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On nanoscience, nanotechnology and nanoproducts: Why everyone wants to join this game

by

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Abstract

Nanotechnology is being hailed as having the potential to transform our world and thus it is not a surprise that many developed as well as developing countries have plunged headlong into investing in nanoscience, nanotechnologies and nanoproducts. Our understanding, however, of how existing capabilities can be deployed and new ones created by firms and countries, to create competitive advantages related to nanotechnology, is far from being clear. In order to provide some insight on these issues, the present chapter gives an overall view of the developments in the nanotechnology sectors. It starts with definitions of nanoscience, nanotechnology and nanoproducts, as well as the distinctions and links between them in section 1. This is followed by a presentation of the nature of the race and the gap between leaders and followers in section 2. The challenges for followers are discussed in section 3. Finally, section 4 concludes with some guidelines for developing countries. We show that though there are immense gaps between the leading developed countries and emerging countries in terms of publications, patents and products, China is doing better than many developed countries and a few other emerging countries are catching up in terms of publications. We conclude that with adequate investment from either public or private sources, emerging countries can build competitive advantages in the short run through a clear focus on niches and/or harvesting the remaining second tier low-hanging fruits.

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On nanoscience, nanotechnology and nanoproducts: Why everyone wants to join this game

1. Defining what the game is all about

Do you remember the first time you encountered the idea that while the universe could be infinitely large, its' basic building blocks are actually very small? These building blocks, the atoms and molecules comprising all matter, in effect make up the world of nanoscience. As such, the basic fodder for nanotechnology, throughout our world's history, has always been at play. As described by Wilson et al. (2002), the alkali and alkaline earth metals (Groups 1 and 2 from the Periodic Table of Elements), as well as the transition metals (Groups 3 to 12), due to their various electrical properties, make good providers of electrons and good conductors, respectively, useful in nanotechnology. Further, carbon and silicon from Group 14 are important base materials for many nanomaterials. In other words, these atoms and various simple molecular combinations of these, not only are the building blocks of nanotechnology, but also of our world. Our understanding of this reality has only developed relatively recently, however. Only through the development of tools, in particular those allowing us to see (scanning probe and atomic force microscopes) and engage (lithography and masks enabling building up through deposits or chiseling away of various surfaces), facilitated through the inert noble gases such as xenon and radon (Wilson et al., 2002), have humans been able to witness, and lately attempt to play with, the ongoing miracle of the composition and dynamics of matter operating at the nanoscale.

The nano-world has generally been defined as occuring between 0.1 and 100 nanometers and therefore covers the quantum physics and DNA spectra (CMP Scientifica, 2001). According to the Cambridge Dictionary, the definition of science is "knowledge from the systematic study of the structure and behavior of the physical world, especially by watching, measuring and doing experiments, and the development of theories to describe the results of these activities". Therefore, "nanoscience" refers to this definition as applied to the nano-world: the study of the nanostructures and nanomechanics occupying the 0.1 to 100 nanometer terrain. The many scientific disciplines comprising what is currently understood to contribute to nanoscience, go beyond chemistry to encompass the sciences of molecular biology, electronics, materials science, physics (optics and quantum) and others. As such, nanoscience is built upon many sciences, is complex, and will rely on capabilities of researchers to integrate these sciences in meaningful ways.

Thus, what has come to be known generically as "nanotechnology" is built upon unique combinations involving many of the basic fields of science. The Cambridge Dictionary definition of technology is "the study and knowledge of the practical, especially industrial use of scientific discoveries". As such, industrial applications or products, such as nanotools and nanomaterials such as nanotubes, would also fall under this rubric. Consumer applications would be considered separately as consumer nanoproducts. Nanotechnology, therefore, does not refer to a single technique but to many different underlying pro-genitor technologies that enable manipulation of matter, such as measuring, designing and mass producing at a nanoscale. Some of the most famous basic technologies to date include SEM (scanning electron microscopy)[1] and nanotubes as a basic construction material for everything from stronger, lighter tennis rackets to the space elevator.

Why are nanosciences and nanotechnology capturing the minds and hearts of scientists and policy makers? Consider this definition: "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 proponents of nanotechnology, such as Richard P. Feynman, Ralph Merkle and K. Eric Drexler, was to provide inexpensive "bottom-up" manufacturing technology. According to Ralph Merkle's home page (August 31, 2010), "a central concept for achieving low cost in molecular manufacturing is that of massive parallelism, either by self-replicating manufacturing systems or convergent assembly". These may be possible at the nano-scale utilizing 'bottom-up' rather than 'top-down' manufacturing processes and systems, potentially achievable through the use of DNA microarrays or nanobots such as flagellated bacteria. While this vision may yet be many years

[1] SEMS allow the investigator to see an object smaller than the wavelength of light. A beam of electrons is manipulated using condenser lenses and scanning coils to create a magnetic field using fluctuating voltage. As the electron beam moves towards an object, it removes secondary electrons from its surface. A secondary electron detector registers different levels of brightness based on the number of electrons emitted and this builds the image with the aspects of the image closer to the beam appearing brighter. Primary backscattered electrons also help determine the atomic number and topographical information. For more detailed information on SEMS, please consult Flegler et al.'s (1993) "Scanning and Transmission Electron Microscopy: An Introduction".

off, a great deal of progress has been made in developing the building blocks for such a nanotechnology future.

1.1 The new beginnings

A first conquest is happening in the creation of the "nanomaterials" space. Carbon atoms and xenon atoms, typically $1/10^{th}$ of a nanometer, in special molecular arrangements, such as "nanotubes" (Harris, 1999), are the basis for this whole new class of nanomaterials. These star products, "nanotubes", are carbon-based graphite cylinders with unusual electrical properties and represent one of the earliest developments in the nanomaterials space. Based on their importance and an increasing number of applications and potential applications, the USPTO (United States Patent Technology Office), IPC (International Patent Classification) on WIPO, and the EPO (European Patent Office) each now recognize "nanotechnology" as a separate class of inventions (class 977, class Y01N, and class Y01N, respectively). In addition, the IPC has added another separate class just for "nanostructures" called Class B82B. Some linkages between the combination of sciences involved with nanoscience and related nanotechnologies, and products are illustrated in the case of nanomaterials in Table 1.

Table 1: Nanomaterials: From science to technology to product innovation

Sciences	**Nanotechnologies**	**Product Example**
Electronics, Mechanics, Physics, Chemistry	Nanobelts, Nanomotors, Nanosprings, Nanowires	The "Nanomotor" from *Klocke Nanotechnik* for military ultra-vacuum and underwater applications
Physics, Chemistry	Nanoparticles, Nanotubes, Nanofibres, Nanocrystals, Fullerenes, Quantum Dots, Nanoporous Materials	*Ecosynthetix*'s starch adhesives for McDonald's hamburger containers which take less time and energy to dry because of the small size of the molecules
Chemistry, Biology, Physics	Organic and Inorganic hybrid nanostructures	Silver nanowires for highly efficient solar PV cells (not yet commercialized)
Biology, Electonics, Physics	Molecular Electronics and Photonics	*California Molecular Electronic*'s "Chiropticene ^{R} switching technology aimed at providing 16 terabits of data storage in a device

		the size of a cubic inch providing 34 times capacity of one of today's 60 GB hard drives

Based largely on the unique properties of nanomaterials which are claimed to be endowed with characteristics such as being stronger, lighter, faster, more self-correcting, less expensive, etc., nanotechnology is being touted as the "next big thing" that is going to have a revolutionary impact on most of our lives and in the most important consumer and business sectors of the economy worldwide. Since nanotechnology is an "enabling technology", just like the internet or electricity, it will provide the tools, materials and devices for a new generation of technological development. Some of the current and short-term-to-fruition product and process applications in the areas of the life sciences, medicine, electronics, optics, information technology, telecommunications, aerospace and energy are given in Table 2.

Table 2: Current short-term areas of application of nanotechnologies (0-5 years) potential low hanging fruit

Area	Description/Examples
High-speed Computing	Development of new electronic devices (IBM's 'Millipede', Intel, Compaq, Motorola, Nanosys)
Computer Memory	NRAM chips and Memory processes using various organic nano semi-conductors (Nantero), porphyrins (ZettaCore), chyropticenes (California Molecular Electronics)
Photolithography	Nano-dip pens to build or repair photolithographic masks (Northwestern U/Nanosphere/NanInk)
Materials/Coatings Manufacturing	Materials such as nanotubes and their large-scale manufacture (CNI/C Sixty, Mitsui), new stain-free and light-weight fabrics (Nano-tex), new materials (tennis rackets and other exercise equipment), paints and coatings, sunscreens and cosmetics (Nanophase Technologies, L'Oreal), dental bond agents (NanoSilver), high-performance tires and car parts like super-strong running boards (GM), new flat screen monitors (Samsung), thin films (Ntera), electronic paper (Bell Labs, E Ink), hard plastics for bottles that are better at sealing in CO2 to keep drinks fresh (Miller Brewing purchased from Voridian Co.)
Micro and Nanofluidics	MEMS, NEMS, labs-on-a-chip, biosensers (Sandia's microfluidics project, Nanogen's automotive sensors, Cyrano Science's electronic nose)
Environment and Energy	Buckytubes which can store hydrogen for batteries, electric motors, nanomotors, and encapsulation systems for bioremediation (U.S. Navy)
Agriculture	Biodegradable chemicals using bioengineering for plant growth/insect protection (Monsanto)
Defense	Landmine detectors (UConn)
Healthcare/Bio-	Biosensors and fluidics as above enabling better medical diagnostics

pharmaceuticals	(MicroCHIPS Inc, Agilent); drug delivery systems (iMEDD and Target Therapeutics for cancer, Smith & Nephew's silver nanocrystal lined bandages for killing bacteria), implants, super-strong artificial muscles (UTexas Dallas, UBC)

One of the most interesting things that has happened at the advent of modern nano in the form of new products is that the first products on the market place are not industrial, as is often the case with new generic technologies, but rather, consumer focused. For instance, with respect to the computer, which is a good example of a typical technology development – the first applications started in the industrial sector (mainframes for the military and so on) and then moved out to the consumer sector. Rather, in the world of nanotechnology, and we would argue that biotechnology is an important part of this nanoworld, the consumer sector has been the first to reap major benefits. Early developments that have been made in the consumer goods sector include new nanotech-based products in automotives, paints, clothing and cosmetics (much based on nano-encapsulation technology). For example, the largest corporate holder of EPO patents in nanotechnologies, for the period 1978-2006, is cosmetics manufacturer L'Oreal (Chen *et al.*, 2008).

1.2 How does science marry technology?

While nanotechnology is coming to capture the public imagination, important strides are being made in the nanosciences, as evidenced by over a dozen Nobel Prizes having been awarded in the area thus far. Further the impact on various disciplines has been broad including for example, the life sciences, electronics and information technology, medicine, aerospace, energy and the environment. These are being so rapidly capitalized in the form of technologies and patented that we are likely to see new applications emerging as in table 3.

Table 3: Projected long-term areas of application of nanotechnologies (+5 years)

Area	Description/Companies where extant or Universities
High-speed Computing	DNA as programming language and structural materials: Post-silicon molecular electronics and quantum computing

	(Molecular Electronics Corp/Rice University, Penn State, NYU, UCLA/HP, QSR/HP/MIT, IBM, AT&T)
Manufacturing	Bottom-up manufacturing of large-scale structures at no cost (a la Drexlerian vision) (Rice University's 'nanocar')
Communications	Full-time interconnectivity through retina, clothing, embedded electronics
Robotics	Nanobots to cure diseases, administer drugs (Quantum International, iRobot, Intuitive Surgical)
Healthcare/Bio-pharmaceuticals	Prosthetics (DARPA), Cosmetic Medicine (skin and hair color changes, wrinkle treatments, fat levels maintenance) (L'Oreal), preventative medicine
Environment and Energy	Smart Dust (UC Berkeley, U Alberta, Dartmouth) for energy storage and harvesting, as well as environmental monitoring; solar cells in roofing tiles (Solar3D, Dow, SunPower), siding that provides electricity using solar paint (U Notre Dame)

How exactly does science marry technology to produce a blockbuster product? If we look at the developed countries that have already invested in these areas, we can identify many clear examples of success from the synergistic effects of scientific and technological integration. For instance, consider the following example coming from the new field of molecular computing. GenoRX, a U.S.-based company, combines CMOS (Complementary metal-oxide-semiconductor) technology, used for constructing circuits, with gene chip technology (cDNA microarrays from a large number of genes) to perform sequencing (massively parallel) on a chip without PCR (Polymerase chain reaction) DNA[2] amplification or fluorescent tagging, which are time consuming processes. According to p.1 of the GenoRX patent (2005), the invention "provides biosensors for the detection of nucleic acids, such as double stranded DNA. The biosensors are electrodes on a solid support that have means for binding nucleic acids near the electrodes. The nucleic acids are captured such that they span the electrode pair, and the capture can be detected by electrical means". In other words, these biosensors use voltage current characteristics between electrodes to determine the readout at the DNA end. Such devices can be seen to have useful applications as diagnostic tools in medicine (i.e. genetic screening), agriculture (i.e. pesticide measurement) and environmental applications (i.e. core samples).

[2] Deoxyribonucleic acid or DNA is a nucleic acid which carries genetic instructions for biological development in all cellular forms of life and many viruses

As Will Ryu (2001) points out – the data density of DNA is impressive. He explains as follows:

> "Just like a string of binary data is encoded with ones and zeros, a strand of DNA is encoded with four bases, represented by the letters A, T, C and G[3]. The bases are spaced every 0.35 nanometers along the DNA molecule, giving DNA a remarkable data density of nearly 18 Mbits per inch. In two dimensions, if you assume one base per square nanometer, the data density is over one million Gbits per square inch. Compare this to the data density of a typical high performance hard drive, which is about 7 Gbits per square inch – a factor of over 100,000 smaller."

The other strength of DNA beyond its memory capacity is that it works in a massively parallel fashion. According to Ryu (2001):

"Just like a CP[4] has a basic suite of operations like addition, bit-shifting, logical operators (AND, OR, NOT NOR) etc. That allow it to perform even the most complex calculations, DNA has cutting, copying, pasting, repairing and many others. And note that, in the test tube, enzymes do not function sequentially, working on one DNA at a time. Rather, many copies of the enzyme can work on many DNA molecules simultaneously. This is the power of DNA computing."

Nanotechnology has also started transforming industrial organization in some markets. Firms experimenting with nanotechnology include established firms as well as new ones. In terms of new firms active in NST, near the advent of 2010, based on a database that we have been working with for over 10 years, a global estimate of the number of companies involved in the nanotechnology space is that there now exist at a minimum, from the G12 countries, in excess of 500 materials companies, approximately 200 tools companies and at least 100 systems and devices companies on a global level.

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[3] adenine (A), thymine (T), cytosine (C), and guanine (G).

[4] CP refers to the central processing unit of a computer, which is the primary element carrying out its functions.

There are also those companies that have evolved to provide the services and information needs for the newly emerging area. For the device and systems companies (i.e., those working on Nano-electomechanical (NEMS) systems in accelerometers, actuators, control systems, nano-fluidics (lab-on-a-chip) and other areas such as intelligent materials like “Smart Dust”), the challenge is that, while technically possible in many cases, quantity production based on sound economics is still not readily feasible, and as such, the world still waits for many of the promised next-generation products.

1.3 What of the future? Rising to the challenges

From a practical standpoint, a key issue for scientists and practitioners in all countries is related to the physical property challenges related to working with these technologies. The physics governing the behavior of molecules changes when moving from the nanoscopic to the mesoscopic scale to the macroscopic scale (Roukes, 2002). At each level of complexity, new properties appear and the challenges of quantum mechanics become multiplied when dealing in this space. “What often emerge at the mesoscale are phenomena that involve the coherent or collective interactions amongst the fundamental constituents-be they electrons, atoms, or molecules. Despite being ‘nanoscopic’ (that is of nanometer dimensions), mesoscopic structures comprise fundamental building blocks in numbers that are too large, in general, to allow easy theoretical modeling using conventional approaches of quantum physics or chemistry” (Roukes, 2002, pgs, viii-ix). Herein lays one of the major problems currently encountered with scale-up by many researchers and companies.

Related to this, a second key challenge that exists related to bringing the promise of nanotechnology to fruition is the problem of scaling up 1. of production processes and 2. from a simple process/product and make it into a product capable of delivering desired benefits to consumers On the production process scale-up issue, for example, no company has yet figured out how to build mass quantities of high-quality nanotubes, and how to do it in a way that is economically feasible. For instance, several companies, in particular the nanotube company founded by Richard Smalley, are trying, but the economics side of the equation is still daunting. Another example of scale-up problems exists for work in the area of inorganic materials, such as gallium arsenide; they offer exceptional performance in computer processors that silicon on its own cannot provide, such as the ability to transmit light; the problem is that these compound materials are very expensive and more brittle than silicon. An indium phosphide wafer, for example, is 3 inches wide and costs $1200 to make, where silicon wafers cost pennies for an 8 inch wafer (Lawton, 2002).

The other big scale-up issue, the third challenge, is the scaling up of consumer benefits. Just as one of a manifold of examples, is the work of Charles Lieber and his colleagues from Harvard, who published a paper in Science (2001) explaining the use of nanowires to construct logic gates[5]; the basic switches of all processors. His machine had 16 transistors and he was able to demonstrate the performance of basic addition using this tiny nanocomputer. The challenge will be marrying the two worlds of tiny infrastructure and the huge and much more complex demand tasks required from consumers.

A fourth challenge is to find investors to finance the high costs of uncertain innovation generation. In almost all countries, the government is the financier for emerging sectors. In the private sector, the venture capital (VC) market is the source of funds. However, VC markets are sluggish in most countries outside of North America and especially so in emerging economies. While the usual investment timeframe is 3-5 years for venture capitalists (VCs), investors for many of the projected blockbuster applications will need to be patient and be prepared to invest more along the lines in the biopharmaceutical sector where payback can take 15 years or more. This said, however, there are many “low hanging fruit” where needed applications are delivering benefits considered important by the end-consumer; they may not exist in the world of increasing returns that many VCs are looking for, but still will deliver solid advantages both to consumers and investors alike.

[5] Logic gates are the basic units of digital circuitry used in computing. Usually a logic gate has 2 inputs and 1 output, where each of the inputs is either a low (0) voltage state or a high (1) state (usually about +5 V). There are 7 basic logic gate types: AND, OR, XOR, NOT, NAND, NOR, and XNOR. In the first example, ‘AND’, if input 1 = 0 + input 2 = 0, then output = 0; if input 1 = 0 + input 2 = 1, then output = 0; if input 1 = 1 + input 2 = 0, then output = 0; if, however, input 1 = 1 + input 2 = 1, then output = 1. In other words, when the inputs are both “true”, then the output is “true”. For more detailed explana related to basic circuitry, please consult a basic text such as “Digital principles and Logic Design”, by A. Saha and N. Manna (2007), Infinity Science Press LLC: Higham, MA.

Venture capitalist investment in the NST sectors focuses on typical risk/return analyses i.e. VCs have to evaluate trade-offs between the time period to positive payoffs, the degree of certainty of positive payoffs and the magnitude of expected payoffs (MANCEF, 2004). To illustrate, device companies (for example, medical sensors for measuring biofluidics) are considered the least risky and most attractive, however they are also further along the technology life cycle and will take time 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 not risky are not as attractive in terms of total return (tending to tap out at about $20 million per application), but they do get to market quickly and therefore provide a good leveraging mechanism in terms of providing cash flow to longer term applications.

To sum up, the nanosciences-nanotechnology combination has so much potential to transform our world that one of the key challenges for the successful transformation of the science and technology into meaningful applications is to overcome much of the hype that has surrounded the discipline. While futurists have helped to fuel many of the good ideas of the discipline, some of them have gone too far in their promises of great wealth, longevity and happiness. Yet others have gone the opposite way with doomsday predictions of gray goo scenarios of mass destruction resulting from out-of-control nanodevices. Even for those able to walk the middle path, when mixed in with the current environment of venture capital looking for the next big investment and technical potential, the result can still be an over inflation of expectations. As David Berube, the author of "Nano-Hype" points out for the US, a trend which is true elsewhere as well, "it doesn't stop there either. Universities across the entire country have opened nanocenters mostly populated by faculty from well-established departments who have been relocated to a new building or a few rooms in a wing." (p. 33) He goes on to quote U.S. Senator Wyden from the early hearings on the Twenty-first Century Nanotechnology R&D Act who stated that "The joke these days in the world of science is that everyone is doing nano work. Just as the '90s saw everyone putting *Dot.com* after titles, everyone is putting *nano* before their science" (Wyden, 2003). Not that the nano will not be able to deliver; it will and then some – the timeframe for payback may just be longer than the span normally supported by venture capital companies, firms or the State.

2. The international nanotechnology race

Now, are all players in the internationally race for nanotechnology stardom equally capable? Even a cursory glace at table 4, which outlines the main developments to-date in the fields comprising nanoscience and nanotechnology, would indicate that the answer is 'no'.

Table 4: A Brief History of Key Developments in the Nano[6]

Date	Key Development	Key People/Institution(s)	Institution of Ph.D.	Institution of Event/Discovery	Country of Event/Discovery
1931	The Electron Microscope	Developed by Max Knoll and Ernst Ruska at Siemens	Max Knoll and Ernst Ruska: Technical Universities of Munich and Berlin	Siemens	Germany
1959	The basic underlying idea	Richard P. Feynman's "There's Plenty of Room at the Bottom" presentation	Princeton U	Caltech	U.S.
1968	Molecular Beam Epitaxy to deposit single atomic layers on a surface	Developed at Bell Laboratories by John R. Arthur Jr. and Alfred Y. Cho	J.R. Arthur: A.Y. Cho: U of Illinois	Bell Labs	U.S.
1974	Coining of the term "nanotechnology"	Norio Taniguchi		Tokyo Science University	Japan
1981	The Scanning Tunneling Microscope	Developed by Gerd Binnig and Heinrich Rohrer at IBM	Gerd Binnig: Goethe U, Frankfurt; Heinrich Rohrer: Swiss Federal Institute of Technology, Zurich	Gerd Binnig: IBM's Almaden Research Center/Stanford; Heinrich Rorer: IBM Zurich Research Lab	U.S./Switzerland
1985	"Buckeyballs"	Discovered by Richard Smalley and colleagues for which they received a Nobel Prize in 1996	Princeton U	Rice U	U.S.
1986	The Atomic Force	Developed by Gerd	Gerd	IBM's Almaden Research	U.S.

[6] Based on Timeline developed by Stix (2002).

	Microscope	Binnig, Calvin Quate and Christoph Gerber	Binnig: Goethe U, Frankfurt; Calvin Quate: Stanford	Center/Stanford	
1989	Manipulation at the atomic scale	IBM writes the letters of the company name using individual xenon atoms on a copper surface	Don Eigler: UC San Diego	IBM's Almaden Research Center	U.S.
1991	The first doctoral dissertation awarded with the word "nano" in the title	K. Eric Drexler from MIT "Molecular Machinery and Manufacturing with Applications to Computation (Nanotechnology)"	MIT	MIT	U.S.
1999	The Molecular Switch	Developed by James Tour and Mark Reed	James Tour: Purdue U; Mark Reed: Syracuse U	James Tour: Rice U; Mark Reed: Yale U	U.S.

Table 4 shows that the vast majority of these key developments have taken place in the USA. Moreover, no emerging or developing country features in the above table. Then, what's in nanoscience or nanotechnology (NST) for these regions? Niosi and Reid (2007) point out that because of its predicted broad impact on society, governments of both developed and developing countries must investigate what the likely applications will be, and whether/how to best facilitate their evolution. They affirm that 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. Latecomer countries can build market capabilities in this area, but only with high levels of government support in terms of training, funding and infrastructure. In line with this hypothesis, table 5 shows that over $4 billion dollars of world-wide government money alone were pumped into the nanotechnology sector during 2008 and the U.S. National Science Foundation (NSF) predicts that the total market for nanotech products and services will reach $1 trillion by the year 2015.

Table 5: Government R&D spending in Nanotechnology, select leading countries

Country	Population 2009 mid-year[d] ('000)	Gov spending in nanotech R&D 2007-2012 stats (US$mill)	Sig Coop Agreements with other countries	Gov Initiatives	Industry Roadmaps
USA[a]	307,212	2,100 for 2012[e] (began 2000)	Yes - numerous	NNI (National Nanotechnology Initiative) (2001)	Yes "NNI Strategic Plan, Dec 2007"
Japan[a]	127,079	890 in 2009 (began 2001); MEXT programme annually investing 600[e]	No	3rd Science & Technology Basic Plan (2006)	Yes "Nanotechnology Business Creation Initiative"
Germany[a,f]	82,330	547 in 2009 (began investing in 1998)	Yes – with EU and ISO members	Nano-Initiative Action Plan 2010 (2006 started planning for 2008-2013)	BMBF Forschungsunion and BMWi branch dialogues
France[e]	65,821	640 during 2008-2012	Yes – with other EU members	Nano 2012 Programme	Yes
China[b]	1,338,613	240 during 2003-2007; 200 during 2008-2009	No	National Center for NanoScience and Technology (2002)	Yes
Russia[a]	140,041	100 in 2009 (began 2007); 890 to be invested between 2008 and 2011[e]	Yes - EU	Strategy for NanoIndustry Development (since 2007)	Yes "Developing of nanoindustry infrastructure in Russian Federation 2008-2010"
India[c]	1,156,898	15 million for Smart Materials development and DST funding is 10 million from 2007-2010	No	Department of Science and Technology has launched a National Nanotechnology Program (2007)	No
Brazil[c]	198,739	35 between 2004-2007; approximately 6 in 2009[e]	Yes - Argentina	National Program of Nanotechnology (2007) consolidating other efforts since 2000 (The Millenium Institutes and other co-op networks involving > 40 institutes) and Rede BrasilNano	No

[a] OECD Working Party on Nanotechnology, Committee for Scientific and Technological Policy, Inventory of National Science, Technology and Innovation Policies for Nanotechnology, 2008.
[b] Chen Wang, Presentation of the National Center for NanoScience and Technology, Beijing,China
[c] Niosi and Reid, 2007, Kay and Shapira, 2009
[d] U.S. Census Bureau, International Database (www.census.gov/ipc/www/idb/country)
[e] OECD 2012 Working Party on Nanotechnology Report
[f] Germany and France were the only European countries highlighted here, but it should be noted that 3.5 billion Euros are to be invested in the Framework Programme 7 between 2007 and 2013 as noted in the OECD 2012 Working Party Report on Nanotechnology.

Though government investment is not the sole determinant, such international disparities are bound to have an impact on the construction of scientific and technological capabilities. Thus, in order to have an idea of the magnitudes of the present capability gaps between developed and developing countries, we examine the scientific publications and patent applications (related to nanotechnology) issuing from 'High income', 'Middle income' and 'Low income' countries (as classified by the World Bank). In the first group there are 65 countries (if we include Taiwan), in the second 101 countries and in the third 43 countries[7,8]. In the rest of this chapter, high income countries will be referred to as HIC and the low and middle income countries as MIC (since low income countries have only incremental capabilities in nanotechnology). Our methodology for extracting publications and patents related to nanotechnology are given in the appendix in sections A1 and A2. We now turn to our results.

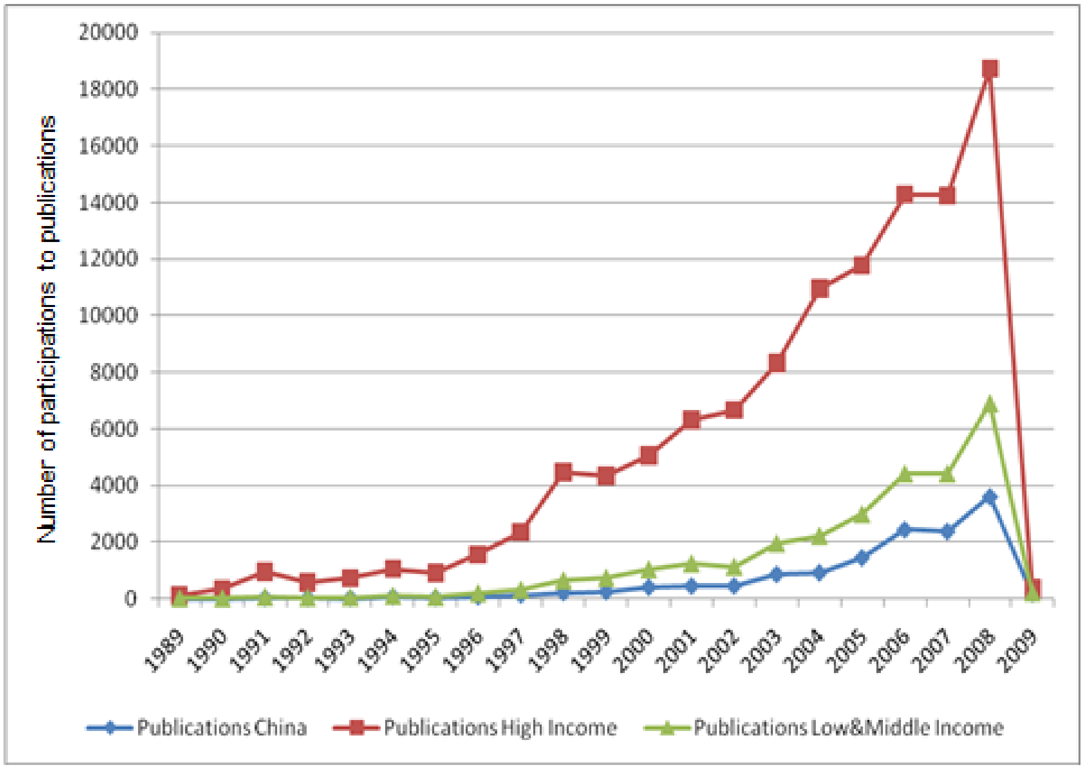
2.1 Outcomes in terms of publications

Trends in scientific publications of the high-income countries vis-à-vis the middle and low income countries are presented in Figure 1 and Table 6. A country was attributed a participation in a publication, if one of the authors affirmed an address in the country concerned.

[7] "Economies are divided according to 2007 GNI per capita, calculated using the World Bank Atlas method. The groups are: low income, $935 or less; lower middle income, $936 - $3,705; upper middle income, $3,706 - $11,455; and high income, $11,456 or more" http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/0,,contentMDK:20421402~pagePK:64133150~piPK:64133175~theSitePK:239419,00.html#High_income

[8] .http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/0,,contentMDK:20421402~pagePK:64133150~piPK:64133175~theSitePK:239419,00.html#High_income

Figure 1: Number of participations to publications



****Please note that figures for 2009 were incomplete at the time of the extraction of data and do not indicate a reduction in the pace of publications. Source: Web of Science – see appendix for methodology. A country was attributed a participation in a publication, if one of the authors affirmed an address in the country concerned.*

Table 6 reveals that about more than one-third of the HIC and more than one-half of the MIC are actually missing the ‘nanotechnology’ train. However, in terms of the absolute number of countries, there are almost as many countries among the MIC that have at least 20 publications in nanotechnology. Moreover, while the gap between HIC and MIC is self-evident, in both sets of countries, universities publish much more than non-university organizations. The thrust of the lower and middle income countries is essentially coming from China, which alone contains more than 50% of the institutions active in nanotechnology.

Table 6: Positioning in terms of scientific publications

Publications from the Web of Science (WOS)	High income countries (65 countries)	Low and Middle income countries with China (144 countries)	
Number of countries with 0 publications in WOS in nano	23, (35,38%)	78, (54,17%)	
Number of countries with at least 1 publications in WOS in nano	42, (64,62%)	66, (45,83%)	
Number of countries with at least 20 publications (i.e. >=20) in WOS in nano	33, (50,77%)	32, (22,22%)	
	High income countries (42 countries)	Low and Middle income countries with China (66 countries)	Contribution of China to low and middle income countries (absolute) percentage
Number of participations to publications in nano	114069	28717	(13801) 48,06%
Number of organizations involved in publications	91257 univ	22176 univ	(11612) 52,36%
	22812 not univ	6541 not univ	(2189) 33,47%
Number of participations to articles in top 10 journals including scientific proceedings	87443	22445	(11329) 50,47%
Participation to Individual publications	23987	6969	(13801) 48,11%

** A country was attributed a participation in a publication, if one of the authors affirmed an address in the country concerned.*

The role of China continues to be impressive when we examine the 'impact' of scientific publications in terms of citations. From the 70321 articles corresponding to the 114069 addresses emanating from the 42 HIC, 77.03% were cited at least once. From the 19066 articles corresponding to 28717 addresses emanating from the 66 MIC 66.73% were cited at least once. However, 46.1% of these citations of MIC correspond to publications authored by China-based scientists.

In terms of productivity, among the top 15 most productive authors, 10 authors have a primary or a secondary affiliation to a Chinese organization (see tables A3 and A4 in the appendix). Out of the 15 most productive authors in MIC only one does not have a Chinese affiliation. When we examine the publications issuing from organizations in MIC countries, among the top 30, besides those from China, there are also sme from emerging countries such as Brazil, India, Mexico, Ukraine, Iran and Russia (see table A5 in the appendix)[9].

The main results on catching-up in terms of accumulation of stocks of scientific publications can now be spelled out as follows. There is a clear gap between HIC and MIC in terms of number of countries involved, number of organizations involved, number of publications, number of citations etc. And within the MIC there is a clear gap between China and the other developing countries according to every indicator. Indeed in terms of scientific capabilities in nanotechnology, China resembles more the HIC model than MIC. There is no evidence of the gap becoming less. Russia, India and Brazil are among the emerging countries that stand out the most in the absence of China, followed by Mexico and Iran in the low and middle income countries group. For star scientists of China, an affiliation in a developed country (mainly USA) is crucial.

There are many factors responsible for the gap in terms of the quantity and the focus of publications between HIC and MIC. It is not only explained by a lack of theoretical knowledge and the lack of equipment, but also by the lack of access to new material and to specialized work forces. For instance, high income countries are the only ones to publish much on micro and nanoelectronics because these fields need high end equipment, high quality materials, specialized workers and up-to-date knowledge. On the other hand, the good news is that pretty much all countries are publishing in the area of biochips. This is explained by the fact that this domain needs only a minimum of equipment, materials and skilled work force.

2.2 Outcomes in terms of patent applications

[9] This should be considered only as a very approximate indicator, because organizations appear under different appellations in the corpus and it is impossible to homogenize the names for all organizations. For example the CNRS of France can be found as one of the following in the corpus : CNRS, CNRS 196, CNRS 5129, CNRS 5628, CNRS 8520, CNRS BELLEVUE, CNRS CPE, CNRS ENSCM UMI, CNRS FRE 2068, CNRS Grenoble, CNRS InESS, CNRS LEMD, CNRS LPN, CNRS LTM, CNRS LTM CEA LETI Minatec, CNRS ONERA, CNRS Paris 6, CNRS Rhodia, CNRS St Gobain, CNRS St Gobain Surface Verre & Interfaces, CNRS Thales, CNRS UM2 ENSCM UMI, CNRS UMR 6174, CNRS UMR 7584, CNRS UMR 7633, CNRS UPRES A 7016, CNRS UPS INSA, CNRS URA 2090, CNRS&INPG)

In terms of patent applications the retard between HIC and the rest of the world is more marked, as indicated in table 7. While about 50% of the HIC are participating, less than 10% of the MIC have even 1 patent in USPTO or EPO. Indeed, as Table 7 clearly points out 98.96% of the patent applications in USPTO and 98.8% in EPO emanate from the HIC. This could be because the number of organizations participating in the patent applications is much higher. Furthermore, the efficiency of the transformation of scientific publications into patents is much lower. This phenomenon is perhaps attenuated by patent applications in local patent offices in the MIC, but we cannot confirm this as such observations are not contained in our corpus. While 3.66 participations to a scientific publications yield a USPTO for HIC, nearly 88.36 participations are required in a MIC for the same. This finding holds similarly for the EPO patents.

Table 7: Participation in Nanotechnology Revolution in terms of Patent Applications

	High income countries (65 countries)		Low and Middle income countries (144countries)		China	
	USPTO	EPO	USPTO	EPO	USPTO	EPO
Number of countries with at least 1 patent in nano in USPTO or EPO	33	35	13	13		
Number of countries with at least 5 patents in nano in USPTO or EPO	25	27	6	8		
Stock of patents	31201	18630	325	225	217	84
Competitive position in terms of total stock of patents in USPTO or EPO	98,958%	98,792%	1.042%	1.208%	0,695%	0,451%
No. of organizations involved in patent applications	5372	4944	268	671	33	57
No. of organizations involved in patent application in at least 3 different years	765	868	26	69	2	4
Participation to Publications/ Patents ratio	3,66	6,12	88,36	127,63	63,60	164,30

In order to understand the nature of the knowledge base in nanotechnology of HIC and MIC more, we apply three basic patent-based indicators: (i) internal structure of patent stocks;

(ii) competitive position in a technology niche; (iii) areas of comparative advantage. These are constructed using the fact that a patent application can be affiliated to more than one technology class. For instance a patent observation in our corpus may be affiliated to Y02 as well as Y04. However, the ECLA nano-subclasses are not marked in all the USPTO patent applications and similarly the nano-class index '977' of USPTO is not presented in the EPO patents[10].

We define the technology focus of a region on any particular technology as follows:

$$\text{Focus of region on technology x} = \frac{\text{number of patents of region affiliated to technology class x}}{\text{Total number of affiliations of region to all technologies}}$$

Table 8 gives the internal structure of patent affiliations such that each column shows the percentage of affiliations to a particular technology of a region according to the above formula, adding up to 100%. According to the image constructed by the USPTO patents, the technology focus of HIC is mainly on technology class 'Y01N0004' i.e. the nanotechnology for information processing, storage and transmission according, while that of the rest of the world is on 'Y01N0006' or Nanotechnology for materials and surface science. However, according to the EPO image, the technology focus is the same world-wide, namely on new materials. Moreover, if we consider the first two most important classes of technology focus, according to Table 8, in the USPTO patents, the two most coveted technologies of HIC are new materials and information processing. On the other hand, the EPO reveals an interest of MIC in nanobiotechnology. China has the same technology focus as HIC.

Table 8: Internal Structure of patent affiliations

	High income countries (67 countries)		**China**		**Low and Middle income countries without China (143 countries)**	
	USPTO	**EPO**	**USPTO**	**EPO**	**USPTO**	**EPO**
Y01N0002, *Nanobiotechnology*	7.45%	12.43%	2.81%	19.32%	20.21%	19.48%

[10] Therefore, the stock of patents in nanotechnology in USPTO and EPO can be greater than or less than the number of technology affiliations indicated in table A1 in the appendix.

Y01N0004, *Nanotechnology for information processing, storage and transmission*	**31.54%**	24.57%	33.71%	14.77%	25.53%	18.18%
Y01N0006, *Nanotechnology for materials and surface science*	25.55%	**32.42%**	**51.12%**	**53.41%**	**31.91%**	**38.31%**
Y01N0008, *Nanotechnology for interacting, sensing or actuating*	10.77%	11.00%	4.49%	7.95%	7.45%	12.34%
Y01N0010, *Nanooptics*	14.27%	13.88%	7.30%	2.27%	12.77%	8.44%
Y01N0012, *Nanomagnetics*	10.42%	5.70%	0.56%	2.27%	2.13%	3.25%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Next we turn to the competitive positions of technology regions in order to try to identify in which technology niches the retard is the least or the most. We define the indicator as follows.

$$\text{Competitive position of region in technology x} = \frac{\text{number of patents of region affiliated to technology class x}}{\text{Total number of patents of all regions affiliated to technology class x}}$$

Arranging the patent affiliations according to the above formula gives us Table 9, with each row showing the percentage of affiliations to a particular technology such that the total for each row of USPTO and EPO patents adds to 100%. Here we see that, at most, 2% of the patent affiliations reside with MIC in any technology. As such, there is real ‘catching-up’ work yet to be done in terms of technological capabilities.

Table 9: Competitive Position in the different classes of nanotechnology patents

	High income countries (67 countries)		**China**		**Low and Middle income countries without China (143 countries)**	
	USPTO	**EPO**	**USPTO**	**EPO**	**USPTO**	**EPO**
Competitive index in terms of affliations to any of the nanotech classes	99.18%	98.90%	0.54%	0.40%	0.28%	0.70%
Y01N0002, *Nanobiotechnology*	99.03%	98.29%	0.20%	0.62%	0.77%	1.09%
Y01N0004, *Nanotechnology for information processing, storage and transmission*	99.19%	99.24%	0.58%	0.24%	0.23%	0.52%

Y01N0006, *Nanotechnology for materials and surface science*	98.57%	98.52%	1.03%	0.66%	0.35%	0.83%
Y01N0008, *Nanotechnology for interacting, sensing or actuating*	99.58%	98.92%	0.23%	0.29%	0.20%	0.79%
Y01N0010, *Nanooptics*	99.47%	99.50%	0.28%	0.07%	0.26%	0.43%
Y01N0012, *Nanomagnetics*	99.91%	99.44%	0.03%	0.16%	0.06%	0.40%

Using the above two indicators it is easy to identify the comparative advantage of any region in a technology by dividing the competitive position of a region in a technology class by its competitive position in all classes. Standard economics theory has pointed out that it is in the short term interest of a country to focus its efforts on the niche in which it has a comparative advantage; but to minimize long term risks, it should not neglect the niches in which it has a comparative disadvantage. According to the USPTO image, the comparative disadvantage of HIC, lies in nanomaterials, while according to the EPO patent image, the comparative disadvantage of HIC is in nanobiotechnology. In all other areas it has a comparative advantage. This indicates that HIC are likely to concentrate on maintaining their technology lead in *Nanotechnology for information processing, storage and transmission, Nanotechnology for interacting, sensing or actuating, Nanooptics, Nanomagnetics.* For China, according to both images, the maximum comparative advantage lies in *nanomaterials*. While according to both images, the comparative advantage of MIC lies in *nanobiotechnology* directing it as the area on which MIC should focus, in the immediate future, while catching up in the other fields.

3. Discussion of results

Given the positioning of high income countries and low and middle income countries in terms of scientific and technological capabilities as shown in the preceding sections, how should emerging countries which belong to the second group (i.e. MIC) invest and support development of the nanosciences and resulting nanotechnologies? Keeping in mind that their strategies will be formulated as a function of this diversity and their present national needs and no dominant clear-cut strategy can be spelled out as a 'magic pill' for catching up, three possible types of strategies seem plausible.

Type 1 strategy for countries with strong scientific, technological and financial capabilities– jump onto building platforms: For countries with solid public policy and/or strong venture capital infrastructure in place, a broad-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, can be effective. Venture capital is not well developed outside of North America, but in these countries a lack of venture capital is often compensated by heavy public investment. Still, type 1 strategy is not possible for most middle and low income countries (i.e. including emerging countries) as the necessary capabilities do not exist and cannot be built quickly.

Type 2 strategy for countries with strong scientific and technological capabilities but weak financial capabilities – identify and focus on niches: For countries with limited financial resources, a more focused approach (either at the technology level and/or at the application level) may be warranted, based largely on needs of the available end market. A major reason that some niche applications develop faster than others is related to the fact that what drives uptake is whether a product or service serves a real and perceivable need in the marketplace – this can partly explain why consumer goods such as stain-proof pants and makeup that truly diminishes the appearance of wrinkles were two of the first major products to achieve success in the nanospace.

Consistently, a key finding in new product development success factor studies has been the need for a *unique, product advantage in the eyes of the customer* (Balachandra & Friar, 1997; Cooper, 1979; Lilien & Yoon, 1989; Mahajan & Wind 1992; Maidique & Zirger, 1984; Rubenstein *et al.*, 1976). Given this, companies and countries that don't have the infrastructure to build the type of broad-based approaches mentioned above should perhaps drive prioritization using their end-user markets for their initial cues in terms of what major end-market needs exist and also, in terms of the skills and core competencies that already exist within the populace that can be built upon.

Type 3 strategy for countries with weak financial capabilities and which need to build scientific and technological capabilities – Go for the low hanging fruit: This said, however, many of the original 'low hanging fruit' mentioned in Table 1 have already been plucked by firms and countries that had the skills initially to be involved at the outset. Further along this line of thinking given the issue of capitalizing on diffusion of ideas and capabilities vs de nouveau creation, for developing countries with limited resources, a focus on current low hanging fruits means going after second-tier type research activities. For example, generics or similars, contract research and manufacturing, services, information provision or integration with extant products, may be a good way for such countries to enter the picture and develop a revenue stream as well as solid capabilities from which to grow. In fact, the overall revenues from such types of companies taken on the whole can often override the blockbuster revenue streams of only a few companies that manage to secure the golden breakthrough product, and it is a whole lot less risky. This is not to say that breakthroughs are not important, but when resources are tight, sometimes operating at the second level can be a much better overall strategy.

4. Concluding remarks

In 2002, MIT's Technology Review came out with an interesting list of the "Nanotube Ten to Watch". There are 7 American, 2 Japanese and one South Korean company in this list. Given that most companies were operating in the materials space at the time, this seemed a logical place to look for some of the forerunners in the field. Their list is provided below in Table 10. Interestingly, these players still, to a large extent, lead the field in terms of publications and overall impact, which shows that the leading countries are still at the head of the pack.

Table 10: Nanotube Ten to Watch

Carbon Nanotechnologies Houston, TX	Richard Smalley/Rice U	Produce and sell commercial-scale nanotubes
Covalent Materials Emeryville, CA	UC Berkeley physicists Alex Zettl and Marvin Cohen	Design and synthesize novel nanotubes and nanowires
IBM Research Yorktown Heights, NY	Team led by Phaedon Avouris	Build integrated circuits out of nanotubes
Bose Electronics Japan	Collaboration with Yahachi Saito from Mie University	Develop nanotube-based field emission devices for outdoor displays
Nantero Woburn, MA	Founded on technology licensed from Harvard University	Fabricate nonvolatile electronic memory using nanotubes
Molecular Nanosystems Palo Alto, CA	Cofounded by Stanford research Hongjie Dai; technology for growing arrays of nanotubes	Use proprietary synthesis technology to make arrays of sensors and field emission devices
Motorola Research Labs Tempe, AZ	Research team experienced in developing field emission displays	Research on flat-panel displays using nanotubes
Nanosys Palo Alto, CA	Licensing agreement with Harvard for nanowire technology developed by Charles Lieber (approximately 15 patents)	Build up a portfolio of nanodots, nanotubes, and nanowires for optoelectronics and nanoelectronics
IC Research	Team headed by Sumio Iijima,	Develop nanotubes as electrodes

Japan	discoverer of nanotubes	for use in fuel cells
Samsung South Korea	One of the largest corporate research groups dedicated to developing nanotube displays	Commercialize flat-screen TVs based on field emission devices using carbon nanotubes

Source: technologyreview.com, March 2002

An examination of their evolution reveals eight features that have stood out as being crucial to their success.

(i) patent ownership;

(ii) visionary leadership often from a scientist coming from academia;

(iii) strong revenue and science base/deep pockets with good government contacts and an ability to develop radical technologies quickly (whether internally because of extant expertise or through acquisition) if an incumbent firm moving into new territory;

(iv) alliances with both universities and leading companies, particularly important for newcomers;

(v) ability to attract capital and not run out of money for newcomers;

(vi) strong distribution and known brand to reach end customers;

(vii) economies of scale in production (ability to achieve scale up).

In other words, firms that are likely to make inroads into NST must start with the classic triangle: 'established technological capabilities', 'managerial vision' and 'deep pockets'. Thereafter, connections with both knowledge creators – like universities and money lenders helps to maintain the tempo of research. However, they cannot appropriate innovation rent unless they have manufacturing capabilities and penetration to ensure brand loyalty. Stepping back to reflect on the features of the 'national system of innovation' that contributed to the success of the top 10 companies identified by MIT in 2002 we can infer the following conditions as being favorable to the development of the NST sector :

(i) **State support for the construction of scientific capabilities:** Public policy has to devote a high level of funding and support to the science base as the capital costs are fairly high to reach a certain threshold of capability. For example, at the low end, it could cost in excess of $1 million just to outfit one lab with a few key pieces of equipment at a given university – even the cost of a SEM (Scanning Electron Microscope) at the end of 2009 was approximately $150,000 U.S. The country must have a strong science base with strength in both publication and patenting activity. Any State wanting to promote NST must therefore start with investment towards the building of scientific capabilities.

(ii) **Private sector capital to support NST:** Private sources of capital, say venture capital must be available and to attract venture capital, entrant firms must have clear ideas of exit strategies for capital (potential for IPO or potential for buy-out)

(iii) **Installation of equipment and other costly infrastructure:** Basic infrastructure in the form of equipment and buildings that are essential to the carrying out of research and creation of new technology need to be created.

(iv) **Building up of human capital:** Researchers have to be trained to deal with the complexity and number of different contributing sciences and antecedent technologies (interfacing and scale-up being 2 major challenges)

(v) **Connections with the rest of the world:** There must be synergetic creation of new knowledge and technology with the rest of the world. The geographic dispersion of capabilities between countries must be lowered either through support to encourage co-authorship, availability of ideas through access to knowledge of ongoing patenting activity worldwide and university alliances and conference attendance or hiring of expertise from abroad, encouraging international investment and so-on.

(vi) **A large domestic market:** A large size market with disposable income will be useful for final commercialization of new products.

To conclude, there are definitely windows of opportunity for countries just entering the nanogame, however, given the intensity of the technology race and the large investments made by many developed as well as developing countries, the terrain has evolved tremendously over the last decade. Under such rapidly changing market conditions, the competitive advantages that countries will build will not only depend on how much they invest but how well they leverage existing capabilities to their advantage. In what follows in the remainder of the book, we will thus examine the paths being carved by a variety of countries, including both developed regions like the USA and the EU as well as emerging economies like China, India, Brazil and Mexico in the nanosciences and nanotechnology fields. Extending the idea of Teece's (1998) dynamic capabilities with respect to firms onto countries, we will study how the selected countries have identified and seized new opportunities, reconfigured, created and protected knowledge and other complementary assets, competencies and technologies to attempt to achieve sustainable competitive advantage in NST. This will in turn enable the identification of common as well as specific factors that have contributed to the impact of public and private investment to further revise firm strategy and public policy to increase the probability of developing strong market capabilities in nanotechnology.

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Appendix

A 1: Methodology used to measure publications

The corpus of scientific publications was constructed using the database 'ISI Web of Knowledge' supplied by Thomson Reuters, and in particular the section 'Web of Science'

(WOS) and within this the 'SCI Expanded' or Science Citation Index Expanded. This is an international reference in bibliometrics covering over 8500 journals in various disciplines indexed by their impact factors, and offering access to a variety of tools for 'search' by author, type of document, language, country, organization, year of publication, source and theme.

The JCR or Journal Citations Report of the WOS is an instrument that analyses SCI Expanded. For instance JCR considers 158 scientific domains and to each journal it attributes one or more of these scientific domains. Thus, we first identified 46 journals as being affiliated to the category "Nanoscience & Nanotechnology" by the JCR. Then we extracted records of publications between 1989-2009 in these 46 journals by formulating our research equation as the union of the titles of the 46 journals and applying it to the field 'SO' or journal source[11] of WOS. This yielded a corpus of 88194 articles in English for the period 1989-2009, for we left out 20 articles written in languages other than English (18 French, 1 Welsh and 1 Rumanian). By delineating our corpus in this fashion, like Loet Leydesdorff (2008), we opted to accommodate the possibility of having 'excess silence' rather than 'excess noise'.

In a second step, some more measures were taken to clean the data. Only articles and conference proceedings that had been published in one of the 46 journals was considered. This brought down the corpus observations from 88194 to 81259 articles. All articles without addresses of author also were removed, reducing the corpus to 73060 articles. Then we also removed 224 articles where authors had multi-country affiliations.

[11] *SO="ACS Nano" OR SO="BIOMEDICAL MICRODEVICES" OR SO="Biomicrofluidics" OR SO="BIOSENSORS & BIOELECTRONICS" OR SO="Current Nanoscience" OR SO="FULLERENES NANOTUBES AND CARBON NANOSTRUCTURES" OR SO="IEE Proceedings-Nanobiotechnology" OR SO="IEEE TRANSACTIONS ON NANOBIOSCIENCE" OR SO="IEEE TRANSACTIONS ON NANOTECHNOLOGY" OR SO="IET Nanobiotechnology" OR SO="International Journal of Nanomedicine" OR SO="International Journal of Nanotechnology" OR SO="Journal of Computational and Theoretical Nanoscience" OR SO="Journal of Experimental Nanoscience" OR SO="JOURNAL OF MICROLITHOGRAPHY MICROFABRICATION AND MICROSYSTEMS" OR SO="JOURNAL OF MICROMECHANICS AND MICROENGINEERING" OR SO="Journal of Micro-Nanolithography MEMS and MOEMS" OR SO="Journal of Nanoelectronics and Optoelectronics" OR SO="JOURNAL OF NANOPARTICLE RESEARCH" OR SO="JOURNAL OF NANOSCIENCE AND NANOTECHNOLOGY" OR SO="JOURNAL OF VACUUM SCIENCE & TECHNOLOGY B" OR SO="LAB ON A CHIP" OR SO="MATERIALS SCIENCE AND ENGINEERING A-STRUCTURAL MATERIALS PROPERTIES MICROST" OR SO="MICRO" OR SO="Micro & Nano Letters" OR SO="MICROELECTRONIC ENGINEERING" OR SO="MICROELECTRONICS JOURNAL" OR SO="MICROELECTRONICS RELIABILITY" OR SO="Microfluidics and Nanofluidics" OR SO="MICROPOROUS AND MESOPOROUS MATERIALS" OR SO="MICROSCALE THERMOPHYSICAL ENGINEERING" OR SO="MICROSYSTEM TECHNOLOGIES-MICRO-AND NANOSYSTEMS-INFORMATION STORAGE AND PROC" OR SO="NANO LETTERS" OR SO="Nano Today" OR SO="Nanoscale and Microscale Thermophysical Engineering" OR SO="Nanoscale Research Letters" OR SO="NANOTECHNOLOGY" OR SO="Nature Nanotechnology" OR SO="Photonics and Nanostructures-Fundamentals and Applications" OR SO="PHYSICA E-LOW-DIMENSIONAL SYSTEMS & NANOSTRUCTURES" OR SO="Plasmonics" OR SO="PRECISION ENGINEERING-JOURNAL OF THE INTERNATIONAL SOCIETIES FOR PRECISION" OR SO="REVIEWS ON ADVANCED MATERIALS SCIENCE" OR SO="SCRIPTA MATERIALIA" OR SO="Small" OR SO="Synthesis and Reactivity in Inorganic Metal-Organic and Nano-Metal Chemistr"*

In a third step, country affiliations were checked and homogenized. Taiwan is absent in the present World Bank list having been assimilated with China, even though according to earlier list, China was among the ‘lower middle-income’ countries while Taiwan was placed in the set of ‘high income’ countries. To counter this we have considered Taiwan as a high-income country. Therefore, in our list there are 65 high income countries including Taiwan. East Germany and West Germany are considered together as one high income country as data for earlier years is clubbed under two countries and for later years under one. There is a similar problem for Yugoslavia which split into several countries. Only Slovenia (high income) and Serbia (upper middle income) had publications in nano and we consider all publications of Slovenia also under Serbia. Given the small number of publications of both, the results do not change significantly either way. A number of countries were spelt differently or written differently (eg. Russia and Russian Federation) and these were homogenized.

A country was attributed a participation in a publication, if one of the authors affirmed an address in the country concerned. We distinguished between universities and non-universities because while the names of universities usually remain unchanged over time, the names of laboratories (both private and public) often evolve over time, making traceability near impossible.

A2: Methodology used to extract patents

For reasons of sheer accessibility we restricted ourselves to the international database USPTO and EPO furnished by the patent offices of the USA and Europe respectively, which are extractable from the package “Micropatent PatSearch® FullText” distributed by Thompson Reuters.

In order to enable a better identification of patent applications related to nanotechnology and assess their quality, in 2003 the European Patent Office (EPO) set up a ‘Nanotechnology Working Group’. One of their actions was to introduce a ‘Y01N’ tag to all patents (all previously granted or applied for and present patent applications) involving nanotechnology as part of the EPO system of classification called ECLA. The ‘nanotechnology’ patents were further sub-divided into six categories covering nanobiotechnology, nanotechnology for information processing, storage and transmission, nanotechnology for materials and surface science, nanotechnology for interacting, sensing or actuating, nanooptics, and finally, nanomagnetics[12]. In the USPTO, ‘977’ is a class signifying affiliation to nanotechnology. Extracting patents with ECLA affiliation ‘Y01N’ and USPTO affiliation ‘977” yielded 56437 patents applied for or granted in the USPTO; and 4298 granted patents and 22898 patent applications deposited in the EPO, for the period 1983-2008[13].

[12] These are Y01N0002, Y01N0004, Y01N0006, Y01N0008, Y01N0010 and Y01N0012 for the six fields mentioned respectively.

[13] We chose 1983 as starting year because the number of ECLA patents exceeded 100 for the first time.

In a second round, we cleaned the corpus to eliminate double counting, by taking out all patents of the same family[14] which had a common abstract, priority country i.e. country of first deposition and priority date i.e. date for first deposition. Then we took out all observations where the address of assignee was not given, the patent application having been deposited in the name(s) of the inventor(s). We also took out patent applications which had a region or a patent office rather than a country as the 'country of priority' (e.g. we took out observations that mentioned EPO as priority country). This gave us a final corpus of 33790 patent applications with 24679 assignees in the USPTO, with 984 co-depositions (with more than one assignee). The EPO contained 27163 patent observations with 29163 applicants, of which 1993 depositions had multiple assignees.

Table A3: The 15 most productive authors in nanotechnology worldwide

Participations	Author	1st affiliation	2nd affiliation
238	INOUE, A	Japan	Peoples R China
226	LEE, JH	SOUTH KOREA	USA
221	WANG, Y	Peoples R China	USA
209	LEE, S	SOUTH KOREA	USA
195	CHEN, Y	Peoples R China	FRANCE
186	ZHANG, Y	Peoples R China	USA
183	WANG, J	Peoples R China	USA
175	Liu, Y	Peoples R China	USA
175	KIM, J	SOUTH KOREA	USA
172	LI, Y	Peoples R China	USA
160	ZHANG, J	Peoples R China	USA
155	LEE, J	SOUTH KOREA	USA

[14] A patent application is first deposited in a country and then it can be deposited in the patent office of another country. Then the two patents will be indicated as belonging to the same family.

149	Kim, JH	SOUTH KOREA	USA
145	Liu, J	USA	Peoples R China
141	WANG, L	Peoples R China	USA

Table A4: The 15 most productive authors in low and middle income countries including China

Participations	Author	1st affiliation	2nd affiliation
135	WANG, Y	Peoples R China	USA
112	WANG, J	Peoples R China	USA
110	ZHANG, Y	Peoples R China	USA
110	Liu, Y	Peoples R China	USA
109	Wang, ZG	Peoples R China	JAPAN
107	Zhang, J	Peoples R China	USA
107	Li, Y	Peoples R China	USA
92	WANG, L	Peoples R China	USA
79	Zhang, L	Peoples R China	USA
77	Liu, J	USA	Peoples R China
75	Zhang, H	Peoples R China	USA
75	Hu, ZQ	Peoples R China	Australia
75	Chen, Y	Peoples R China	FRANCE
74	Chen, J	Peoples R China	USA
71	Valiev, RZ	RUSSIA	USA

Table A5: The 30 most productive organizations in Low and Middle Income Countries including China

Occ	ORGANISME	PAYS
2620	CHINESE ACAD SCI	Peoples R China
742	RUSSIAN ACAD SCI	RUSSIA
739	INDIAN INST TECHNOL	INDIA
541	SHANGHAI JIAO TONG UNIV	Peoples R China
461	TSING HUA UNIV	Peoples R China
417	HARBIN INST TECHNOL	Peoples R China
391	NANJING UNIV	Peoples R China
380	JILIN UNIV	Peoples R China
367	Peking Univ	Peoples R China
327	ZHEJIANG UNIV	Peoples R China
297	FUDAN UNIV	Peoples R China
288	UNIV SCI & TECHNOL CHINA	Peoples R China
252	INDIAN INST SCI	INDIA
245	City Univ Hong_Kong	Peoples R China
232	RAS	Russia
232	POLISH ACAD SCI	POLAND
231	XIAN JIAOTONG UNIV	Peoples R China
213	UNIV SAO PAULO	BRAZIL
189	BHABHA ATOM RES CTR	INDIA
186	Hong_ Kong Univ Sci & Technol	Peoples R China
185	UNIV SCI & TECHNOL BEIJING	Peoples R China
184	UNIV NACL AUTONOMA MEXICO	MEXICO

181	**WUHAN UNIV**	**Peoples R China**
173	**NATL ACAD SCI UKRAINE**	**UKRAINE**
173	**DALIAN UNIV TECHNOL**	**Peoples R China**
161	**Hong_ Kong Polytech Univ**	**Peoples R China**
160	**SHANDONG UNIV**	**Peoples R China**
147	**UNIV ESTADUAL CAMPINAS**	**BRAZIL**
145	**ACAD SINICA**	**Peoples R China**
140	**Univ Hong_Kong**	**Peoples R China**
140	**Sharif Univ Technol**	**Iran**