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Technological progress and innovation plays a central role in a country's economic progress. As an economy advances to the global technological frontier and narrows the technological gap, an innovation-based growth strategy that focuses on investments in R&D and technology creation offers the greatest potential for economic growth. In this paper, we discuss the requirements for a successful transition, in terms of changes to the technology infrastructure, economic institutions and the incentives' structure. This paper outlines the efforts made by Singapore to re-make itself as an innovation-based economy, and the challenges faced by the government in transforming the nation's infrastructure and institutions to develop innovation capabilities and encourage entrepreneurship.

1. Introduction

Since becoming an independent nation in 1965, Singapore has grown at an average annual rate of about 8% until the late 1990s. Singapore has no external debt, and its foreign exchange reserves, at more than US$110 billion in 2004, ranks as one of the highest in the world, and the highest, on a per-capita basis. Singapore's economic development model over the past four decades has combined an open-economy framework with strong government involvement in labor, land and industrial development policies. While this approach has enabled Singapore to transit from the Third World to First World status in the span of less than 40 years (Lee, 2000), there has lately been some concerns that this development model is no longer appropriate or relevant now that the country has to compete 'close to the technological frontier' of a global knowledge economy – where capital, ideas and talent are mobile – as opposed to the earlier, easier task of technological catchup.

Singapore's growth strategy in the 1960s and 1970s focused on the attraction of multinational companies (MNCs) to locate in the city-state, to produce for global export markets. This strategy was initially borne out of necessity. As an island economy with few natural resources, employment creation was an urgent task in the early years of independence. Later, this strategy of targeting foreign direct investment by MNCs became part of the economic development strategy that seeks to position Singapore as a major business hub in the global network of trade and capital flows. Generous tax incentives and grants were given to MNCs to locate their regional operations in Singapore. While this economic strategy was immensely successful in accelerating growth, the side-effect was that Singaporean companies came to play a largely supporting role in the MNCs with little incentive to invest in indigenous capabilities in high-tech innovation. Manufacturing currently accounts for 25% of the contribution to GDP, with electronics being a key subsector in terms of employment creation.

Singapore is fast reaching the limit of this development strategy. From 2000 to 2002, Singapore experienced a fall in its total factor productivity performance, as a result of severe capacity underutilization in Singapore's manufacturing sector caused by adverse shocks in the global economy. The global slowdown in electronics demand and technology spending in the aftermath of the tech-bubble burst in April 2000, coupled with the negative impact of the September 11 event in 2001, had significantly affected the electronics manufacturing and IT services cluster in Singapore. Singapore must now look for alternative sources of growth and reduce its reliance on MNCs. The current heavy dependence on electronics in the manufacturing sector has made the Singapore economy vulnerable to the vagaries of the global business cycle. Singapore's relatively high levels of wages and domestic costs also render it vulnerable to competition from lower-wage economies, such as China and India in Asia, and Mexico further afield. Already, there are signs of hollowing out in Singapore's manufacturing sector, as MNCs relocate their Asian manufacturing facilities to China, not just because of the lower cost of operation, but to tap directly into the burgeoning consumer market there. It is becoming increasingly more difficult for Singapore to compete for global investments from MNCs, not just because of high costs of doing business in Singapore, but also because of the general reluctance of MNCs to shift their innovation centers to Singapore.[1]

Competition for capital and talent is also emerging from high-tech regions that include Israel, Ireland, Shanghai and Beijing in China, Seoul in South Korea and Bangalore in India. These regions provide the critical mass of advanced knowledge institutions (universities, public research institutes and corporate laboratories), venture capital, entrepreneurial talents, knowledge workers, sophisticated corporate end-users, well-developed financial markets, etc.

As Singapore enters a new phase of national development, its economic future will depend increasingly on its ability to engage in technological creation and create internal engines of growth. This transformation, however, will take time, as innovation capabilities and new supporting institutions are being strengthened and transformed. Besides the establishment of publicly funded research institutions and a renewed push to invest in basic research and infrastructure, there was also coordinated effort to review and modify government policies to stimulate innovation and entrepreneurship. Changes to the regulatory framework and the institutional environment are being made to encourage innovation in Singapore. The government has already set aside more than US$1 billion fund in 1998 to invest in venture capital funds and to promote entrepreneurship. Technical professionals and skilled workers are being courted through an aggressive 'foreign talent' policy. Funding for basic research at the universities and at government-established research institutions has also been increased substantially.

The shift to an innovation-based growth strategy requires coordinated changes to be made to a nation's technology infrastructure, economic institutions and incentive systems. The appropriate economic structure for science and innovation that creates an environment for investments in scientific and technological endeavors is essentially the same one that fosters a climate for investment, jobs and sustainable growth. The factors that are necessary for a conducive environment for innovation are: macroeconomic stability; openness to trade, foreign direct investment as well as immigrant talent; strong intellectual property rights protection; and a set of policies to ensure fair competition. Adequate intellectual property protection plays a strong role in creating incentives for R&D and innovation, and in promoting the diffusion of knowledge, while a well-structured competition policy, by creating a level playing field, facilitates the entry and exit of firms into new markets, thus stimulating innovation and commercialization of new technologies.

The transition to the technological frontier requires the development of a set of micro-economic capabilities and incentive structures, through government policies that focus particular attention on the careful coordination among interdependent components. In this paper, we discuss the challenges that an economy faces as it shifts to an innovation-driven growth strategy. We shall focus on the role that governments can play in this process, and review Singapore's current efforts to chart a new economic strategy to compete closer to the global technological frontier. In particular, we shall discuss Singapore's efforts to strengthen its technological infrastructure, adapt its institutions and develop innovation capabilities.

The rest of the paper is structured as follows: In Section 2, we discuss the role that technological progress plays in economic growth. Next, the requirements for a successful transition, in terms of changes to the nation's technology infrastructure, economic and market institutions and the incentives structure are first outlined in Section 3, and discussed in greater detail in Sections 4–6. In Section 7, we discuss Singapore's efforts to promote entrepreneurship as part of its innovation policy, and the difficulties encountered. In Section 8, we discuss the implications of Singapore's economic transformation for R&D managers and entrepreneurs. Section 9 summarizes and concludes the paper.

2. Technological progress and economic growth

In the 21st century, innovation and technological progress will play a central role in both national and global economic development. The ability to create, disseminate and exploit knowledge is a major source of competitiveness, wealth creation and enhancement of quality of life.[2] A nation's technological capabilities clearly underpin its competitive advantages and growth potential. (World Economic Forum, *The 2002–2003 Global Competitiveness Report*, Chapter 1, p. 9). Asian economies, such as South Korea, Taiwan and Singapore, have transformed their economies by improving the technological performance of their industries through purposeful science and technology policies. With their deepened technological capabilities, they are now able to compete consistently and successfully on a global scale in a growing number of industries (e.g. in electronics manufacturing). These economies have combined policies for investment in technological infrastructure and with those that facilitate the flow and use of commercially relevant technologies.

The fundamental objective of a nation's science and technology policy is the development of a set of capabilities to scan, assess, select, use, assimilate, adapt, improve and create technology that is appropriate for the particular stage of economic growth. The appropriate growth strategy for a country at any point in time depends on where it is located relative to the global technological frontier (Acemoglu, et al., 2002).

For a less-developed economy situated far away from the technological frontier, the availability of low-cost labor and access to natural resources are the dominant sources of competitive advantages. For exports, firms produce commodities – if they possess the requisite natural endowments – or relatively simple products designed in more advanced countries. Technological progress takes place through the assimilation of technology through foreign direct investment, imports and through imitative technology adoption. This is the *factor-driven growth stage*, according to the framework described in Porter (1990).

As economic development takes off, the economy may shift to an *investment-driven growth stage*, where the focus is now on technology acquisition by moving up the technology ladder, as well as the accumulation of physical and human capital. There is an increase in investment in efficiency infrastructure – such as tele-communications, and air, sea and land transportation – to support manufacturing activities. The regulatory framework is streamlined, and investment incentives are provided to facilitate access to capital and rapid productivity improvements. In this investment-driven stage, efficiency in production is the dominant source of competitive advantage.

Finally, in the *innovation-driven growth stage*, the emphasis is on investments in R&D, innovation and entrepreneurship. The ability to produce innovative products using state-of-the-art production processes is the dominant source of competitive advantage. Economic institutions and market incentives are structured and aligned to support innovation and entrepreneurship. Science and technology policies emphasize basic research and there are high levels of public and private investments in R&D.

The transition from an investment-driven growth strategy to an innovation-driven growth strategy is often a subtle one. For an economy located away from the technological frontier, an investment-based growth strategy is likely to yield greater returns than an innovation-based growth strategy, at least initially. This is because the benefits of technological progress can be realized quickly by moving up the technology ladder, as it is less costly and easier to absorb and adapt the existing body of knowledge than it is to invest and develop new technology with uncertainty of commercial success. However, as the economy advances to the global technological frontier, the greatest potential for economic growth comes not from just catching up with the technological leaders through capital accumulation and imitation of their technology and growth strategies, but by investing in R&D and creating new technologies and products. Science and innovation policies at this stage are focused on the creation of new knowledge, through cutting-edge research at the frontier.

Singapore's technological transition with respect to the global technological frontier followed broadly the sequence outlined above, except that as a small island nation, it lacks the natural resources and its journey through the factor-driven growth stage relied heavily on its supply of low-cost labor.[3] From the mid-1960s to the late-1970s, post-independence rapid export-led economic growth was characterized by high dependence on technology transfer and diffusion from foreign MNCs. This was followed by a period, from the mid-1970s to the late-1980s, of local technological deepening, when the government initiated the development of science parks and investment in local technological infrastructure. These two periods constituted the investment-driven growth phase for Singapore, which also successfully developed itself as an air and shipping hub.

By the late 1980s, amid concerns that the economy is reaching the limits of its investment-driven growth phase, there was an intensification of efforts by the government to develop capabilities in basic research and strengthen its technological infrastructure This led to the formulation of the first 5-year National Technology Plan in 1991 (Ministry of Trade and Industry, 1986, 1991). Since then, there have been two other National Science and Technology Plans, one in 1996 and another 2001, that provided roadmaps for Singapore's transition to an innovation-based economy. We shall discuss the details of these science and technology plans in Section 5.

3. Institutions, infrastructure and incentives for innovation

A nation's technological progress and development of innovation capabilities are the results of interactions among four groups of players in the economy: (1) the administrative organizations that formulate and coordinate science and technology policies and oversee he public research institutions, (2) the higher institutions of learning, (3) the private sector that adopts and commercializes the products of innovation and (4) institutions that interface among the different groups actors.[4]

A successful transition to an innovation-based growth strategy requires that the set of micro-economic capabilities and incentive structures, as embodied in the nation's institutions and its technological infrastructure, evolve as the technological gap narrows. As the effectiveness of one part of the institutional environment depends on the state of the other constituents, these changes will require careful coordination among the interdependent components; otherwise, the limited progress or lack of improvement in one area may stall development or even undermine the effectiveness of other parts of the system.[5]

While many factors contribute to the shift to an innovation-based growth strategy, we can discern three critical aspects of a successful transition. These are: (a) a well-developed technological infrastructure, (b) a set of capabilities-focused science and innovation policies and (c) a coordinated shift in government institutions and policies. Governments play an important role in all three aspects (which we shall discuss in the following sections).

Firstly, governments are responsible for developing the technological structure and the appropriate institutions and macro-economic policies to support R&D. Firms invest in innovation and in efficiency-enhancing technology if they can expect sufficient returns and if competition forces them to do so. The experience of many OECD economies has also shown that a market environment that removes the barriers to competition is crucial for innovation. Broad programs of structural reform have been undertaken in countries such as Australia, Denmark, Ireland and the Netherlands to strengthen competition, push firms to improve performance and encourage innovation.

Secondly, besides formulating the appropriate science and innovation policies, governments can play an important role in nurturing the seeds of innovation and creation of knowledge through direct investment in basic research, or through the provision of appropriate tax incentives. Specifically, governments can act as the principal investor in those areas of basic and applied research[6] in which private enterprises cannot operate effectively. As basic research typically occurs on the technological frontier, its economic value is often difficult to forecast, or even to gauge accurately in retrospect (Dasgupta and David, 1994). Moreover, economic payoffs from the application of new ideas or technologies may also take a long time to be realized. In cases where a private firm cannot capture all the gains from R&D successes, underinvestment in basic research would occur as private returns will be less than potential social returns.[7]

Thirdly, besides structuring and reshaping economic and market institutions to facilitate innovation, governments can reduce the cost of entrepreneurial risk taking by promoting interactions between institutions of higher learning and the private sector, encouraging cooperative research, as well as by providing tax incentives for the commercialization of research output.

Although economic theory also recommends generalized subsidies, as opposed to specific sector targeting and support, as the optimal incentive policy for supporting innovation and commercializing its output, in practice, many important technologies have been encouraged in their early stages by public sector support. The United States provides many examples of this type of direct government assistance and sector targeting. For instance, R&D in computers and atomic energy were developed in response to military needs, with substantial funding from the US government. Similarly, military procurement was a major source of support for the US semiconductor industry. In Singapore's case, a recent example of sector targeting in R&D is the decision in late 1999 to invest in the development of innovation capabilities in bio-medical sciences.

4. Technological infrastructure and innovation capabilities

The presence of a well-developed technological infrastructure – encompassing the network of research organizations, the education system, as well as institutions to protect intellectual property rights – provides the foundation for the development of innovation capabilities and the pursuit of scientific research and endeavors. The multi-faceted technological capabilities of a nation include indicators such as the patenting rates, number of research scientists and engineers, as well as the output of scientific publications.

The statistics are in line with the findings in the 2001 United Nations Development Programme (UNDP) Report, which found that countries located at different distances from the global frontier differ markedly in their technological abilities. The UNDP Report found that 29 advanced industrial nations that make up the OECD accounted for 91% of the patents issued in 1998. OECD countries also invested more annually on R&D (at US$500 billion) than the value of the total economic output of 61 of the world's lowest-income countries (at US$464 billion) in 1998. Compared with low-income countries, OECD countries have 12 times the per capita number of scientists and engineers working in research and development, and publish 25 times more scientific journal articles per capita. In the OECD, the ratio of patents filed by non-residents to those filed by residents is 3.3–1, while it is 690–1 in low-income countries. (Source: UNDP, http//:www.undp.org.)

Over the past few decades, Singapore's technological capabilities have strengthened steadily. It is now consistently ranked by the World Economic Forum (WEF) and the Institute for Management Development (IMD) as among the top 10 countries in the world in areas such as quality of school science and technology education, adoption of information and communications technology (ICT), licensing of foreign technologies, use of advanced technologies in production and process management capabilities. In the 2003 IMD World Competitiveness Report, Singapore ranked number one in attracting top-flight foreign talent among 29 economies with a population of fewer than 20 million.

In Figure 1, we plot the average GDP growth rates from 1980 to 2000, against the corresponding gross expenditure on R&D, as a percentage of GDP. Like many of Asian economies, Singapore's R&D expenditure from 1980 to 2000 was relatively low, compared with the expenditure of developed countries. By contrast, the developed countries located at the technological frontier, led by the United States in the lower right-hand corner of Figure 1, invested a greater percentage of their GDP in R&D.

In Figure 2, we plot the ratio of average R&D expenditure as a percentage of GDP (GERD) from 1995 to 2000 over the average GERD 1980–1995, against the corresponding ratio for the GDP growth rates. Compared with other countries, Singapore has increased its R&D investments sharply since the mid-1990s, reflecting the government's aggressive efforts to increase R&D investment intensity and deepen the economy's technological capabilities (Table 1).

While there have been substantial increases in R&D investment intensity in recent years, there are areas that Singapore can still improve upon. According to the 2001 Global Entrepreneurship Monitor Report (Reynolds et al., 2001), Singapore is ranked lower (ranking between 10th and 17th in the world) in terms of technology-creation indicators like R&D spending and R&D personnel, availability of venture capital and intellectual property protection. Singapore is lowest in specific measures of innovation such as the quality of basic research institutions, intellectual property generation, entrepreneurship and creation of firms.

The development of Singapore's technological infrastructure and innovation capabilities can be traced to the development of the Singapore Science Park (SSP) in 1980.[8] The development of the SSP was part of the set of coordinated government policies on science and technology policy (including research and human capital formation), IT infrastructure and promotion of entre-

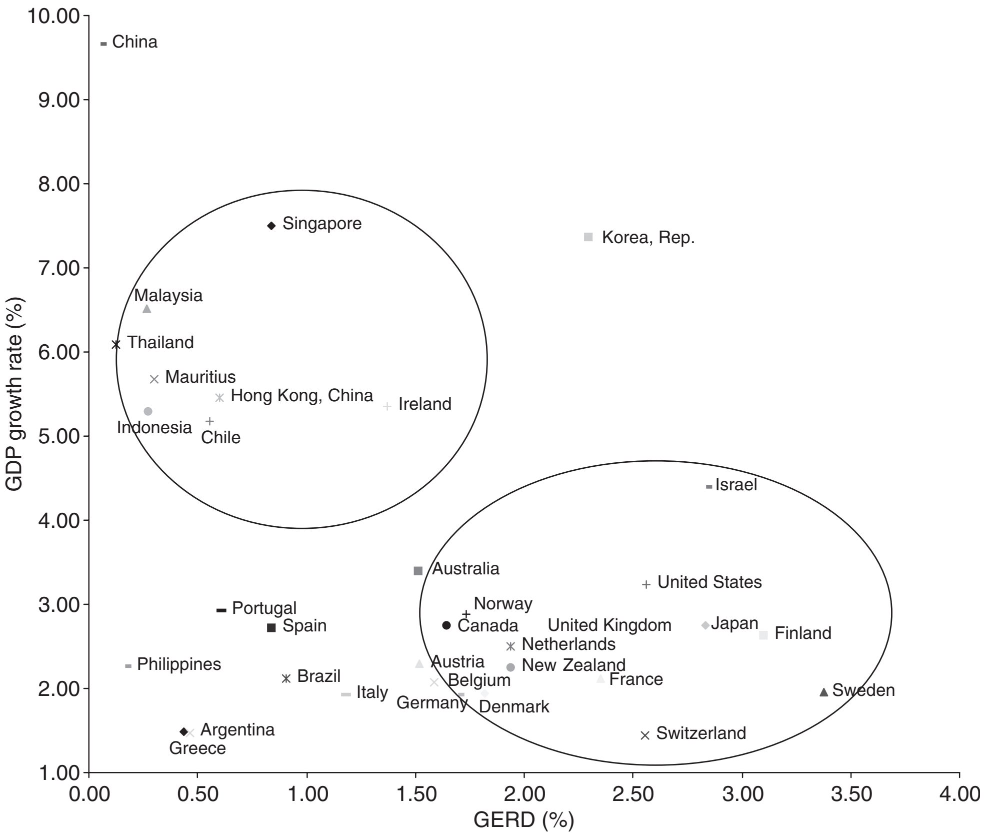

Figure 1. GDP growth rate versus R&D expenditure as percentage of GDP (GERD): 1980–2000.
Note: 1. The GDP growth rate is calculated as a compounded annual average rate from 1980 to 2000.
2. The GERP is calculated as a percentage of GDP each year, and averaged over all available data points from 1980 to 2000.
Source: World Development Indicators 2002, The World Bank.

preneurship (see Ministry of Trade and Industry, Singapore, 1986, 1991). Each of these policies has been supported by a generous allocation of resources dedicated to specific goals. As an example, in the case of promotion of entrepreneurship, startup grants and venture capital and a variety of government assistance have been provided.

One of the initial motivations of the SSP was to provide and upgrade local *infrastructure to* house MNCs as well as new industries that require proximity to the institutions of higher learning. Additionally, the SSP was to provide a focal point for research, development and innovation in Singapore, with an emphasis on industrial R&D. A secondary objective of the Singapore Science Park is to *signal* to foreign firms and investors Singapore's readiness to promote and attract high-tech and knowledge-intensive industries (Koh and Koh, 2002). To position Singapore as a regional R&D hub, high-tech companies from Australia, New Zealand are being courted to locate their R&D activities in the SSP, and to use Singapore as a gateway to penetrate the markets in China, India, Southeast Asia and Indo-China.

In 2000, the government announced the development of S$15 billion new science park – the One-North project – to strengthen the technological infrastructure as Singapore targets life sciences as a new growth pillar for Singapore.[9] To be developed over 15 years, the objective of One-North, modeled after Silicon Valley, is to create the ambience of a multifaceted research community, with international schools, integrated public transport and other supporting amenities. When completed, One-North will house state-of-the-art R&D infrastructure to provide a wider focal point for R&D and entrepreneurial activities in the bio-sciences and information technology. Residential development, schools and other amenities are included in the One-North Master Development Plan.

A new research facility, The Biopolis, located in the One-North Science Park, has already commenced operations and now offers cutting-edge facilities for laboratory-based R&D activities tailored to biomedical sciences companies. Generous financial incentives, in the form of tax relief, R&D grants and training subsidies, will

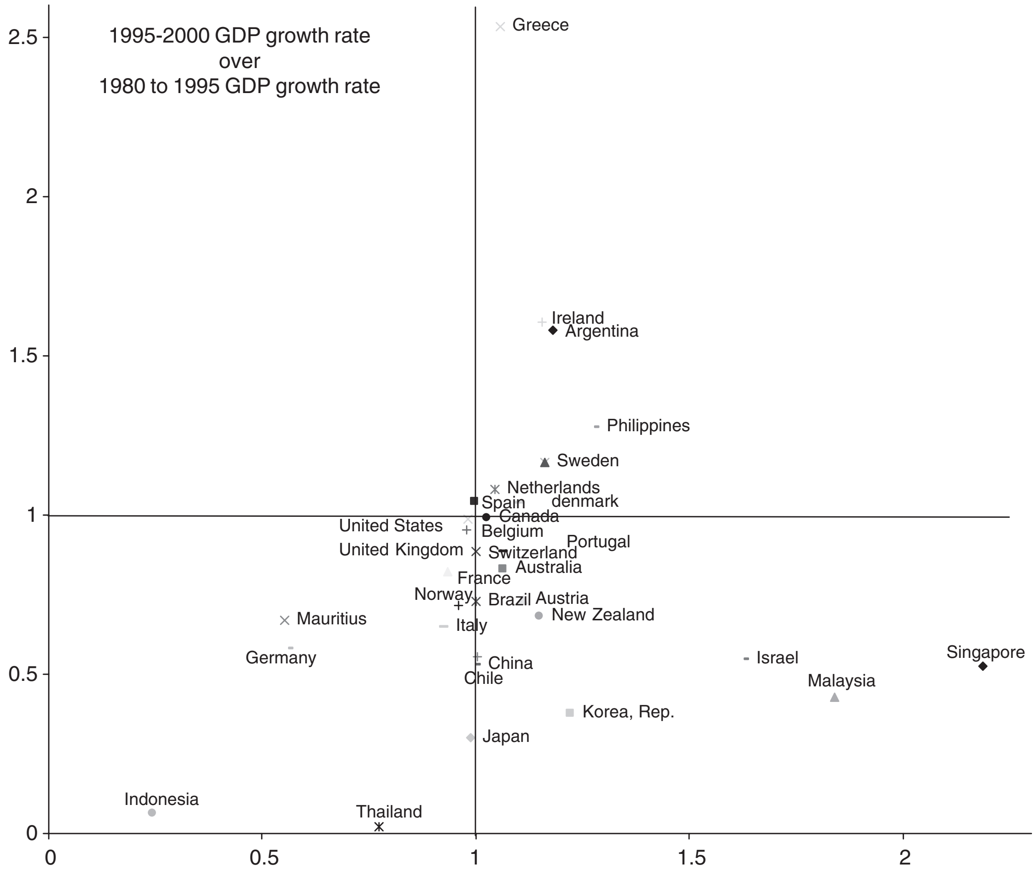

Figure 2. Change in GDP growth rate versus change in R&D expenditure as percentage of GDP (GERD). Source: World Development Indicators 2002, The World Bank.

also be given to companies to start up their operations. Together with efforts to develop high-tech entrepreneurship, these initiatives form part of the high-level strategy to transition to innovation-based economy.

In Table 2, we present a set of indicators for Singapore to show its progress in developing its technological infrastructure and innovation capabilities. Like many of the fast-growing East Asian economies (China, Singapore, Malaysia and Thailand), Singapore had spent relatively little on R&D until recently. Expenditure in R&D has increased steadily since 1978, in both absolute amounts and as a percentage of GDP. Between 1987 and 2005, Singapore's gross expenditure on R&D had increased by more than seven times, reaching S$3.43 billion in 2002, or 2.15% of GDP. By 2002, Singapore's R&D intensity had risen to over 2%, exceeding the level of the United Kingdom and the Netherlands, although still behind the more advanced Scandinavian countries. Private sector expenditure on R&D accounted for 60.8% (S$2.09 billion) of total R&D expenditure, or 1.31% of GDP.

Singapore has made significant progress in terms of its pool of scientific talent, as shown in Table 2. The number of Research Scientists and Engineers per 10,000 labor force has risen from less than 30 in 1990 to over 91 by 2002, with the latter figure being above the OECD average. Another impressive improvement for Singapore is in the area of scientific output.

Table 3 compares the growth rate of international scientific publications of Singapore with other countries. In terms of publications per capita of population, Singapore had achieved a level in 1998 that is similar to that in France and Germany, and exceeded Japan. The annual growth rate of Singapore's scientific publications stands at about 13% (second highest after South Korea), compared with an average of less than 3% for all advanced countries.

Finally, Table 4 summarizes Singapore's patenting record over the period 1976–2002. Before the 1990s, there was an relatively slow growth in patenting rates, as measured by the number of USPTO patents granted to Singapore-based inventors. In terms of patenting

Table 1. Economic growth and technological capabilities.

		GDP growth rate (%)[1]: 1995–2000	Per capita GDP growth rate (%)[1] : 1995–2000	GERD (% of GDP)[2]	RSE[3]	Average No. of scientific articles published (1997)	Average number of patents filed by residents and non-resident: 1999
Small industrialized countries	Austria	2.47	2.31	1.52	35	3,432	162,125
	Belgium	2.76	2.52	1.58	51	4,717	120,986
	Denmark	2.66	2.24	1.82	49	3,950	161,569
	Finland	5.10	4.82	3.10	94	3,897	159,034
	Netherlands	3.51	2.91	1.94	49	11,008	123,515
	Norway	3.06	2.45	1.73	69	2,501	50,662
	Sweden	2.88	2.79	3.37	71	8,219	165,052
	Switzerland	1.78	1.38	2.55	48	6,935	162,402
Newly industrialized economies	Hong Kong	3.40	1.38	0.60	2	2,080	6,040
	Ireland	9.65	8.52	1.37	40	1,118	120,796
	Israel	3.81	1.41	2.84	37	5,321	49,414
	Singapore	6.35	3.60	0.84	34	1,164	51,495
	Korea, Rep.	4.77	3.74	2.30	43	4,619	133,127
G7	Canada	3.66	2.70	1.64	49	19,910	69,777
	France	2.48	2.11	2.35	57	26,509	138,458
	Germany	1.74	1.62	1.70	58	36,233	220,762
	Italy	1.89	1.72	1.18	30	16,405	128,263
	Japan	1.45	1.22	2.83	104	43,891	442,241
	United Kingdom	2.81	2.42	2.05	48	38,530	192,876
	United States	4.19	2.92	2.56	71	166,830	294,700

[1]The GDP growth rate is the compound annual average rate from 1995 to 2000.[2]GERD stands for Gross Expenditure on R&D. It is calculated as a percentage of GDP, and averaged over all available data points.[3]The number pf research scientists per 10,000 labor force, averaged over 1980–2000, using available data. In absolute numbers, China has the second highest number of researchers in the world, with 743, 000 behind the 1.3 million in the US but ahead of Japan and Russia, with 648,000 and 505,000, respectively. (2003 OECD Report).Source: World Bank Development Indicators.GDP, gross domestic product; GERD, gross expenditure on R&D; RSE, Research Scientists and Engineer.

Table 2. Singapore's technological capabilities.

Year	Expenditure on R&D				GERD (S$m)	GERD/GDP (%)	Public R&D expenditure/ GDP (%)	RSEs	RSEs/10,000 labor force
	Private sector (S$m)	Higher education sector (S$m)	Government sector (S$m)	Public research institutes (S$m)					
1978	26	8	4	–	38	0.21	–	818	8.4
1981	44	24	13	–	81	0.26	–	1,193	10.6
1984	107	70	38	–	214	0.54	–	2,401	18.4
1987	226	95	54	–	375	0.86	–	3,361	25.3
1990	310	120	99	43	572	0.84	–	4,329	27.7
1991	442	147	97	71	757	1.00	–	5,218	33.6
1992	578	156	105	111	950	1.19	0.47	6,454	39.8
1993	619	157	107	116	998	1.07	0.41	6,629	40.5
1994	736	180	142	117	1,175	1.10	0.41	7,086	41.9
1995	881	193	110	181	1,367	1.16	0.41	8,340	47.7
1996	1,133	239	167	253	1,792	1.40	0.51	10,153	56.3
1997	1,315	278	216	296	2,105	1.50	0.56	11,302	60.2
1998	1,536	306	300	351	2,492	1.81	0.69	12,655	65.5
1999	1,671	310	305	371	2,656	1.90	0.70	13,817	69.9
2000	1,866	338	424	381	3,010	1.88	0.72	18,302	83.5
2001	2,045	367	425	396	3,233	2.11	0.77	18,577	87.6
2002	2,091	438	438	438	3,405	2.19	0.84	19,377	91.0
2003	2,081	448	448	448	3,424	2.15	0.86	21,139	98.3

Note:[1]GERD refers to gross expenditure on R&D.[2]RSEs refers to Research Scientists and Engineers.Source: National Survey of R&D in Singapore, National Science and Technology Board and Agency for Science, Technology and Research.

per capita, Singapore's performance in 2001 has exceeded several OECD countries, such as France, Norway and the United Kingdom. However, Singapore's patenting record still lags behind Taiwan, Germany, Japan and the United States. Nonetheless, the recent surge in patenting activity in Singapore provides a marked contrast to historical experience, and augurs well for the future.

According to Agency of Science, Technology and Research (A*STAR), the total number of patents filed by Singapore-based organizations (including foreign affiliates) has increased steadily from 142 in 1993 to 1739 in 2002. In 2001, revenue derived from commercialized products and processes attributed to R&D performed in Singapore amounted to close to S$50 million. Revenues generated from licensing intellectual property to outside parties have also increased steadily since 1990 (Source: National Survey of R&D in Singapore, A*STAR, 2003).

There is still much room for improvement. Although public sector R&D conducted by universities and government-funded research institutes accounted for close to 40% of total R&D expenditure, it accounted for a very small share of the US patents granted to Singapore-based inventors: 4.5% during 1991–1995, 6.6% during 1996–2000 and 7.5% during 2001–2002. Although the public research institutes and universities in Singapore managed to spin off a number of companies in the late 1990s, the combined impact of these efforts had been relatively modest. The collaboration between industry and universities in R&D remains weak.

Moreover, as Mahmood and Singh (2003) found in a study of US patent data, the patenting activity in Singapore, as well as Hong Kong, over the past 30 years has consistently been much lower than in South Korea and Taiwan. The authors also found that a large proportion of Singapore's patenting activity was the result of MNCs rather than domestic firms. On average, in the 1990s, MNCs accounted for more than half of the R&D investment in Singapore. These findings are in line with earlier studies that provided evidence of weaker technological capabilities in Singapore in the 1970s and 1980s.

5. Capabilities-focused science and innovation policies

The optimization of the interface between technological progress and economic growth has become one of the most important aspects of government

Table 3. Output of scientific publications.

	Country	Number of articles, 1998 (per million inhabitants)	Growth rate of number of publications, 1990–1999 (%)
Small industrialized countries	Austria	449.36	3.84
	Belgium	475.49	2.60
	Denmark	770.27	1.61
	Finland	737.43	3.63
	Netherlands	684.75	0.95
	Norway	588.20	1.25
	Sweden	945.44	0.72
	Switzerland	973.40	2.60
Newly industrialized economies	Hong Kong	89.73	9.14
	Ireland	343.59	4.18
	Israel	873.87	0.63
	Singapore	**433.44**	**12.96**
	South Korea	119.58	21.96
	Taiwan	244.71	12.29
G7	Canada	640.87	−1.03
	France	465.97	2.68
	Germany	463.69	2.14
	Italy	296.60	3.77
	Japan	371.42	3.15
	United Kingdom	665.77	0.89
	United States	612.04	−1.06

Note: Article counts (on a per capita basis) are based on fractional assignments; for example, an article with two authors from different countries is counted as one-half of an article for each country.Source: Science & Engineering Indicators 2002, Agency for Science, Technology and Research, Singapore.

Table 4. Growth trend of USPTO patents awarded to Singapore inventors, 1976–2002

Countries	1976–1980	%	1981–1985	%	1986–1990	%	1991–1995	%	1996–2000	%	2001–2002	%	Cumulative Total 1976–2002	%
Singapore Assignee	6	35.3	24	68.6	40	48.8	108	36.9	480	50.9	529	57.5	1187	51.8
Individuals [2]	4	22.2	14	40.0	23	28.0	30	10.2	61	6.5	61	6.7	193	18.4
Companies	2	11.1	10	28.6	16	19.6	64	21.9	353	37.4	396	43.0	841	36.7
Universities and public research institutes	0	0.0	0	0.0	1	1.2	14	4.8	66	7.0	72	7.8	153	6.7
Foreign Assignee	11	64.7	11	31.4	42	51.2	185	63.1	463	49.1	391	42.5	1103	48.2
Individuals	0	0.0	1	2.9	1	1.2	2	0.7	5	0.5	0	0.0	9	0.4
Companies	11	64.7	9	25.7	40	48.8	182	62.1	436	46.2	377	41.0	1,055	46.1
Universities and public research institutes	0	0.0	1	2.9	1	1.2	1	0.3	22	2.3	14	1.5	39	1.7
Total	17	100	35	100	82	100	293	100	943	100	920	100	2,290	100

Notes: [1]Patents where at least one inventor is a Singaporean. [2]In the US patent database, some patents are not given specific assignees. These patents are included with those assigned to a Singaporean individual as long as at least one inventor is a Singaporean. Source: Wong (2003), and Database of the US Patent and Trademark Office (USPTO).

policy. Besides developing the technological infrastructure, and structuring the appropriate economic institutions to encourage innovation and stimulate entrepreneurship, government-funded R&D contributes to economic growth in several ways. Firstly, it has a direct impact on innovation that shows up as growth in industrial productivity. Secondly, as noted by David, Hall and Toole (2000), public funding of R&D can contribute indirectly, by complementing and stimulating private R&D investment. In other words, public R&D may complement, rather than substitute and crowd out private R&D. Thirdly, besides providing the foundation for successful innovation resulting in the creation of new products and markets – and ultimately, enhancement of consumer welfare – publicly funded R&D also benefits the private sector through the improvement of production processes and existing products.

A good example of how science and innovation policy can continually affect innovation and economic growth is the United States, especially since the 1970s. Fears that its competitiveness was being eroded by Japanese industry prompted the US government to introduce programs to strengthen research collaboration between industry, universities and government-funded research institutions (Pavitt, 2001). The 1980 Bayh–Dole Act, the 1980 Stevenson–Wydler Act and the 1985 Federal Technology Transfer Act led to a fundamental change in the way scientific discoveries at universities and the Federal laboratories were commercially exploited. The number of US universities that engage in technology transfer and licensing now number more than 200, and the volume of university patents has increased fourfold since 1985 (Mowery and Shane, 2002).

Government funding of basic research has also enabled United States to maintain its high-tech leadership in drugs, medicines and life sciences. In terms of the share of scientific publications by field of research, the United States continues to lead in space sciences, clinical medicine, biomedical research and biology.[10] The extension of patent protection to publicly funded research (through the Bayh–Dole Act of 1980) has had a significant impact on the rate of technology transfer from science. Universities in the United States continue to conduct a major portion of publicly funded basic research and there is a long history of close collaboration with industry.

Anti-trust regulations have been amended to facilitate research collaborations between the public sector and the private sector. The National Cooperative Research Act was passed in 1984 for this purpose. Similarly, the Advanced Technology Program was created in 1988 to promote high-tech competitiveness and reduce the risk of private investment in innovations with great commercial promise by supporting cost-shared early-stage R&D projects.

In the case of Japan in the 1990s, the prolonged recession and the success of Silicon Valley prompted the Japanese government to adopt a more flexible, competitive and open research environment. These deliberations culminated in the Science and Technology Basic Plan of 1996, which encouraged technology diffusion across different industry sectors, and a more flexible employment system for researchers in government research institutes to encourage mobility and the likely diffusion of knowledge associated with it (Methe, 1995).

In Singapore's case, industrial planning and sector targeting have always been part of the government's economic growth policy, and was a key factor in its transformation from a regional entrepot trade and shipping hub in Southeast Asia to a global hub for communications, financial services and petroleum refining. Under the first 5-year National Technology Plan for 1991–1995, budgeted at S$2 billion, the policy initiatives included the acceleration of infrastructure development, encouragement of private-sector R&D and the development of technical manpower to support R&D. At the same time, and a number of key research areas were identified for strategic development; these include biotechnology; food and agro-technology; information technology and telecommunications; microelectronics and semi-conductors. The National Science and Technology Board (NSTB) was tasked with the development of new research institutes in these identified research areas. By 2003, publicly funded research institutes accounted for over S$400 million, or 13%, of the aggregate R&D expenditure.

In the Second National Science and Technology Plan for 1996–2000, Singapore's technology development strategy was 'to build a world-class science and technology base in fields that match Singapore's competitive strengths and that will spur the growth of new high value-added industries.' (NSTB, 1996). The emphasis shifted towards the development of domestic capabilities in applied and basic research. Government expenditure on R&D increased sharply as efforts intensified on the creation of domestic engines of growth. Milestones on R&D investment intensity (2.6% by 2000) and research talent pool (65 research scientists per 10,000 workers by 2000) were set. These targets were easily achieved by 1998, which also saw the announcement of several new policy initiatives to promote technology entrepreneurship, against the backdrop of a global technology boom.

Under the current Third Science and Technology Plan for 2001–2005, the government has set aside S$7 billion to develop additional infrastructures and to attract international talent to Singapore. As the focus shifted towards basic research, away from the heavy emphasis on applied R&D in the 1980s and early 1990s, the proportion of aggregated R&D expenditure devoted to basic research increased from less than 12% in 1996 to over 15% by 2002. Applied research, at 31%, still commanded a larger share of the total research expenditure. However, in the private sector, roughly 63% of R&D expenditure was still spent on experimental development, 33% was spent on applied research and only 4% was spent on basic research.[11]

In the wake of advances in the field of biosciences, the Singapore government mapped out an ambitious program in late 1999 to develop R&D capabilities in bio-medical sciences, with the objective of complementing Singapore's existing growth sectors in electronics, chemicals and engineering. The Singapore's long-term strategy is to develop Singapore as a world-class hub for biomedical sciences and become a regional R&D leader in the fields of pharmaceuticals, medical devices, healthcare services and biotechnology. A number of initiatives were rolled out as part of this ambitious plan. Firstly, in 2000, the government launched a US$1 billion Life Sciences Fund to invest in bio-medical research. In 2002, another US$1 billion was committed to this fund. Another S$2.3 billion will be injected to develop the research infrastructure in pharmaceutical research, beginning with the Tuas Biomedical Park, currently being built on 160 ha of reclaimed land in the southwestern part of Singapore.

Besides wooing leading life-sciences companies to Singapore, an international panel was established to advise the government on the establishment ethical and legal framework for biomedical research. This led to the formation of the Bioethics Advisory Committee and the Biomedical Research Council in 2000. A Biomedical Sciences Investments Management Team was also set up to make equity investments in promising startups, and to catalyze new company formation. By 2002, approximately S$150 million was invested in 50 companies.

While biotechnology is a key focus right now, the government has not ignored other sectors. It is committing resources in other sectors such as information and communications technologies, environmental technologies (e.g. desalination technology) that have global market potential. This diversification strategy is a wise one, as the strategy to focus on life sciences is not without risk. It will take at least five to 10 years to build innovation capabilities in this sector, and already, there is fierce competition from other Asian countries that are targeting the life sciences sector as well.

In a concerted effort to increase the local talent pool, the Singapore government has also adopted a liberal immigration policy to attract foreign scientists and engineers to staff the research institutions. At present, almost 20% of scientists and engineers working in Singapore are foreigners. To build the pipeline of future scientists and research professionals, a National Science Scholarships (NSS) scheme was launched by A*STAR in 2001. The NSS scheme provides scholarships for Singaporeans to study and train in the biomedical sciences in top universities in the United States.

6. Institutions, incentives and government coordination

The institutional environment that fosters a conducive environment for technology creation includes economic stability, openness to trade and foreign direct investment, strong intellectual property protection regimes, a policy to ensure fair competition, availability of talent and venture capital, as well as a private sector supportive of new technology products. However, a balance needs to be struck between providing incentives for innovation, through protection of intellectual property, but allowing for rapid diffusion of new technology. Moreover, governments should ensure that inefficient organizations and publicly funded research institutions are constantly being replaced by more efficient organizations.

For a successful transition to an innovation-based growth strategy, the government must coordinate the development of a set of micro-economic capabilities and incentive structures, as embodied in the nation's institutions and its technological infrastructure.[12] As the different components of the institutional environment are inter-related, careful coordination among the interdependent components is necessary to ensure the same pace of progress; otherwise; the effectiveness of the whole system may be undermined.

In Singapore's case, the requisite macro-economic conditions for a successful transition to an innovation-based economic strategy were largely in place by the 1990s. The critical challenge for the government was to manage the coordination between the various science and innovation policies and to ensure that the various economic and financial policies – such as tax regimes, regulations on loans, stock market listing rules, etc. – are structured and aligned properly to support the objective of a transition to an innovation-based growth strategy. Since the 1980s, responsibility for coordinating science and innovation policies has rested on the Ministry of Trade and Industry (MTI), which is also tasked with the responsibility of formulating key economic policies for the country. As a result, MTI was able to ensure coherence and harmony in the implementation of the various economic and innovation policies, which are undertaken by different agencies supervised by MTI. The key agencies are the Economic Development (economic promotion) and the Agency for Science, Technology and Research (coordination of research programs and commercialization and licensing).

Given the substantial capital outlay for programs in basic research, strong evidence that publicly funded basic research can yield commercial benefits has increasingly become a funding criterion in many government-funded research programs worldwide. However, the risk is that too much focus on commercialization may reduce the quality of scientific research. As David et al. (1988) noted, 'the outputs of basic research rarely possess intrinsic economic value. Instead, they are critically important inputs to other investment processes that yield further research findings, and innovations . . . policies that focus exclusively on the support of basic research with an eye to its economic payoffs will be ineffective unless they are also concerned with these complementary factors.'

Singapore encountered this problem too in the 1990s, when government-funded research institutions were pressed to undertake commercially relevant research. Moreover, these research institutions were encouraged to commercialize their technologies. Many startups were hastily spun off without careful consideration of their viability. There were also little incentives to foster cooperation among the research institutes. Moreover, instead of licensing the technologies that were developed within the research institutions, the preference was to incorporate and spin off companies built around these technologies, and reward researchers involved in these spin offs sizable equity stakes. In 2001, the government decided to take the commercialization function outside of the research institutes and centralize it in a commercial arm of the A∗STAR, which coordinates the activities of these research institutes.[13]

Finally, while it is important to provide a conducive environment for innovation, it is equally important to invest in educating the workforce, as well as developing a high-quality information infrastructure that allows the flow and dissemination of knowledge and information.

In Singapore, there has been a strong emphasis on technical education since the 1960s. The government provides almost all the funding for schooling at the primary, secondary and tertiary levels, and there are numerous scholarships available to nurture talent, including sending the best students overseas to study at top universities in Europe and the United States. More recently, the emphasis in the education system has also shifted away from examination-based assessment methods towards activity-based assessment methods to de-emphasize rote-learning and to allow for research-based learning. Entrepreneurial activities are being promoted in schools, and the school curricula have increased the content on life sciences.[14]

As for information infrastructure, the Singapore government has practically wired up the whole of Singapore. There is a high level of Internet usage, and Internet connectivity is now close to 90% of households, and there has been a systematic effort to encourage the use of information and communication technologies to improve productivity. The government is a lead user of many new technologies; especially information technologies. The government has taken the lead to re-engineer many of its functions and services to put them online. One can pay reserve library books, traffic fines, income taxes, as well as apply for marriage licenses without going down to a government office. Even the Singapore courts have embarked on programs to streamline its processes. Lawyers can file court papers online and video-conferencing technologies are frequently used. Singapore is also among the first in the world to use electronic road pricing to address its road congestion problem.

Reflecting the shift in focus to basic research under the Third National Science and Technology Plan, the NSTB was re-organized in 2000, to become the A*STAR, to focus on promoting research and developing R&D manpower. In this new role, A*STAR performs a function similar to that of the National Science Foundation in the United States.

7. Promotion of entrepreneurship and venture capital

Globally, venture capital was responsible for a significant amount of the entrepreneurial activity and investment in some of the emerging technological fields, such as nano-technology and ultra-wideband wireless technology (Source: Venture Economics). The impact of venture capital on innovation patented inventions in the United States has been studied by Kortum and Lerner (2000). The authors found that a well-functioning capital market and availability of risk capital can spur innovation and entrepreneurship. In particular, they found that increases in venture capital activity in an industry are associated with significantly higher patenting rates across 20 industries over three decades. While the ratio of venture capital to R&D averaged less than 3% from 1983 to 1992, venture capital had accounted for about 8% of the industrial innovations.

While MNCs will continue to play a key role in Singapore's economy, there is an urgency to nurture home-grown winners, as well as attract promising startups from overseas to Singapore, to provide new sources of innovation, industry regeneration and future employment creation. Venture capital will play an important role in fostering entrepreneurship and economic growth, as Singapore transitions to an innovation-based economy. Historically, however, venture-capital-backed entrepreneurship had not played a significant role in Singapore's economic development. Many of Singapore's successful corporations formed since the 1960s were either spin-offs from established companies or were government-linked companies. Although there are more than 100 venture capital firms based in Singapore, the frequent complaint is that the availability of good investment opportunities in Singapore is limited. As a result, more than 85% of the venture funds are invested outside of Singapore.

The development of Singapore's venture capital industry can be traced back to 1985, when the government undertook an economic review amidst concerns over the hollowing-out of the manufacturing sector following its worst recession since gaining independence. The economic review led to package of policy measures designed to lift the economy out of the recession. One of the policy recommendations was to develop the venture capital industry in Singapore and to nurture domestic firms to become world-class companies (Ministry of Trade and Industry, 1986).

Since 1998, the Singapore government has unveiled several new policy initiatives to promote entrepreneurship. These initiatives include a comprehensive plan to promote skills upgrading and accelerate the attraction of foreign talents, as well as a Technopreneurship 21 program to nurture high-tech startups. These initiatives also included a coordinated liberalization in business regulations across different government agencies to encourage entrepreneurship. Besides the amendment of bankruptcy laws, the regulation and taxation governing company stock options were revised, and new tax-offset provision for losses incurred by investors in high-tech startups were introduced to encourage investment in private equity. Listing rules on the Singapore stock exchange were amended to make it easier for technology firms to go public.

Additionally, a US$1 billion venture capital fund was established in l999 to encourage Silicon Valley venture capital firms to locate regional operations in Singapore. In light of the limited investment opportunities in Singapore, this initiative did not result in an appreciable increase in venture capital investment in Singapore. Through various government agencies and government-related companies, the Singapore government has also funded a number of new local and foreign venture capital funds based in Singapore. The school curricula are also being revised to emphasize the teaching of entrepreneurial skills at the tertiary education level and among working technical professionals.

Through the Economic Development Board, the government has operated a Startup Enterprise Development Scheme (SEEDS) to provide matching funding for young companies. In January 2005, a new scheme that provides loans to small and medium enterprises (SMEs) was launched. An objective of this government effort is to foster entrepreneurship and develop a risk-taking business culture, to enable Singapore to transition to an innovation-based economy.

Under the SEEDS scheme, SMEs can turn to the government to borrow at prevailing market interest rates. Finally, a number of new programs were recently introduced by A*STAR to help local enterprises upgrade their technology and develop innovation capabilities. For instance, A*STAR has implemented a scheme to second its research scientists to a selected number of local firms to identify their technological needs, and to help them map out strategies to innovate and develop new products.

8. Implications for R&D managers and entrepreneurs

While the government has implemented a range of policies to stimulate R&D and entrepreneurship in Singapore, there are still a number of obstacles to R&D management and entrepreneurial pursuits in Singapore. To begin with, the presence of ‘early-adopters’ corporate consumers who are willing to try new innovative products and services is an important factor for the success of new ventures. However, because of Singapore’s small domestic market, few large companies in Singapore are willing to try the products of young unproven companies, with most preferring to deal only with established companies. This preference (or bias) limits the growth of SMEs in Singapore.

In general, firms planning substantial R&D efforts, whether it is a small enterprise or an MNC, must look beyond the Singapore market when they launch their products in order to recoup their investments and secure a viable market. However, expansion into the regional markets is also not an easy matter. Local business practices and cultural norms vary across Asian cities, so that what works in Singapore may not work in Hong Kong or Taiwan.

This fragmentation of markets makes it difficult for Singaporean venture to expand beyond national frontiers. Products and services must be customized to local conditions, and this increase the operation costs. The uncertain scalability of business outside of Singapore raises the risk of R&D investment and new ventures, and thus raises the threshold of required return for investing in a new venture or R&D project. Nonetheless, with the efforts by the Singapore government to attract firms from the region to base their R&D projects in various science parks – such as Biopolis and One-North – in Singapore, and to use Singapore as a gateway into other Asian markets through joint ventures with foreign companies, the scalability issue is being addressed. These joint ventures offer a means to overcome the entry barriers into foreign markets as the local partners provide the necessary local knowledge for market expansion.

9. Conclusion

From an island city-state with few natural resources, Singapore has not only managed to survive and prosper, but has transformed itself from a Third-World economy into a First-World nation.

As it reaches the limit of its investment-growth phase, Singapore faces a new challenge of transforming itself into an innovation-driven economy.

Systematic efforts are being made to refashion its institutions and infrastructure to manage the transition to an innovation-based economy. Coordinated policy changes to the national innovation system remain a key challenge. The public sector bureaucracy has been streamlined, and there are nascent efforts to develop stronger global network links with key high-tech regions to expose research institutions to the global collaboration opportunities.

Given Singapore's small size and the need to achieve critical mass in most areas of scientific endeavor, there is a need for greater public funding for investment in basic research – despite more support for technology commercialization activities from universities and public research institutes. To sustain the development of its technological capabilities, linkages between the publicly funded research institutions and tertiary institution, as well as with the private sector, need to be strengthened further.

Singapore must also continue its 'open-door' policy to attract global talent, even though such a policy has not found favor among many Singaporeans concerned about the competition for jobs. Another challenge is to stimulate entrepreneurship in Singapore. Social and cultural attitudes towards entrepreneurship are changing, but there needs to be greater acceptance of non-conformity and tolerance of failure. Ongoing educational reforms will play a critical role in changing social perception towards entrepreneurship.

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Notes

1. The mandate of the Singapore Economic Development (EDB) is to attract at least S$9 million each year from MNCs to Singapore. According to unofficial estimates, the amount of investments that EDB has managed to obtain commitment in 2003 so far is S$7.5 billion. By contrast, China has attracted more than US$50 billion in foreign direct investment in 2003.
2. A widely used notion of *competitiveness* is based on the definition provided by the US Competitiveness Policy Council. The term refers to the nation's ability to produce goods and services that meet the test of international markets while citizens earn a standard of living that is both rising and sustainable. Two well-known studies of competitiveness are the Global Competitiveness Report of the World Economic Forum (WEF) and the World Competitiveness Yearbook of the Institute for Management Development (IMD).
3. One of the early studies on the technological progress of Singapore is Fransman's (1984), which examined the role played by the capital goods sector in the development of Singapore's technological capabilities.
4. There are numerous studies on national innovation systems; see for example, Dosi (1984), Freeman (1992), Lundvall (1992), Nelson (1993), Freeman and Soete (1997) and Kyriakou (2002).
5. The role of economic institutions in economic growth is discussed in Nelson and Winter (1982), Matthews (1986), Hodgson (1988, 1994, 1998), Greif (1998), and Nelson and Sampat (2001).
6. A useful way to distinguish between basic research and applied R&D is that the former seeks to gain a more comprehensive knowledge without specific applications in mind, although it may be in fields of present or potential commercial interest. The scientific breakthroughs that ensue then lead to applied research, and in turn, to development and diffusion of commercial products (Pavitt, 1991, 1998).
7. Nelson (1959) provided the economic justification for government support of basic research, namely "the existence of external economies which would

not be fully explored or exploited, if business firms undertaking the basic research tried to capture all the benefits for themselves, either through secrecy or property rights." Arrow (1962) stressed much more strongly that the output of basic research was in the form of information that was costly to produce, but virtually costless to reproduce, and therefore had the properties of a public good that deserved government support.

8. The SSP covers total area of 65 ha, and employs more than 7,000 engineers and scientists and support staff. It has signed formal alliances with the Sophia Antipolis of France and the Heidelberg Technology Park of Germany.
9. The name, One-North Science Park, has been chosen because Singapore is situated 1° north of the Equator. Further information on One-North can be obtained at http//:www.onenorth.com.
10. In one study, universities were responsible for 18% of all US patents in the fields of genetic engineering and recombinant DNA, while 16% of patents dealt with natural resins/peptides or proteins, and 12% of patents involved microbiology and molecular biology (see Kumar, 2000). In another study, 73% of the papers cited by US industry patents resulted from research programs public science conducted at academic, governmental and other institutions funded by the Federal government (Narin, et al., 1997).
11. Toh and Choo (2002), and Toh, Tang and Choo (2002) provide recent studies on the contribution of R&D to Singapore's economy.
12. The role of economic institutions in economic growth is discussed in Nelson and Winter (1982), Matthews (1986), Hodgson (1988, 1994, 1998) Greif (1998), and Nelson and Sampat (2001).
13. The commercialization arm within the Agency of Science, Technology and Research is appropriately named "Exploit Technologies."
14. Some schools and universities are allowing students to help run bookshops or set up catering services in the school canteens. Business study trips to places such as China, Vietnam and India are also regularly being organized during the school vacations, to get students to understand the local business and cultural practices.