe tends to concentrate on stages 3 through 7, while employment in Southeast Asia and other countries tends to concentrate on stages 1 through 3 (although semiconductors have begun to be processed in Southeast Asia as well).

Source: Adapted from Gourevitch, Bohn, et al. (2000).

Table 3
New Typology of R&D Characteristics

Characteristic	6.0 Pure Science	6.1 Basic Research	6.2 Applied Research	6.3 Exploratory Development	6.4 Advanced Development
(a)	(b)	(c)	(d)	(e)	(f)
Search	intrinsic knowledge	new knowledge for radically new marketable product	differentiated product "on paper"	prototype in a system	prototype for manufacture
Research objective	uncover new scientific principle	same as 6.0 but with applications that are unknown or diffuse	transform, variate and reapply known concept for new application	implement concept as engineered system	reduce costs, uncertainties of manufacturing
Output	concept-based IP (papers, patents)	product-based IP for transfer to 6.2, 6.3	differentiated product for specific market	detailed product design or prototype	manufacturable product
Measure of performance	IP	product-based IP	differentiated/niche product with IP	market results (e.g., time to market)	market results (e.g., number of rejects)
Time horizon (theoretical)	infinite/long-term	long-term	medium-/short-term	short-term	immediate
Techniques	scientific experimental and mathematical techniques	same as 6.0	scientific techniques (formulation of equations, algorithms)	engineering design tools, including simulation	same as 6.3 plus testing, Q/C
Qualifications and skills	Ph.D. in fundamental science, mathematics or engineering	same as 6.0, plus management expertise and oversight	B.S./M.S./Ph.D., well-trained and experienced	same as 6.2, but Ph.D. unnecessary	same as 6.3, plus people-related management skills, process know-how
Size of effort	depends on branch of knowledge under study	critical skill mass related to whole product; specialization and integration	smaller critical mass appropriate for exploiting niche hand-me-down from 6.1	scales up with size of system	related to production

IP = intellectual property. Q/C = quality control.

Table 4
Examples of R&D Characteristics
(With Respect to "Search" and "Objectives")

Example:	6.0 Pure Science	6.1 Basic Research	6.2 Applied Research	6.3 Exploratory Development	6.4 Advanced Development
Communications algorithm (A)	conceptual development of (A)	conceptual development of (A) for commercial application	development of multiple variations of (A)	implementation of (A) on circuit or in software	implementation of circuit in production prototype
Hard disk drive head	separable research on new materials, optical reading and slider-suspension engineering	integrated and concurrent research on new materials, laser, etc., for total product	application of new materials to new head (component)	development of new head prototype	development of production prototype

Table 5
Human Resource Development

Year	(A) Engineers and Managers (number)	(B) Total Employees (number)	(A)/(B) (% of total)
HEWLETT PACKARD			
1987	410	2,649	15.5
1997	2,126	9,701	21.9
1999	2,108	9,002	23.4
NEC[1]			
1987	68	476	14.3
1997	153	556	27.5
1998	152	527	28.8

Source: Company sources.
1. The Engineers and Managers category includes officers.

Table 6
Salary for New Engineering Graduates, 2000

(Scaled to Japan = 100)

Country	Index
Japan	100
Hong Kong, China	80
Singapore	70
Malaysia	45
Korea, Rep. of	40
PRC	25

Source: Company sources. Based on nominal exchange rates. All numbers are rough estimates.

Table 7
Distribution of Public Sector R&D Expenditures, 1987-1998

Year	Higher Education	Research Institutes	Government Sector	Total Public
1987	64	-	36	100
1990	46	16	38	100
1991	47	23	22	100
1992	42	30	28	100
1993	41	30	28	100
1994	41	27	32	100
1995	40	37	23	100
1996	36	38	25	100
1997	35	37	27	100
1998	32	37	31	100

Source: Adapted from the Singapore National Science and Technology Board (1998), Tables II.1 and II.2.

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