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Biotechnology and Nanotechnology: Science-based Enabling Technologies as Windows of Opportunity for LDCs?

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Summary. — In this paper, two relatively new science-based technologies—biotechnology and nanotechnology—are assessed to determine whether they provide windows of opportunity to less developed countries (LDCs) for catch up. By examining international patent and firm foundation trends in both industries, we found that Brazil, China, and India have jumped into these two potential catching up technologies. The paper turns to a discussion of the approaches to overcoming entry barriers that have been successful in this context and also describes why only a few countries are currently in a position to take advantage of them to facilitate catching up.

Key words — less developed countries, evolutionary economics, windows of opportunity, biotechnology, nanotechnology

1. INTRODUCTION

Evolutionary and neoclassical economics take opposite stands regarding technological and economic convergence among countries. While the more traditional (neoclassical) approaches consider that countries tend to converge toward the levels of productivity of more advanced countries, evolutionary economics suggests that countries follow different paths (technological as well as organizational). However, in the evolutionary economics tradition, Perez and Soete (1988) have argued that in the early phases of a given technology trajectory, less developed countries (LDCs) may enjoy windows of opportunity which allow them to catch up. These early windows of opportunity may be provided by a number of factors (Abramovitz, 1989), which include the availability of an appropriate institutional framework, the ability of governments to design and implement appropriate economic policies, and the technological and skill level of the population.

Rovner (2003) highlights the difference between incremental innovations (62% of revenues, 39% of profits) and next-generation innovations (38% of revenues, but 61% of profits). These firm-level statistics are echoed at the country-level where the effect of R&D on multifactor productivity growth is apparent. Studies of this nature (Cameron, 1998) typically show that a 1% increase in the stock of R&D leads to a rise in productivity output of 0.05–0.15%. Specifically, Freeman (1987, p. 5) has found that "technical and related social innovations are the main source of dynamism and instability in the world economy and that

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technological capacity is the main source of the competitive strength of nations." As such, LDCs that learn to foster and participate in the early stages of a given emergent technology have a good chance at impacting the success of their economic strength in the long run.

Organizational ecology is an important stream of research that supports an understanding of emerging technologies and their diffusion (Reid & Pliniussen, 2002). The underlying premise of path-dependent technological trajectories (David, 1985; Dosi, 1988) which comes from this stream of research is important to our understanding of the evolution of the biotechnology and nanotechnology sectors because there are still many paths down which these sectors could potentially progress. In order for governments and corporations to have an impact on the eventual markets for the technologies making up these sectors, the earlier they act, the better.

As such, in this paper, we examine biotechnology and nanotechnology, two emerging science-based sets of enabling technologies that are still in the early stages of their technological life cycles and which promise long-term pay-offs to countries engaging in their development and commercialization. The main focus of the paper is to assess whether these emerging technologies do indeed offer windows of opportunity for LDCs to catch up, and if so, which strategies enable successful involvement. To facilitate this discussion, we focus on institutional frameworks as discussed by Abramovitz (1989). Specifically, we investigate clusters and alliances (including facilitation of start-ups and government support) and (secondarily) publications initiating from LDCs. Additionally, we focus on patent (government/university and industrial) and product strategies in developing countries. Last, as suggested by Thorsteinsdottir, Saenz, Quach, Daar, and Singer (2004), Hernandez-Cuevas and Valenzuela (2004), and Forbes and Wield (2002), windows of opportunity for LDCs to be involved with biotechnology and/or nanotechnology exist for LDCs, even if it does not necessarily mean that they will become major contenders for catch up with developed countries. The paper deals with some strategies and examples for LDCs at this level.

2. BIOTECHNOLOGY

During the last 30 years, commercial biotechnology has developed in the US, beginning with the foundation of Genentech in 1976. In the University of California at San Francisco, professor Herbert Boyer and venture capitalist Robert Swanson founded Genentech to commercialize discoveries made by Boyer and Cohen in the new field of recombinant DNA technologies. Between the time of its foundation and their first IPO, in 1980, Genentech produced a first human protein in bacteria and cloned human insulin and human growth hormone. Since then, over 5000 dedicated biotechnology firms (DBFs) have been created in the world, several hundreds of which are publicly quoted in stock exchanges, mostly in the US, Western Europe, and Canada (Bas & Niosi, forthcoming; De la Mothe & Niosi, 2000).

Key applications of biotechnology include biopharmaceuticals for human and animal health, diagnostic tests, agricultural products, environmental processes and products, and food. Today, biotechnology consists of a set of generic technologies (Table 1) (such as genetic engineering, monoclonal antibodies, or DNA amplification) used for different applications (Table 2). Main users of biotechnologies include the pharmaceutical industry, agriculture, mining, forestry, pulp, and paper.

In spite of the fact that biotechnology is not an industry, and as such has no SIC code and no patent code (and that makes difficult the identification of biotechnology firms and

Table 1. *Main biotechnologies*

Recombinant DNA
Antibodies/antigens
Peptide synthesis
Rational drug
Monoclonal antibodies
Gene probes
Gene therapy
DNA amplification
Bioaugmentation
Bioremediation
Bioreactors
Phytoremediation
Biogas cleaning
Tissue culture
Somatic embryo genesis
Biopesticides
Bioprocessing
Bioprocessing
Biobleaching
Bioleaching
Microbial inoculants

Source: Statistics Canada.

Table 2. *Areas of application of biotechnologies*

Area	Description
Biopharmaceuticals	Discovery of therapeutic agents for use in healthcare (human and animal diseases) as well as rational drug design, drug delivery systems, and vaccine manufacturing
Diagnostics	Development of biologically-based systems, tests and kits for the clinical sector, environmental field, or other uses
Agriculture	Plant and animal genetics to produce organisms with new, desirable properties
Environment	Bioremediation, pollution control, waste treatment, renewable fuels using biological processes
Chemicals	Biotechnology-oriented chemicals such as chiral intermediates, biopolymers, and biosurfactants
Food biotechnology	Biotechnology processes to produce food products and food ingredients, plus the production of nutraceuticals and other health-enhancing food additives

Source: The Bioindustry Association (UK), 2004.

intellectual property), some companies are called "dedicated biotechnology firms." These enterprises devote all of their resources to the development of biotechnologies, as defined above. They produce proteins and genetically-modified organisms (GMOs) such as new plants, new animals, and new bacteria, as well as new biologically-based chemicals and processes. The precise definition of these firms varies from one country to the other, thus accounting for the fairly large variation in the estimates of the number of firms operating in biotechnology.

Judged by the number of firms involved, some developing countries are taking advantage of the window of opportunity created by this new, human-capital intensive set of technologies (Tables 3–6). These countries include China, India, and Brazil. It is not by chance that these are the three largest countries in the Third World, and the most probable contenders for a place among industrialized countries in the 21st century.

(a) *China*

In biotechnologies, as almost in every other technology, China is rapidly emerging as a global contender. The Chinese government as well as some of its provincial ones, have given massive support to basic research and early product development, intellectual property regulation, and venture capital. China also benefits from its enormous population allowing domestic clinical assays, and its vast pool of overseas Chinese students, many of whom return to the homeland to teach and/or build up new companies (Louet, 2004). Also, the cost of conducting R&D in China may be a small fraction of what it takes to conduct R&D in advanced

Table 3. *Total number of biotechnology firms in the world, as of 1997–99 and 2002–03*

Country	Number of firms (2002–03)	Number of firms (1997–99)
USA	1457	1273
Canada	391[a]	358[a]
Japan	387[b]	394
Germany	360	279
UK	331	275
France	239	380
Other Western European countries	749	713
Total developed countries	4268	3513
LDCs	>1000	<1000
Total world	~=5200	~=4500
Source	BIA (2004)	OECD (2001)

[a] *Source*: Statistics Canada.
[b] As of December 2003; *Source*: JETRO.

Table 4. *Public biotechnology firms 2002–03*

Country	Number	Percentage[b]
USA	339	54.77
Canada	89	14.38
UK	48	7.75
Germany	13	2.10
Sweden	9	1.45
Japan	8[a]	1.29
France	6	0.97
Other developed countries[c]	92	14.86
Total developed countries	604	–
LDCs	15	2.42
Total	619	–

[a] As of December 2003; JETRO (2004) *Source*: Nature Biotechnology (2004) and Ernst and Young (2004); The Bioindustry Association (UK) (2004).
[b] % of Total including LDC's.
[c] "Other developed countries" include Australia, Belgium, Czech Republic, Finland, Iceland, South Korea, New Zealand, Netherlands, Poland, Russia, Singapore, South Africa, Switzerland, and Taiwan (which is part of China).

Table 5. *Biotechnology firms in major LDCs*

	Number of firms	Public firms	Leading firms
Brazil	150 (1)	1	Biomm[a]
			Biobras[b]
			Vallee
China (including Hong Kong)	136		Hong Kong DNA Chips LeaderGene
India	96	3 (?)	Biocon India[a]
			Panacea Biotech[a]
			Wipro[a]
Argentina	35		Biocientifica
			Biosiddus
Chile	31		Bios Chile
Mexico	27		Empresas La Moderna

(1) ABRABI, 2004.
(2) Ernst and Young (2004).
[a] Publicly traded.
[b] A subsidiary of Danish NovoNordisk since 2003.

countries, making Chinese DBFs competitive with their more advanced rivals in the West. Finally, China not only has a good infrastructure of public research in universities and government laboratories, including those of the Chinese Academy of Sciences, but it also hosts a certain number of R&D-active private companies, such as the Shanghai Mendel DNA Center Co., the Shanghai CAS Shenglonda Biotech Group Co., and the Shanghai Bio Road Gene Development Co., all of them having been granted patents in the US in the most promising areas of human health. All in all, Chinese companies and institutions have been granted over 40 US patents, most of them after year 2000, which is a clear proof of their increasing capabilities. Those patents are well spread into ag-biotech and human health biotechnology. China is also number one in Asia for the number of DBFs: 136 according to Ernst and Young, 2004 report (E&Y, 2004). Finally, China has some 139 human drugs at different stages of the clinical assay pipeline (Louet, 2004). It is also one of the world leaders in the adoption of agricultural biotechnology for human consumption.

Table 6. *US patents in biotechnology (1976–2004)*

	US patents with keywords in abstract
Seven large developing countries	
India (IN)	84
China (CN)	47
Mexico (MX)	36
Brazil (BR)	17
Argentina (AR)	10
Chile (CL)	4
Egypt	0
Total 7 LDCs	105
Seven large or medium size industrial countries	
Japan (JP)	1234
Germany (DE)	627
France (FR)	459
Canada (CA)	452
United Kingdom (GB)	415
Switzerland (CH)	224
Italy (IT)	103
Total	3514

Source: USPTO: as of September 22, 2004.

Table 7. *Indian patents in biotechnology*

Name	US patents 1976–2005
Council of scientific and industrial research	22
Indian universities	3
Other public laboratories	13
Companies	46
1. Panacea Biotec	14
2. Wockhardt	8
3. Biocon	8
4. Indian Herbs Research and Supply	8
5. Cadila	3
6. Themis Medicare	2
7. Bharat Biotech	1
8. Novo Nordisk (Denmark)	1
9. Nicholas Piramal	1
Total	84

(b) *India*

India is the next contender for catching up in the Third World in the biotechnology arena (Kumar *et al.*, 2004). In contrast to China, universities and government laboratories hold a majority of Indian patents; as in China, most of these patents are in ag-biotechnology and human health. Yet, at least nine Indian biopharmaceutical companies have been granted US patents. In fact, India is second in Asia in the number of DBFs, with some 96 companies in 2004, according to Ernst and Young, 2004. Some of these companies are now accumulating a large portfolio of US patents. Among the Indian top 20 firms (according to www.Biospectrumindia.com), at least nine have been granted US patents; some 10 Indian companies held a total of 46 patents by the end of 2004 (Table 7). The private sector is buoyant: growing at a rate of over 20% a year, it is employing over 9000 people and generating revenues of $US 700 million in 2003–04. Investments in FY2004 were $137 million. As in China, funding, IP, and regulatory problems exist, yet the sector is thriving. Delhi, Bangalore, Mumbai, and Calcutta represent important hubs where the main biotechnology companies are located. Also, the leading companies are quoted in the Indian stock exchanges. Already 10 r-DNA human health products have been approved in India and six r-DNA products are already manufactured in that country, as well as a noted hepatitis-B vaccine. The large domestic pharmaceutical sector is another asset in the building of a human health national innovation system. In ag-bio, a transgenic cotton was released for production in 2002. India has been more cautious than China in the adoption of GMOs for human consumption, but since 2002 it has been promoting agricultural biotechnology in Asia (Jayaraman, 2002). Yet, by 2001, China had released more than 250 ag-bio products for production or field trials, as compared to only one for India (Newell, 2003).

(c) *Brazil*

Brazil is the only top contender from Latin America, close to its Asian competitors (Resende, 2003). The Brazilian Association of Biotechnology (ABRABI) estimates the number of core biotechnology firms to be 150, but other sources put the figure as high as 300. Rio de Janeiro, Belo Horizonte, Sao Paulo, and Brasilia are the main hubs. A few of these companies are public (Biomm entered the Sao Paulo stock exchange in 2002, the first biotechnology one in this market) and have been granted US patents. Yet in 2002, Danish NovoNordisk absorbed the previous Brazilian biotechnology leader, Biobras, also quoted in the stock exchanges. At that time Biobras had almost 500 employees, some of which founded Biomm in late 2001. Embrapa, a public company has also been granted US patents.

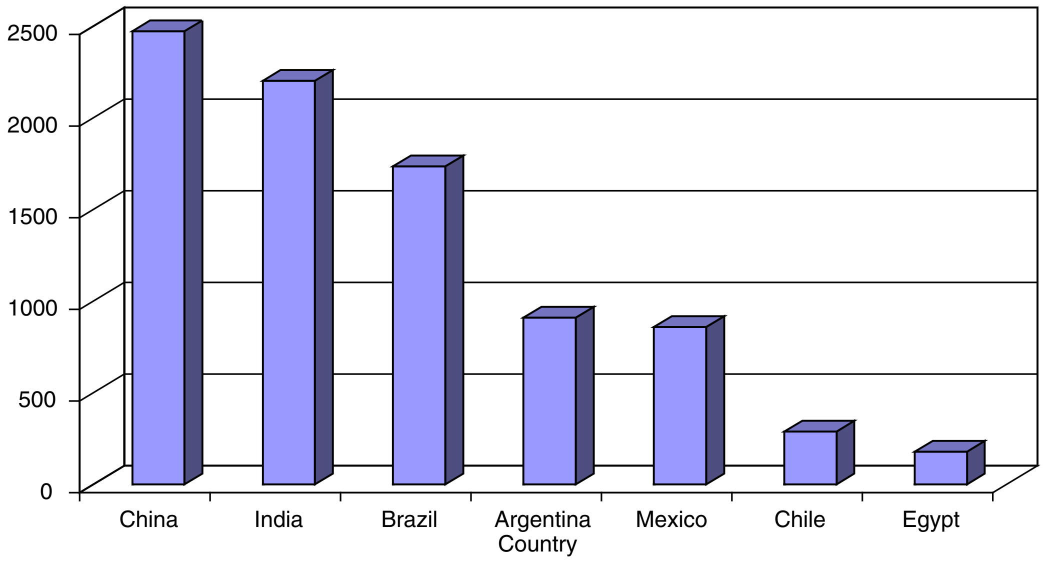

Figure 1. *Biology and biomedical publication, 2001, selected developing countries.*

Yet the Brazilian scientific base is comparable or even superior in terms of number of publications *per capita*, to those of China and India, due to the much smaller population of Brazil (Figure 1). To understand these paradoxes, several explanations have been proposed. First, Brazilian university professors are prohibited from taking jobs in industry while they are at academia (Ferrer *et al.*, 2004). The typical North American biotechnology university spin-off scenario is thus removed from the Brazilian high-technology landscape. Second, intellectual property protection for biotechnology has arrived late and is yet less extended than in North America. Plant varieties have been protected since 1996, but other products and processes are not, thus reducing the incentive to patent in local firms. Yet, Brazil is a potential giant, like China and India, and one that should count in world biotechnology in the near future (Fonseca *et al.*, 2004).

(d) *Other Third World candidates*

Other Latin American and African countries have sometimes been considered possible contenders for future biotechnology windows of opportunity due to their rapid rise in scientific publication (Hill, 2004). *Argentina* has a very good record of publication (much higher than that of the three giants on *per capita* terms) but a very low score in terms of patents. Just 10 biotechnology patents invented in Argentina were found in the USPTO database using biotechnology keywords. None of them belonged to one of the approximately 150 Argentinean DBF's. The Argentinean biotechnology corporate leader, Biosiddus, has no US patents. Like Brazilian universities, Argentinean ones do not release professors for private sector activity, and intellectual property protection is scanty. All 10 patents invented in Argentine biotechnology belong either to foreign firms (six patents) or to individual local inventors (four patents). Neither R&D funding nor IP regulation are national priorities. *Chile* occupies a similar position to Argentina in the commercial world of biotechnology: a fairly good record of publication but only four US patents invented in Chile, three of them belonging to foreign companies and one to a foreign university. *Cuba* has produced several impressive vaccines such as one against Meningitis B, and another against hepatitis B and pneumonia, as well as other therapeutics and diagnostic kits (Thorsteinsdottir *et al.*, 2004). However, by 2003, it only earned US$100 million per year in exports, even though its potential gains in hard currency are much larger. Additionally, Cuba is patent averse, so that its new products may be copied, without much gain for the country. One of the more progressive industrial countries of Africa is *Egypt* and yet it has no US patents and a low publication record (Figure 1). Despite a decent publication record, *Mexico* has few patents and few private companies. In 2001, South Africa had launched a National Biotechnology Strategy, which created incentives and invested public funds, but patents and private companies are yet few, and SA's policy on GMOs are still undecided. All in all, several developing countries have been investing in biotechnology. But for the three largest developing countries—China, India, and Brazil—all of the others have yet to overcome major policy and public opinion hurdles.

3. NANOTECHNOLOGY

Nanotechnology encompasses technologies operating on the scale of 0.1–100 nm. One definition states that "nanotechnology involves the intentional manufacture of large-scale objects whose discrete components are less than a few hundred nanometers wide" (Molecular Drug Discovery, April, 2001). The vision of early pioneers of nanotechnology, such as Ralph Merkle and K. Eric Drexler, was to provide inexpensive "bottom-up" manufacturing technology. While this vision may be many years off, a great deal of progress has been made with developing the building blocks for such a nanotechnology future, particularly in the "nanomaterials" space. For example, nanotubes, the basis of much of the material being made, are graphite cylinders with unusual electrical properties. As described by Harris (1999), we can see that single wall nanotubes are the basis for a whole new class of materials (Table 8).

Based largely on the unique properties of nanomaterials (i.e., strong, lightweight), nanotechnology is being touted as the "next big thing." Since nanotechnology is an enabling technology, providing tools, materials, and devices for further technological development, governments must investigate what these impacts are likely to be in terms of applications, and whether/how to best facilitate their evolution. In support of this, over \$3 billion of world-wide government money alone has already been pumped into the nanotechnology sector during the last couple of years.

Table 8. *Main nanotechnologies/nanomaterials*

Nanoparticles
Nanotubes and fullerenes
Nanofibres
Nanowires
Nanobelts
Nanomotors
Nanosprings
Nanocrystals
Dendrimers
Nanoporous materials
Molecular electronic materials
Molecular photonics materials
Organic nanostructures
Quantum dots
Organic and inorganic hybrid nanostructures
Related process innovations

Source: USPTO.

Current and projected product and process applications have been and are being developed in the areas of the life sciences, medicine, electronics, optics, information technology, telecommunications, aerospace, and energy (Tables 9 and 10). One of the key defining characteristics of the field of nanotechnology is the many different underlying pro-genitor technologies contributing to its composition. These technologies have bases in molecular biology, electronics, materials science, physics (optics and quantum), and others. As such, nanotechnology is built upon many sciences and is inherently complex. The combination of multiple complex technologies involved with the development of many nanotechnologies will necessitate the training and support of researchers capable of this type of technological integration—this will require high levels of government support in terms of training, funding, and infrastructure. As such, as with biotechnology, the three main contenders for catching up in the nanospace are China, India, and Brazil.

(a) *China*

Since China's accession to the WTO, it has successfully used two complementary strategies to attract FDI (>\$50 billion US in 2002): preferential tax policies and incentives to qualified companies (e.g., development zones for new high-tech players). While China has been successful in its attraction of FDI, its ability to attract venture capital and more mature investment financing has been somewhat more limited. As a result, the ability to transition to more mature levels of high-tech developments has been somewhat stagnated. As one example, most of the 300 companies and 7000 scientists engaged in nanotechnology development in China are concentrating solely on nanomaterials, considered by some to be an area which may quickly become a commodity. Those application areas which will likely have greater value add for customers, such as nanoelectronics and nanobiotech developments, have lagged greatly behind that of other countries such as the US, largely because of the lack of more mature investment financing. Nevertheless, China continues to aggressively support start-ups in

Table 9. *Short-term areas of application of nanotechnologies (0–5 years)*

Area	Description/companies
High-speed computing	Development of electronic devices
Computer memory	Memory processes using various organic semi-conductors, porphyrins, chyropticenes
Photolithography	Nano-dip pens to build or repair photolithographic masks
Materials/coatings	New fabrics, paints, coatings for cosmetics
Micro and nanofluidics	MEMS, NEMS, labs-on-a-chip, biosensers
Environment and energy	Hydrogen storage for batteries, electric motors, nanomotors
Agriculture	Bioengineering for plant growth/insect protection

Table 10. *Long-term areas of application of nanotechnologies (+5 years)*

Area	Description/companies where extant
High-speed computing	DNA as programming language and structural materials: molecular electronics and quantum computing
Manufacturing	Bottom-up manufacturing of large-scale structures
Communications	Embedded electronics
Robotics	Nanobots
Health care	Prosthetics
Environment and energy	Biomass

this area as evidenced by its commitment to $2 billion Yuan ($240 million US) during 2003–07 to this sector. Another $2–3 billion Yuan is also committed from local governments (Nemets, 2004). Currently, some 30 institutions are working in basic research in the nano area including the Chinese Academy of Sciences (CAS) Physical Institute, CAS Chemical Institute, Tsinghua University (Beijing), Beijing University, Hangzhou University, Nanjing University, and several in Shanghai. In addition, Shanghai, Beijing, and Shenzhen each have their own nanotechnology centers (Nemets, 2004). In addition to mainland China, Taiwan's nanotech industry is also active with output expected to be worth 300 billion Taiwan dollars ($8.82 billion US by 2008). Some 800 local companies may get involved in this sector with the Taiwanese government committing 20 billion to Taiwan over six years to bolster the industry.

While Chinese companies have few patents related to biotechnologies (Table 6), and none yet granted in the US, the situation is better in the nanotechnology sector, but there is still much room for improvement (Table 11).

Yet, we consider China to be the most likely contender for catching-up with advanced countries in all fields of biotechnology and nanotechnology: as the economy grows, new funds may be invested, IP and regulatory frameworks upgraded, and human capital will flow into the new area (The Economist, 2002).

Table 11. *Total patents in nanotechnology*

Patents filed in own country	%
Japan	48
China	4
US	6
Europe	9
Other	5
Patents filed in other countries	**%**
Japan	5
Korea	6
US	17

Source: Baughman, Zakhidov, and de Heer (2002).

(b) *India*

India is also a contender for catch up in the Third World in the nanotechnology arena. Specifically, several software companies located in Hyderabad, which may well lead the software and analysis side of the nano-revolution, receive numerous financial benefits, including income tax holidays, customs exemptions, and accelerated depreciation rates on computer equipment. India also has the advantage for international alliances of having English as one of its official languages.

In addition, to specific government incentives, part of the strength of the Indian movement lies in the public infrastructure including 40 national research institutes, 120 medical colleges, and 100 teaching hospitals. Also, including the 300 sciences colleges, India produces close to 500,000 engineering graduates per annum. If the rapid development of software serves as an example, then Indian nanotechnology can count on an abundant supply of highly qualified scientists, technicians, and engineers.

While India has no dearth of engineers and intellectual property, it lacks quality labs and institutional funding, the likes of a NNI. It does have the Indian Institute of Technology, but the funding levels for nanotechnology in particular are not high, particularly on a *per capita* basis. For example, the government has committed $15 million US over the next years for Smart Materials development and the Department of Science and Technology has launched a National Nanotechnology Program with total funding of $10 million over the next 3 years, but this is a drop in the bucket compared to China's commitment. This having been said, however, there are several grassroots organizations sprouting up to take advantage of the new field: India Nano (tech transfer), Forevision Instruments, and Indiaco Innovation (VCs). There are also research teams extant in the chemistry departments of many of the universities. For example, The University of Delhi's chemistry department has developed 11 patentable technologies using nanoparticles for drug delivery (four were granted US patents).

(c) *Brazil*

In 2000, the Brazilian national research funding agency created the co-operative network for Basic and Applied Research in Nano S&T. According to a report by The Royal Society (2004), the cooperative networks involve 40 Brazilian Research institutes as well as two companies (France Telecom and PQSD), have 260 researchers and have published greater than 1000 research papers. The networks received R$3.2 million ($1.5 million US) the first year and this will increase from 2004 to 2007. This same report describes another Nano S&T initiative from Brazil's federal government is the Millenium Institutes which are a partnership between MTC and the World Bank. Total investment is R$90 million ($41 million US) with three institutes directly related to nanotech. The development of the Nanoscience and Nanotech Program 2004–07 is scheduled to receive R$77.7 million ($35 million US). Most of the research occurs in universities and the federally sponsored networks are conducting research mainly in the areas of nanomaterials, interfaces, molecular nanotech, nanobiotech, and semiconductors. As with biotechnology, the research base for nanotechnology is superb and shows excellent promise, however, lack of patenting to date may translate into less aggressive industrial entry.

(d) *Other Third World candidates*

To date, *Mexico* has mostly focused its efforts in the areas of manufacturing of nanomaterials, somewhat similar to China's strategy. For example, Clariant a large chemical company, in 2002 commissioned a new production facility at Coatzacoalcos to manufacture chemicals for nanobiomaterials. Interestingly, in Beijing August 16, 2004, Mexico and China signed a memorandum of understanding which officially established cooperation and exchange in science and technology. Another initiative that holds great promise for Mexico is the University of Texas initiative "Nano-@-the-Border." This program offers the possibility of an international partnership with Mexico through CONACYT and universities in Mexico. This institutional arrangement holds great potential value for Mexico as there is a great deal of technical expertise in the materials field due to the Texas cluster being the first to get involved in nanomaterials scale production. While *Argentina* is a late contender, it has recently become involved in an EU-Argentina co-op agreement on Science and Technology which, given the involvement of the EU with nanotechnology, will likely involve some investment there over the next few years. *South Korea* has been an early mover with patenting in the nanospace and plans to spend $2 billion US over the 10-year period of 2001–10. Taken in combination with the fact that South Korea was an early adopter of a comprehensive broadband policy, deregulation, and involving strong competition, this allowed entry into markets involving fast networking, high-quality video and data voice services. As such South Korea is well positioned for the window of opportunity presented by the software/analysis challenges of nanotechnology. This infrastructure will likely also be indispensable for connecting with the next wave of proteomics analysis instruments because many nanotech companies will require the ability to perform massive number crunching for data analysis and control.

Mexico, Argentina, and South Korea therefore represent other potential future candidates to enter the fray. Yet, the number of companies, the university infrastructure, lack of venture capital, and government support, as well as the limited human capital pool, puts them in a distant category compared to the three leading countries.

4. STRATEGIC APPROACHES TO OVERCOMING ENTRY BARRIERS

The current scenario, therefore, suggests that the three largest developing countries—China, India, and Brazil—have jumped into the two potential catching up technology sectors of interest in this paper. Interestingly, these three countries have put their efforts into different strategies, each with varying results. China has concentrated on infrastructure (investment in R&D clusters, and facilitation of start-ups through venture capital, tax incentives, and other incentives) and patenting. As with China, India has concentrated its efforts on infrastructure, however, has not had the same focus on patenting, particularly at the industry level. Finally, Brazil has been very successful in its support of basic research, however, has not concentrated on patenting and therefore there has not been a high level of translation to the industry level. On the whole, China, India, and Brazil are catching up in biotechnology and nanotechnology to varying extents. In addition to their size, these three countries have successfully utilized additional strategies to be considered as players in the biotechnology and nanotechnology arenas, and we suggest that there may be other LDCs capable of using one or several of these strategies to selectively enter windows of opportunity provided by these sectors.

(i) *Strategy one: early patenting in areas with the potential to attract foreign venture capital*

Patents are key to protecting IP in both the biotechnology and nanotechnology arenas; without patents a country can show scientific priority through publication but not knowledge that can be used in industry with the ability to attract private sector investment. An investigation of patenting activity carried out by Reid and Pliniussen (2002), in the area of nanostructure materials carried out using the USPTO database, reveals this to be an early "take-off" field in the overall nanotech sector (see Tables 9 and 10 for lists of nanostructure development/application areas). It is interesting to note that while only 20% of the first 100 patents granted in the field of recombinant DNA (biotechnology) were to foreign patent applications, 45% of the nanostructure-related granted patents were granted outside of the USA (USPTO database). Additionally, while the recombinant DNA patents were not dispersed widely across many countries (i.e., mainly only in the USA, Japan, and a few European countries), the nanostructure patents were widely dispersed across more countries including Korea, Singapore, and China (including Taiwan). These findings are supported by Kogut (1991) and Sorenson and Stuart (2001), who found that the geographic dispersion of initial technological capabilities tends to persist over time and impacts on the future product capabilities of firms. Given the greater level of dispersion of nanotechnology (nanomaterials) patents in comparison to biotechnology (recombinant DNA), this bodes well for a greater dispersion in terms of future product capabilities across countries. Further, we see evidence in the education system in several of the LDC countries that these developments will be supported. For example, recent NSF statistics (2004) show that the number of engineering graduates in the US, China, and India were 100,000, 400,000 and 500,000, respectively. Taken in combination with patenting activity in these countries, these persistent capabilities on the technology level for such countries will impact their wealth in the future, particularly given that venture capitalists use patenting activity as a benchmark for investment in the nanotechnology area.

Venture capitalist investment in the sector (Micro and Nanotechnology Commercialization Education Foundation, 2004), focusses on typical risk/return analyses: device companies are considered the least risky and most attractive, however, they are also further along the technology life cycle and will take the longest to receive return. Materials companies are considered to be in the middle in terms of risk/attraction—the biggest risk being scale-up problems. Tool companies, while risky and not as attractive in terms of total return (tending to tap out at about $20 million per application), did get to market quickly and therefore provided a good leveraging mechanism in terms of providing cash flow to longer term applications, and also to help lock-in expertise.

For countries with a venture capital infrastructure in place, then, a broader based approach to development, either in terms of platforms (embracing all three types of development—tools, materials, and devices—with a given technology focus) or focusing on more than one sector, may be effective strategies. However, for those countries where a strong venture capital infrastructure is not in place, a more focused approach (either at the technology level and/or at the application level) may be warranted.

(ii) *Strategy two: cluster and alliance strategies*

Innovation clusters are defined as geographic concentrations of competing and cooperating companies, suppliers, and associated institutions. Silicon Valley is one of the most successful examples. Studies (e.g., Harvard Cluster Mapping Project; Porter, 1998) indicate that economic productivity and innovative output are strongest where regional or national clusters are cultivated to include anchor institutions or organizations accomplished by a system of supporting elements which include support for start-ups. Government-supported institutions are therefore critical to support and help the start-up of new industry. For example, Canada and the US are both showing some success from technology transfer stemming from their respective national nanotechnology initiatives.

Another critical aspect that should drive cluster prioritization should be end-user markets located in the same proximity as the technology developments. For example, with the automotive sector cluster located in Michigan (e.g., GM, University of Michigan), automobile manufacturers were one of the first user markets for MEMS accelerometers in air bags. Cluster thinking is good for the economy because it strengthens community identification and it offers opportunities for leveraging core competence with a technology developed with short-term market opportunities to larger and longer-term market opportunities.

Additionally, just as we have seen successful strategic alliances (many between companies from different countries) between pharmaceutical and biotech companies, so too we are starting to see evidence of the same phenomenon with nanotech. Smaller new players in the nanomaterials and nanotools sectors will likely ally themselves with larger incumbents (such as HP, IBM, Motorola) in order to take advantage of their resources and capabilities, particularly, access to markets and market distribution. The advantage for incumbents may be access to new technology or to markets where they have not yet established themselves.

5. CONCLUSIONS

Three countries appear at first sight to be seriously engaged in the windows of opportunity currently offered by biotechnology and nanotechnology: Brazil, China, and India. These are, not by chance, three of the largest countries in the developing world. In industries where major funds need to be invested to get some results (each new drug in the market may cost on average $800 million) only the largest countries may take advantage of these windows of opportunity. Niche strategies do not work in biotechnology. In this area, only human health uses offer some returns on investment. But human health biotechnology is extremely expensive and returns, when they arrive, come after many years. This having been said, there are two strategies which may be used to increase potential for jumping into nanotechnologies for smaller LDCs. First, there is some intersection between the fields of biotechnology and nanotechnology (e.g., quantum computing). Therefore, country involvement in one technology may help to reap the benefits of a new technology by leveraging related technologies, and thereby, bringing down the cost of involvement, particularly if focused in one niche segment (the example of India's software involvement with biotech which could be leverage into the nanoworld). Second, similar to the argument that small firms can partner with large firms (the example of biotech and pharmaceutical companies) to good effect, small countries may also follow a similar alliance strategy (the example of Mexico and China).

However, in general, the would-be contenders look as though their efforts thus far are too fragmented (Argentina, Mexico) or too small (Chile, Cuba) to become "contenders" in terms of real catch up with developed countries, however, given appropriate strategies the first group might be players in the future. Through their sheer size, the three majors of the Third World could become leaders of the foreseeable future in biotechnology and nanotechnology.

While nanobio, quantum, and organic computing are likely to be key playing fields for

US firms (where there already exists more than 100 firms), there are many other short- and longer-term arenas where LDCs have potential to be key players. For example, nanomaterials, bottom-up manufacturing tools, robotics, nanobots, prosthetics, and software/analysis are all areas where the talents of LDCs should play a major role.

To come back to the theoretical discussion opened by Perez and Soete (1988), just a few countries seem to host the amounts of human capital and funds allowing them to get involved with these advanced technologies in their early phases. These are the largest Third World countries, and all of them show a remarkably strong public sector, able and willing to maintain a long-term effort in order to catch-up with advanced countries. The size of the human and investment capital, plus a major priority by country authorities seem to be preconditions for some countries to take advantage of the windows of opportunity which currently exist in a way which enables "catch up." Given these pre-conditions, Brazil, China, and India are among the largest LDCs, and they have used certain strategic approaches to overcome some of the aforementioned entry barriers. In this paper, we have discussed some of these approaches (niche and cluster strategies, early patenting in areas with the potential to attract foreign venture capital, public policy that allows support for the development of an entrepreneurial culture, and the involvement in international alliances to enhance learning opportunities and promote bridging to gain access to markets). Windows of opportunity therefore exist with these new technologies, but only a few countries that are in a position to do so, have currently taken advantage of them. If other countries (such as South Korea, Argentina, and Mexico) take advantage of some of the aforementioned strategic approaches to overcoming barriers to entry, they may be able to take advantage of more opportunities in the future.

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