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Network Building in the Innovation Journey: How Chinese Science Institutes Jump on the Nanotech Bandwagon

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Abstract This article examines the process in which Chinese science actors undertook nanotechnology research as an innovation journey. In this journey, Chinese science actors sought domestic and overseas networks to overcome resource and infrastructural constraints. To analyze salient issues at different stages of this journey, I draw on an established framework from the literature of technology innovation. Thus, the "Chinese nanotech innovation journey" is divided into five temporal stages. My findings suggest that network resources are able to compensate for an inadequate infrastructure in significant ways. Yet, the utility of networks depended on overcoming communication difficulties and trust barriers and the adoption of a learning-by-doing attitude. This research combines quantitative data and ethnographic fieldwork. In the conclusion, I discuss the broader implications of this research and directions for further studies.

Keywords Nanotechnology · technology and innovation management · knowledge networks and management · Chinese high-tech organizations

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1 Introduction

Researchers have agreed that network building is an important part of the innovation process. According to Andrew Van de Ven (1986: 601), innovation is a "network-building effort that centers on the creation, adoption, and sustained implementation of a set of ideas among people . . . [and] this network-building activity must occur both within the organization and in the larger community of which it is a part." While networks facilitate the diffusion of innovation, they are also valuable resources for learning (Ahuja 2000), knowledge transfer (Tsai 2001), and creativity enhancement (Powell, Koput, and Smith-Doerr 1996). Can networks also compensate for infrastructural constraints?

In emerging economies such as China and India, an adequate industrial infrastructure—which entails subsystems of (1) institutional arrangements, (2) resource endowments, (3) consumer demand, and (4) proprietary activities (Van de Ven et al. 1999)—is not necessarily available for innovation activities. Innovation in those contexts could be extremely difficult if not impossible. Yet, some science actors in emerging economies had performed unexpectedly well in large-scale innovation journeys in recent years (Salter and Faulkner 2011). Did they utilize networks very effectively in innovation?

To shed light on this central question, this article focuses on science actors and institutes in the People's Republic of China. Drawing on the concept of industrial infrastructure mentioned above, Chinese science actors seemed unable to attain great achievement in large-scale innovation journeys. Although these actors can expect strong consumer demand due to the country's very large population size, the Chinese high-tech sector appears to lack (1) transparent and reliable institutional arrangements, (2) strong resource endowment, and (3) sufficient knowledge to transform scientific findings into proprietary activities (Leung 2009). Yet, in recent years, Chinese science institutes were able to produce a large number of English-written articles in journals on high-tech science (Cao, Suttmeier, and Simon 2006; Guan and Ma 2007; Kostoff, Barth, and Lau 2008). This opens up an excellent opportunity to examine what production strategies Chinese science actors have formulated and the role of network building for innovation in China.

Studying these questions necessitates an in-depth analysis of the perception and interactions among science actors in specific contexts. Perception and interaction are influenced by the physical and cultural environments of science institutes—universities, research centers, academic laboratories, and corporations—in which science actors conduct research and perform everyday tasks (Star 1995; Fujimura 1996; Powell et al. 1996). Given China's ambition to gain influence in the global high-tech arena, these science institutes—particularly the prestigious ones—receive strong productivity pressure to signal innovativeness (Cao et al. 2006). One way to signal innovativeness is by jumping on high-tech "bandwagons" (Fujimura 1996)—large-scale technological innovation activities originated in industrialized economies. Some Chinese science institutes were more prepared to handle the challenges associated with innovation; others had to overcome more barriers. My analysis pays attention to variations among Chinese science actors and institutes.

As far as high-tech bandwagon is concerned, this article focuses on nanotechnology. This high-tech science has attracted a lot of attention in recent years (Roco 2007).

Since around 1999, Chinese science actors have shown interest in it and have begun to invest funding and time to take on nanotechnology (Chinese Academy of Sciences 2005). For Chinese science actors, pursuing nanotechnology is like embarking on a large-scale innovation journey (Van de Ven et al. 1999). In the nanotechnology innovation journey (hereafter "nanotech journey"), different salient issues arose, propelling Chinese science actors to develop and emphasize different production and network strategies. While domestic and international networks have been drawn, the utility of them has changed over time. To capture variations and changes in the nanotech journey in China, a process approach (e.g., Van de Ven et al. 1999; Langley 2007) with a macro orientation is suitable. For my research purposes, the framework developed by Everett Rogers (1995) is particularly useful.

In the next section, I highlight several contextual forces underlying the Chinese nanotech journey. With this contextual background, I discuss the relevant literatures that have oriented my research and led me to formulate a number of initial expectations. Afterward, I summarize the research methods and report my major findings. Finally, I discuss the broader implications of my research findings and suggest further research directions.

2 Context: Jumping on the Nanotech Journey within Constraints

Chinese science institutes did not have a favorable starting point to pursue nanotechnology. While nanotechnology required a high level of research and development (R&D) inputs, Chinese science institutes were typically short of R&D resources. For example, China's intramural R&D expenditure was about US$2.5 billion in 1992, equivalent to only 1.58 percent and 2.23 percent of the corresponding figures in the United States and Japan. In 2003, China spent US$20 billion in R&D, or 7.14 percent and 15.87 percent of that spent in the United States and Japan (National Bureau of Statistics 2006). Such a discrepancy was aggravated by the two economies' private sectors. Private businesses still account for a very low proportion of China's overall R&D expenditures in high-tech science (National Bureau of Statistics 2006). Based on these public and private investment figures, it seems that China might stay "low-tech."

In nanotechnology specifically, China was no match with the most industrialized economies such as the United States and Japan in terms of public funding (Roco 2007). Thus, the US federal government has invested more than US$1 billion in nanotechnology as of 2006 (Roco 2007). Based on various estimates, China has invested no more than 20 percent of what the United States has (Kostoff, Barth, and Lau 2008; Leung 2009). Yet, nanotechnology was still viewed as a feasible channel for China to become "innovative" and gain increased influence in global science. With a much lower R&D budget, how many Chinese science actors embarked on the nanotech journey? What kinds of support did they receive from the government?

According to Hongchen Gu and Jürgen Schulte (2005), as of 2001, more than 4,500 Chinese scientists in China had conducted nanotechnology research in one way or another. Gu and Schulte estimated that 60 percent of these nano-scientists worked in the Chinese Academy of Sciences (CAS)—the most productive CAS institutes in nanotechnology research were all located in Beijing (Kostoff et al. 2006). Tsinghua University and Peking University (PKU) were two other highly productive institutes—both of them are also located in Beijing (Fig. 1). In addition to Beijing, Shanghai is another prolific region in terms of nanotechnology research (Kostoff et al. 2006; Leung 2009).

Importantly, high-tech science such as nanotechnology has political significance from the perspective of Chinese government. As the Chinese economy experienced continuous growth, the government has heightened its ambition in the global arena of science and technology in recent years. Policy documents had emphasized the government's objective to make China an "innovative country" (Cao et al. 2006; State Council of China 2006). This is consistent with the country's historical preoccupation with becoming par with—even surpassing—the scientific capacity of Euro-American countries (Suttmeier 1997).

This government agenda has translated into productivity pressures on the part of Chinese science institutes. The most high-profile, prestigious universities and research institutes were brought to the forefront. Although these institutes were consistently given a much larger proportion of government funding for R&D purposes than less prestigious institutes (National Bureau of Statistics 2006), they were also assumed to produce a large quantity of research. In short, the strongly funded institutes were expected by the People's Republic of China government to "shine in the world."

Against this background, the Chinese government had introduced a variety of policies to help enhance science institutes' capabilities. One example was to provide lucrative salary package to "bring back" overseas Chinese scientists (including foreign-born ethnic Chinese scientists and Chinese-born scientists who have migrated

Fig. 1 A nano-biotechnology company in Beijing

to and permanently settled in a foreign country) to Chinese science institutes. David Zweig et al. (2008) called this the "reverse brain drain." Nonetheless, the reverse brain drain has helped Chinese science institutes enhance their capabilities only haphazardly. Many still find the increased productivity pressures difficult to cope with.

3 Theoretical Background

This article adopts Rogers's (1995) framework of innovation. This framework is appropriate for two major reasons. First and foremost, this framework emphasizes interactions between science actors in the innovation process and is well suited to illuminate the distributive nature of innovation (Star 1995; Ramlogan et al. 2007). Like other innovation activities, the Chinese nanotech journey encompassed an ecology of science actors and agents—each of them contributed to the innovation journey but could have different agendas, interests, and political and social capitals (Star 1995; Fujimura 1996). Second, Rogers's framework provides useful concepts to analyze this ecology by treating innovation as an ongoing process. This is realistic with respect to the emergence of a new science (Metcalfe, James, and Mina 2005). For example, it takes time for science actors to build network structures, and utilizing these structures meaningfully and beneficially might take even longer.

Empirically, the usefulness of Rogers's framework has been demonstrated in previous research of innovation (Van de Ven et al. 1989; Marcus and Weber 1989; Lee 2004). Two applications of Rogers's concepts in Minnesota examined the innovation process at the macro-organizational level. First, Van de Ven et al. (1989) focused on the decision-making process within organizations. Drawing on data from a large health-care system, they argued that the innovation journey might be "stuck." In their observation, two hidden cycles in the management—a vivacious and a beneficent one—ran parallel to each other and "locked" the organization into a specific stage of the innovation process. Alfred A. Marcus and Mark J. Weber (1989) extended the idea of stagnation to study the diffusion of safety standards among nuclear power plants empirically. Different issues occupied the administrator's attention at different times, and the authors showed that the authoritative (or "rule-bound") approach is less effective than the autonomy approach in the process of an externally induced innovation. More recently, Lee (2004) examined how the computerized nursing care plan diffused among nurses in Taiwan in the late 1990s. The author found that the plan gained acceptance in different stages of the diffusion process because of its relative advantages, compatibility, complexity, trialability, and observability. The findings are consistent with the predictions in Rogers's framework.

Also, the application of Rogers's framework facilitates dissecting a large-scale innovation process into temporal stages. A stage-by-stage approach implies possible changes in the innovation journey. Studying these changes can reveal how network building among science actors evolved and how network ties, relationships, and exchanges developed into "network structures" (Fennell and Warnecke 1988; Valente 1995). Network structures—the structure and quality of social networks—constitute reliable resources for science actors in the innovation journey (Greenhalgh et al. 2004) and, in the case of Chinese science actors in the nanotech journey, compensate for infrastructural constraints. Among other things, network structures provide science actors with (1) shared material and intangible resources, (2) relational rents, (3) knowledge and learning opportunities, and (4) stable expectations of "rights and duties" (between network partners) (Palmer, Friedland, and Singh 1986). Research showed that these network resources compensate for an inadequate infrastructure (Karlsson 1997).

Using Rogers's framework, I divide the Chinese nanotech journey into five temporal stages: (1) agenda setting, (2) matching, (3) redefining/restructuring, (4) clarifying, and (5) routinizing. The first two stages form the initiation phrase of the innovation journey, whereas the latter three stages form the implementation phrase. At the agenda-setting stage, government agencies are expected to take the leadership role. The most important issue at this stage was to establish the goals and missions behind entering the nanotech journey and to ensure that science institutes understand the government's outlook and ambition. Previous research highlighted the importance of government intervention in the innovation process. For example, governmental agencies of advanced economies such as the United States favored the "competition" orientation as a way to promote entrepreneurialism, whereas developmental states such as South Korea and Singapore in the 1980s concentrated on penetrating into existing markets (Salter and Faulkner 2011). For Chinese government agencies, the overarching concern is to increase China's visibility and influence in the global arena of science and technology via pursuing nanotechnology. Since Chinese science institutes relied heavily on government agencies for funding and other research support, they would be unlikely to deviate from the government's goals.

But given limited resources, how could visibility be increased? Organizational ecologists have told us that the specialist orientation can lead to an advantageous position in certain environments (Hannan and Freeman 1987; Carroll 1985). In the nanotech journey, the specialist orientation would allow Chinese science institutes to target a narrower range of resources and skills (Carroll 1985). Similarly, other researchers have suggested that organizations with limited resources sometimes employ the focus strategy to pursue specific goals (Hirsch 1972). For example, Paul Hirsch (1972) observed that movie producers used a "selective promotion" strategy to increase sales during the industry's downtime in the 1980s. As was the case for developmental states in the 1980s (Salter and Faulkner 2011), I expect that Chinese government agencies and research institutes would set the focus strategy as a guiding orientation. Such a strategic orientation should be observable in government funding concentration and the research outputs of science institutes.

In addition to the focus strategy, which is mostly internally oriented, the external networks strategy would be of equal importance (Powell 1990; Messner 1997; Salter and Faulkner 2011). That is, both government agencies and science institutes would recognize that networks—particularly overseas ones—could become significant resources to compensate for infrastructural constraints. I expect to observe a fairly high amount of organizational effort to promote the establishment and utilization of external networks among science institutes in the agenda-setting stage.

From the matching stage onward, the leading role would gradually shift to science institutes. Productivity pressures would lead these institutes to carefully identify doable research topics that were deemed compatible with organizational capabilities (Rogers 1995; Fujimura 1996). Doing so increased the likelihood of fulfilling the mission of increased visibility in the world. The focus or specialist strategy would continue to be regarded as appropriate because, as mentioned, adopting a proper focus could help Chinese science institutes to build their strength through concentrating resources on a narrower set of skills (or developing a "niche" in ecological terms) (Hannan and Freeman 1987; Baum 1996). It is difficult to anticipate what exactly the scientific focus would be from an organizational theory viewpoint. But whatever the focus, due to strong productivity pressures, the chosen subarea would be regarded as a "fertile" area.

Having matched capabilities with doable research topics, Chinese science institutes would begin the implementation phrase of the nanotech journey. The first stage is "redefining" nanotechnology. The relevant science actors—including scientists and policy makers—would be engaged in promoting the nanotechnology subarea(s) that has been deemed fertile in the matching stage. This is in essence a process of legitimization or enactment (Weick 2001). For something with a high level of interpretive flexibility such as nanotechnology (Winner 1993)—where different definitions of the science are plausible—redefining is critical. At this stage, Chinese science institutes sought to convince the nanotech community that the research products of their chosen subarea were legitimate nanotech products. Establishing this legitimacy would require understanding the norms and standards in the global nanotech community.

Along with "redefining" the contents of nanotechnology, Chinese science institutes would also restructure the organization to compensate for R&D weaknesses and/or augment existing capabilities. Most important, I expect Chinese science institutes to adopt the "network form" more extensively (Powell 1990; Messner 1997). In the organizational world, networks are formed in a variety of different ways, such as joint ventures (Ahuja 2000), strategic alliances (Gulati 1995), business groups (Keister 2000), contracts, franchising, and outsourcing (Podolny and Page 1998), and collaborations (Powell et al. 1996). Collaborations are common in science and are beneficial in terms of resource acquisition, learning, and other collective goals (Powell et al. 1996). This form of networks would be sought frequently by Chinese science institutes. While collaborations might be facilitated by the establishment of a physical entity (e.g., a joint research center), collaborating "virtually" (e.g., through e-mail exchanges) is also quite possible (Rogers 1995).

Finally, the Chinese nanotech journey would reach the clarifying and possibly the routinizing stages. Given China's less developed infrastructure, some Chinese science institutes might find it difficult to go beyond the clarifying stage. That is, these institutes continue to search for and/or evaluate different research possibilities of pursuing nanotechnology research because they can only claim limited or even no success in the nanotech journey. The more capable institutes would be able to routinize nanotechnology research and productions and even incorporate them into day-to-day organizational practices. For example, these institutes could reach and maintain a high productivity in terms of research papers, patents, and industrial products. Given that the more prestigious research institutes tend to receive more governmental support, I expect them to be more able to reach the routinization stage.

More generally, I expect Chinese science institutes to be heavily influenced by government agencies throughout the Chinese nanotech journey. This is due to a highly centralized political system in China and the fact that science and technology has a high political status in China (Suttmeier 1997; Cao et al. 2006). In each stage of the innovation process, Chinese government agencies would exert their influence on science institutes to ensure that the latter would fulfill the political objectives behind nanotechnology. In practice, the two groups of organizations would show a high degree of coordination, even though they were formally distinct entities. It is as though the two had reached a clear consensus regarding how the nanotech journey would be best taken.

Network building in the journey would entail obstacles of various kinds, and the level of success would vary among Chinese science institutes. Most Chinese science institutes would favor network partners within geographical proximity. However, overseas networks could provide useful information and other resources that were unavailable from domestic networks. Considering different levels of resource endowment, the more prestigious and capable institutes would be willing to absorb the additional costs of "networking abroad." In contrast, less prestigious and less capable institutes would see overseas networks as too "expensive" to build and utilize.

4 Method

The conceptual framework that I adopt from Rogers (1995) implies a temporal sequence. Moreover, the network of actions is assumed to be coherent, casually connected, and influenced by contextual forces. Following this framework, my analysis includes both quantitative and ethnographic data. I intend to construct an interpretive account of the Chinese nanotech journey grounded with rich process-oriented data (see Langley 2007). This approach is capable of generating new insights on less familiar settings.

To meet efficiency concerns, I narrow my coverage by first examining available data. With respect to nanotechnology research productivity in China, Beijing contained the most prolific and influential science institutes, followed by institutes in Shanghai, Zhejiang, Guangzhou, and other Chinese regions (Kostoff et al. 2006). I am particularly interested in the "best performers." Thus, I focus on the three most influential institutes in Beijing: CAS, Tsinghua University, and PKU. I also included other prolific and less prolific institutes in Shanghai, Xi'an, and Hong Kong to understand the variations among Chinese institutes. Regarding the networks of these research institutes, my sample included corporations, government agencies, and several American academic institutes.

Tables 1a and 1b summarize my informants' academic background, affiliations, and strength of overseas ties. To interview them, I followed a "top-down" approach (Odendahl and Shaw 2002). That is, I began by contacting the most senior scientists—those who either directed a specific nanotechnology research center or chaired an academic department. Some of these scientists agreed to my interview requests; others did not due to scheduling conflicts and confidentiality concerns. But in almost all cases, they referred me to potential informants that they regarded as influential nanotechnology scientists. The referral was almost always appropriate, judging from my preparatory bibliometric research. Combining this referral (or what may be called the snowballing strategy) with the top-down approach allowed me to avoid unnecessary distraction in the data collection process (Emerson, Fretz, and Shaw 1995).

I have interviewed—both formally and informally—more than seventy faculties, students, business executives, and related staffs from the United States and China with transcription records. Some of my informants had more than one academic and/or business affiliation. Table 1a lists their primary academic institute affiliation. In my research, I had attempted to include at least thirty other informants. However, these other potential informants did not respond to my requests, refused to be interviewed, or did not participate in an interview at sufficient length. They were treated as "unavailable informants" and were dropped from my analysis. For my research purposes, dropping them did not affect the major thrust of my analysis. The majority of my informants were from China. From the United States, I have included both ethnic Chinese and non-Chinese informants. About 80 percent of my informants came from the most productive institutes in nanotechnology research, either in China or in the United States. The other 20 percent either were not engaged in active nanotechnology research or had only attained a modest productivity in the new science. The purpose of including these "other" informants is to capture an alternative viewpoint in the nanotech journey.

Interviews took place in the offices of informants, laboratories, research centers, locations hosting academic, and professional conferences and even during class lectures. In addition to in-depth, face-to-face interviews, I conducted participant observations in these different research sites, such as nanotechnology conferences. My ethnographic data are not intended to yield generalizable statements in the statistical sense. Rather, they serve as resources for me to interpret and make sense of the Chinese nanotech journey. Also, they could inform further studies.

Available quantitative data are extracted from bibliometric studies (e.g., Kostoff et al. 2006) and other documentary sources. I collected these data from libraries and government agencies in both China and the United States. These data enabled me to identify the most prolific institutes, specific nanotech research centers, and individual scientists. Later, I collected additional publication and patent data using WebScience (which contains the Scientific Citation Index database) and other common search engines. I also contacted researchers and government officials in China, and some of them gave me access to data not available to the public. They have enriched and influenced my ethnographic research.

Table 1a Summary of interview informants

Interview numbers	Academic institute
1–15	CAS
16–24	Fudan University
25–28	Harvard University/MIT
29–39	PKU
40–48	Shanghai Normal University/Shanghai University/Tongji University
49–62	Tsinghua University
63–66	University of Wisconsin
67–69	Hong Kong University of Science and Technology
70–75	Miscellaneous (in Xi'an, Shanghai, Beijing)

Table 1b Profiles of selected informants

University/discipline	Position	Directorate role?	Ph.D. overseas?	Work experience overseas?	Overseas collaboration?[a]
Tsinghua					
Chemistry	Professor	No	Yes (Europe)	Postdoc in Berlin	Strong
Chemistry	Professor	Department vice chair	Yes (Europe)	Visiting scholar in Belgium	Strong
Material Science	Professor	Dean	No	Visiting scholar in US/Germany	Moderate
Electronics	Professor	No	No	Visiting scholar in Hong Kong	Moderate
PKU					
Chemistry	Professor	Lab director	Yes (Japan)	Postdoc in Japan/Hong Kong	Strong
Electronics	Professor	Director	Yes (US)	Visiting scholar in Europe, US, Hong Kong	Strong
Physics	Professor	No	Yes (France)	Postdoc in France	Strong
Electronics	Professor	No	No	Visiting scholar in US and Japan	Moderate
CAS					
Chemistry	Professor	Director	Yes (Japan)	Visiting scholar in Japan	Strong
Chemistry	Researcher	Deputy director	Yes (Japan)	Visiting scholar in Japan	Strong
Physics	Researcher	No	No	No	Weak/none
Mechanics	Professor	No	No	No	Weak/none
Fudan					
Material Science	Professor	No	Yes (US)	Postdoc in Canada	Strong
Material Science	Associate professor	No	No	Postdoc in US	Strong
Chemistry	Professor	No	No	Visiting scholar in Canada, Israel, US	Strong
Chemistry	Associate professor	No	No	Postdoc in Hong Kong, Ireland	Strong
Others (China)					
Chemistry	Professor	Associate director	No	No	Weak/none
Material Science	Professor	No	No	No	Weak/none
Others (US)					
Biological engineering	Professor	Yes	No	No	Strong
Chemistry	Professor	Yes	No	Adviser in China	Strong

Note: This table is intended to show the diversity of my informants but does not include all of them. Fourteen informants were from Tsinghua University, eleven from PKU, fourteen from the CAS, nine from Fudan University, fourteen from other universities in China/Hong Kong, and eight from other universities in the United States.

[a] Magnitude of overseas collaborations was reported by informants and verified by publication records. "Strong" indicates four or more overseas collaborative projects per year; "moderate" means one to three overseas projects per year; "weak or none" means rare or no overseas collaborative projects in the informant's career.

With the aid of China's Intellectual Property Office, I collected a data set with respect to the number of nanotechnology-related patents between 1999 and 2005. The Intellectual Property Office was the agency that Chinese science actors went to for the sake of patent applications and registrations. Given that patents were taken as an indicator of productivity in Chinese science institutes (Cao et al. 2006), science actors were relatively careful in fulfilling all patent application requirements with the Intellectual Property Office. The completeness of the data set has been verified by research assistants and an officer in the Intellectual Property Office.

5 Results

There were different salient issues, obstacles, and coping strategies in each stage of the Chinese nanotech journey. While Rogers's original framework conceptualized the temporal sequence of the innovation process in theory, it is useful to add a time element to demarcate each stage. I have consulted various data sources and created an approximate timeline for the progression of the Chinese nanotech journey (see Table 2). In my analysis, the Chinese nanotech journey began in 1999 and continues to the present. In practice, some events and actions "crossed" between stages, resulting in temporal overlaps. As such, my timeline is approximate rather than definitive. In the following, I discuss my findings with respect to each stage of the Chinese nanotech journey. Some of my empirical findings confirmed my expectations; others offer unexpected results.

5.1 Agenda Setting (1999–2002)

The Chinese government agencies that have been most involved in the nanotech journey included the Ministry of Science and Technology, Ministry of Education, and National Science Foundation China (NSFC) (National Bureau of Statistics 2006; Appelbaum and Parker 2008). These were the country's science and technology policy makers and developed policy initiatives to guide R&D funding allocations and ensure that research institutes would fulfill the goals of these initiatives. At the agenda-setting stage, the focus strategy won the support of policy makers in Chinese government agencies. For example, the Ministry of Science and Technology recognized the potential of nanomaterials and nanostructures early on in the Chinese nanotech journey.

Table 2 Analytic stages of the Chinese nanotech journey progression

Period	Stage
1999–2002	Agenda setting
2000–2003	Matching
2001–5	Redefining/restructuring
2005–present	Clarifying
2005–present	Routinizing

The agency initiated the Nanomaterial and Nanostructure Basic Research Project in 1999, providing funding for a select group of Chinese scientists to start research projects in these two areas (Chinese Academy of Sciences 2005; State Council of China 2006; Appelbaum and Parker 2008).

The focus strategy also operated at the organizational level. Thus, the National Steering Committee for Nanoscience and Technology was set up in 2000. One of the most important decisions made by this committee was that nanotechnology development in China would be concentrated in the most established institutes in the country, particularly CAS, Tsinghua University, PKU, Shanghai Jiaotong University, and Fudan University (State Council of China 2006; Appelbaum and Parker 2008).

This strategy of concentrating resources on selected institutes was reinforced by government funding for research. In China, the NSFC is a major funding agency for basic science that corresponds to the US National Science Foundation. Based on NSFC's data, the agency provided a little less than renminbi (RMB) 12 million (about US$1.7 million) in 1999. In 2008, NSFC's funding for nanotechnology increased to about RMB 300 million (about US$43 million; see Table 3). The increase was significant for China internally, yet it hardly compared with the investment for nanotechnology in the United States and other industrialized economies. The US investment for nanotechnology has already exceeded US$1 billion (Roco 2007). Given limited funding resources, the "targeted" institutes would capture the major share of them.

Table 4 lists the top ten NSFC recipients for nanotechnology research in five selected years between 1999 and 2008. Several institutes—including several CAS institutes, Tsinghua University, and PKU—remained the top recipients throughout the period. Among hundreds of science institutes in China, these top ten institutes had consistently obtained 30 percent or more of all nanotechnology funds provided by the NSFC in any year during this ten-year period. In 2001 (not shown in Table 4), the top ten

Table 3 Funding for nanotechnology research by the NSFC, 1999–2008

Year	No. projects	Funding amount (million RMB)[a]
1999	65	11.51
2000	88	16.97
2001	60	23.87
2002	276	88.71
2003	311	88.80
2004	397	117.08
2005	439	124.97
2006	529	162.46
2007	532	195.38
2008	803	295.68
Total	3,500	1125.42

Note: [a]As of January 2009, 1 RMB (Chinese yuan renminbi) ~ US$0.146; US$1 = 6.835 RMB.

Table 4 Top recipients of NSFC funding for nanotechnology research

Institute	Funding (million RMB)
2000	
Institute of Metal Research, CAS	1.7
PKU	1.34
Nanjing University	1.24
Tsinghua University	1.04
Jilin University	0.88
Xi'an Jiaotong University	0.76
Institute of Physics, CAS	0.74
University of Science and Technology of China	0.62
Zhejiang University	0.515
Tianjian University	0.43
Total NSFC funding	16.97
NSFC funding for the top ten	9.265
Top ten's percentage	54.6 percent
2002	
PKU	7.79
Tsinghua University	7.51
Institute of Chemistry, CAS	7.02
Nanjing University	4.99
Institute of Physics, CAS	4.69
Hunan University	3.44
Xiamen University	3.30
Dalian Institute of Chemical Physics, CAS	2.40
Sun Yat-Sen University	2.005
Fudan University	1.90
Total NSFC funding	88.71
NSFC funding for the top ten	45.05
Top ten's percentage	50.78 percent
2005	
Tsinghua University	8.01
Nanjing University	7.95
PKU	4.56
Fudan University	4.38
Shanghai Jiaotong University	4.19
Zhejiang University	3.76
Sun Yat-Sen University	3.16
Wuhan University	2.78
Xiamen University	2.57
Southeast University	2.56
Total NSFC funding	124.97
NSFC funding for the top ten	43.92
Top ten's percentage	35.14 percent

Table 4 – *continued*

Institute	Funding (million RMB)
2006	
Tsinghua University	12.95
Nanjing University	9.51
PKU	6.98
Zhejiang University	5.18
Sun Yat-Sen University	4.62
Hunan University	4.36
Shanghai Jiaotong University	4.06
Tianjin University	2.86
Hefei Institutes of Physical Science, CAS	2.85
Institute of Metal Research, CAS	2.82
Total NSFC funding	162.46
NSFC funding for the top ten	56.19
Top ten's percentage	34.59 percent
2008	
Institute of Physics, CAS	12.45
Tsinghua University	10.67
Institute of Chemistry, CAS	10.13
Xiamen University	10.01
PKU	9.92
Fudan University	8.26
Nanjing University	7.56
Zhejiang University	7.55
Jilin University	6.35
Dalian University of Technology	5.62
Total NSFC funding	295.68
NSFC funding for the top ten	88.52
Top ten's percentage	29.94 percent

captured 80 percent of all NSFC funding for nanotechnology. After 2001, such a dramatic concentration of funding decreased. This indicates that NSFC (and possibly other Chinese funding agencies) reduced the intensity of its focus strategy in terms of funding allocation in later stages of the Chinese nanotech journey.

At this stage, Chinese policy makers realized that drawing on both domestic and international networks would enable scientists to jumpstart nanotechnology research while setting attainable goals. In 2001, the Shanghai Nanotechnology Promotion Center was founded to facilitate exchanges between enterprises and research institutes. The center organized networking events for science actors on a regular basis, facilitating interested business enterprises to meet with research teams from academic institutes. It also organized short-term business classes for academic scientists to learn about patenting procedures, business laws, intellectual property, and other commercial topics.

Regarding international networks, top government officials reached out to build institutional partnerships with foreign research institutes. These partnerships take time to form and formalize. While the initiatives began at the agenda-setting stage, the formal partnership with research and exchange activities often came into being after years of preparation. One example is the Partnership in International Research and Education in Electron Chemistry and Catalysis at Interfaces between US and Chinese researchers (Schneider, Grodzinski, and Liang 2011). Similarly, a number of US-China partnerships in nanotechnology research applied specifically to cancer had been in preparation for years and were formalized only recently (Schneider et al. 2011).

From the scientist's perspective, the learning benefits of overseas networks were great. But my scientist informants were very cautious about building and utilizing networks cost-effectively. One of my informants from a prestigious university in Beijing put it this way: "I can tell you one thing: the reason why we are not far behind from cutting-edge American scientists is because of very fast information channels. Now in the labs, we almost don't need to go to the library. Newspapers from around the world, electronic magazines and journals—all have electronic versions" (interview 58, March 2005). This scientist told me he enjoyed exchanging ideas with foreign scientists but felt that he could not afford the time and money costs for frequent international travels. Other informants of mine were more receptive to international travels. Those with a higher level of seniority, with overseas experience, and/or from prestigious institutes were often more able to secure travel funds from various government agencies. Several of my informants who had experience in making funding decisions explained the importance of cost-effectiveness. For one thing, influential Chinese scientists were regarded as having more specific ideas to build useful networks based on the Chinese situation. Similarly, overseas experience enabled individual scientists to network selectively and efficiently. These scientists were regarded as capable of protecting China's interests and providing advice for policy making.

5.2 Matching (2000–2003)

If agenda setting was about what "should be done," matching was about what "can be done." At this stage, government agencies and science institutes collectively determined—gradually as it might be—what types of nanotechnology projects were most feasible and fertile. Nanotechnology is concerned with matter in the scale of 1–100 nanometers (nm) (the diameter of a human hair is about 50,000 nm; 1 nm is smaller than a DNA molecule). Doing research at this extremely small scale entails tremendous technical challenges. On the other hand, the emerging science carried a high level of interpretive flexibility (Winner 1993) for science institutes not only to identify but also to construct the links between doable research and publishable results (or commercializable products).

In line with the government focus, the majority of my informants agreed that the subarea of nanomaterials matched with China's R&D environment particularly well. According to Li-ming Liang and Cai-xia Xie (2003), 39.1 percent of NSFC-funded projects in nanotechnology contained keywords related to “nanomaterials” in 1999; in 2000, the corresponding number rose to 51.2 percent (Liang and Xie 2003). As Chinese scientists continued to invest in nanomaterials, they had actually become the top performers in terms of research quantity (though not quality) (Kostoff, Barth, and Lau 2008). This evidence confirms my expectation about this stage partially; that is, the specialist (or focus) strategy enabled Chinese science institutes to secure a “niche” in the global “ecosystem” of nanotechnology research.

Nonetheless, behind this stunning performance were efforts of articulation, rationalization, and alignment work. This stage of the Chinese nanotech journey is similar to other emerging sciences in which science actors engage in crafting what science is “doable,” based on different interests, opportunities, and constraints (Fujimura 1996). Matching was not confined to existing constraints but involved searching and constructing a possible path. Thus, according to my informants, not only was nanomaterial research economical—and hence matched with a low level of resource endowment in Chinese institutes relative to their counterparts in the industrialized world. Nanomaterial was also “fertile” enough to allow Chinese science actors to cope with productivity pressures. Given that the research team did not necessarily have sophisticated equipment to conduct research, a clever thing to do was to work on something in line with “Chinese advantages.”

Labor cost advantage was one of these advantages. Some of my informants believed that they could yield new findings in nanomaterial research simply through repeated experimentations (essentially multiple trial-and-error tests to “find” new results). In most Chinese science institutes, the salary for technical support staff and graduate students was often low. One of my informants even said that a researcher could always combine two materials, say, X and Y, together and synthesize them to make a new material, Z. Then the researcher can combine Z with X or Y (or other materials) again and produce yet another brand-new nanomaterial.[1] Based on this logic, there was virtually unlimited potential associated with nanomaterials at least in terms of publishing academic articles. While specialization was traditionally regarded by economists as increasing productivity through refined skills, the choice of nanomaterials among my informants was a result of matching capabilities and “good enough” products. The preference for nanomaterials developed among Chinese science actors because this subarea of research allowed the possibility to search for problems with available solutions (March 1981).

The focus strategy was augmented by collaborative networks. NSFC funding data showed that nanomaterials projects with a multidisciplinary approach received more funding than those with a singular disciplinary approach, on average (Liang and Xie 2003). This was due to a practical concern, according to a chemical engineer in Beijing. This scientist believed that chemical engineering did not “care” about material research in the past. Now, nanomaterials have been recognized as a promising new area, and chemical engineering researchers have to know the structural properties of nanomaterials. He said: “When we did chemical engineering in the past, we didn’t pay attention to issues regarding materials. Now, you will care a lot about [the structural

[1] In practice, the ability to produce a lab sample of a new material does not guarantee its manufacturability. That is, the new material may or may not be capable of mass production and used in applied products.

Table 5a Nanotechnology-related patents registered by the Intellectual Property Office, 1999–2005

Year	No. applications
1999	239
2000	525
2001	1,986
2002	1,678
2003	2,278
2004	2,067
2005	948[a]

Note: [a]As of 9 September 2005.

properties of] materials. . . . In the past, chemical engineering didn't care about all these. . . . Chemistry and material [science] were not the same thing. In the past, we didn't learn this [material research]. But it is changing now" (interview 62, March 2005). This informant told me that he needed to convince funding agencies how his research fitted with nanotechnology, and some knowledge in related areas made him knowledgeable enough to articulate the relevance of his research.

For the average academic institutes in China, collaborative nanotechnology research tended to involve researchers from the same or adjacent region(s) (Kostoff et al. 2006). Yet, science actors from top institutes remained highly interested in collaborating overseas, especially for those having overseas study and/or work experiences. Consistent with my expectations, it was the informants from prestigious institutes that were more likely to view overseas networks as highly desirable and worth the additional costs.

Chinese government agencies would like new research initiatives to incorporate the international dimension in their projects, but the preferred executors were still researchers from traditionally prestigious institutes at the matching stage. Around 2002, scientists from CAS, PKU, and Tsinghua University began to discuss the establishment of a national center that would attract international attention. The result would be the National Center for Nanoscience and Technology, to be opened in Beijing in 2003 (Xinhua News 2005).

International collaboration also played an important role in applied product development. According to patent data in Tables 5a and 5b, the sheer number of collaborations in nanotechnology patents has continued to increase since 1999. In 1999, there were 239 applications for nanotechnology-related patents; 121 of them were collaborative projects.[2] In 1999, 8 percent of the collaborative projects were domestic ones

[2] I compared the location of the primary applicant and its "representative agency" to determine if a collaboration had happened. If the location of the primary applicant and its representative agency was within the same location, then it was regarded as "no collaboration." If the primary applicant's location and the representative agency's location were in different Chinese provinces or in different countries, then it was regarded as "domestic" or "international" collaboration, respectively. For example, if the primary applicant's location was Beijing and his representative agency's location is Shanghai, then it was coded as a

Table 5b Collaboration in patent applications

Year	Collaborative/total projects	Domestic collaboration	International collaboration
1999	121/239	10 (8 percent)	111 (92 percent)
2000	188/525	24 (12 percent)	164 (88 percent)
2001	284/1,986	76 (25 percent)	208 (75 percent)
2002	382/1,678	75 (20 percent)	307 (80 percent)
2003	554/2,278	127 (23 percent)	427 (77 percent)
2004	311/2,067	161 (52 percent)	150 (48 percent)
2005	948[a]		

Note: [a]As of 9 September 2005.

(involving Chinese partners in at least two different provinces), and 92 percent were international. Yet, over the years, the percentage of international collaborations relative to all collaborative projects went down steadily. For example, in 2002, there were 383 collaborative projects with patent applications; 80 percent of them involved international collaboration. This suggests two things: first, Chinese science actors had become more selective in choosing international partners; second, Chinese science actors were more receptive to domestic collaboration. This latter form of collaboration might not be intended solely to make use of the fame of the partner, as international collaboration could provide, but involved actual division of labor in R&D work and other material exchanges.

5.3 Redefining/Restructuring (2001–5)

To a great extent, the "restructuring effort" among Chinese science institutes was a logical extension of the focus or resource concentration strategy. That is, Chinese government agencies concentrated funding on selected institutes in view of low resource endowments relative to industrialized economies. As the Chinese nanotech journey proceeded, government agencies created new organizational entities to consolidate resources. This was done by combining the country's strongest institutes. In 2003, the National Nanoscience and Technology Center came into being. It was located within the Institute of Chemistry at the CAS in Beijing. The center included some of the most competent scientists from CAS, Tsinghua University, and PKU. The close proximity of the three institutes—all within walking distance in the Haidian district in Beijing—allowed them to share information and facilities, host international events, and serve as a large research hub for researchers from other parts of China and abroad. There were similar joint research centers on the commercial front.

Restructuring also fostered proprietary activities—or transforming basic science into applied products (Van de Ven et al. 1999). My informants were generally interested in proprietary activities but did not necessarily possess the know-how to do so.

domestic collaboration. If the primary applicant's location is an overseas country, since the representative agency would always be located in China in this data set, it was coded as "international collaboration."

Accordingly, government agencies encouraged the development of institutionalized university-industry partnerships, which enabled both the academic and industrial partners to exploit the potential of nanotechnology by lending strength and support to each other. One of my academic informants in Beijing saw industrial partners as enabling him to bring research to the commercial world. He said: “A single person has limitations. One can learn materials or chemistry at great depth, but you don’t know how to apply [your results]. Therefore, communication [with industry] is necessary” (interview 8, February 2005). For this scientist, the ability to exploit one’s academic strength to develop industrial applications was the most important task during the nanotech journey. He obtained useful knowledge from his industrial network ties for this purpose.

University-industry collaboration is not without difficulties. The two parties might have a very different motivation behind R&D activities and work differently. From the business standpoint, quick return on investment is critical to ensure profitability. From an academic perspective, rigorous research and precise findings are what define high intellectual quality. Based on my interviews and observations, many academic scientists in Chinese institutes complained that industrial partners did not really “care about” the difficulties in scientific research. Local and smaller enterprises often paid excessive attention to economic returns; a foreign partner might be more open to failures after making their funding investment but needed to maintain close contact with the academic partner.

In the positive light, handling difficult commercial partners—whether domestic or international ones—could have long-term benefits for academic scientists. First, the two sides were motivated to state clearly “rights and responsibilities” of each other. This was sometimes accomplished by establishing institutional agreements between universities and enterprises. In many partnerships, the large-scale international partner was often more experienced in commercializing applied products than the local academic partner (Appelbaum and Parker 2008). As my informant told me, an experienced partner often transferred useful knowledge in propriety activities. This enabled academic scientists to increase predictability of R&D progress and redefine their research focus.

At the redefining stage, the more ambitious informants of mine believed that the economic future of nanotechnology included a global dimension. They had developed an acute consciousness of the international marketplace. One of my informants, with interests in material science and engineering at a less prestigious university in Shanghai, discussed the merit of his nanoluminescent product (a powder that could glow in the dark). The following quote exemplifies how he articulated the business potential of nanotechnology by referring to dramatic events that happened outside China: “The [nanotech] market is certainly big. For example, in a catastrophe like 9/11, you run out of energy all of a sudden. If your building is equipped with something [such as nanoluminescent powder] that can illuminate, it’s very helpful. Something that circulates within the building [would have been quite useful] (interview 48, May 2005). This scientist obtained his PhD in China and did not have strong overseas ties, nor did he direct any lab or nanotechnology center. As he told me, it was often difficult for Chinese scientists to find a trustworthy overseas partner. Meanwhile, potential overseas partners might be skeptical about the research capability of a Chinese partner. This type of two-way trust barriers made it difficult for many Chinese scientists to initiate and establish overseas ties. At the time of my interview, this informant was still actively looking for an overseas industrial partner.

For those who could maintain long-term relationships with overseas colleagues, there was useful relational rent—knowledge-sharing routines and resources—to derive from networks. Importantly, Chinese science actors sometimes had to keep working with their nanotechnology projects without necessarily being fully knowledgeable about the details in research, commercialization, and internationalization issues. The relationships of overseas and domestic network ties enabled Chinese science actors to implement learning by doing and absorb knowledge gradually (Argote 1999). That is, the science actor can try specific R&D strategies with bounded rationality (Cohen and Levinthal 1990; March 1991), and network ties share experience and even provide emotional support.

For example, one of my informants was a material science professor from a prestigious university in Beijing. He had already applied for and owned a number of patents in nanotechnology but was still unable to make profits from them. More recently, he learned from his Japanese colleague about what is proper to include in a patent document. For him, this was about redefining his research product to fit with the requirements of a profitable patent, using the right language and framing: "I have a few patents myself. Some of them are 'professional inventions,' which is the most honored one. Surely, there are economic benefits [with respect to what category the patent is classified into]. Depending on how the buyer feels about your invention [and thus how much they pay you], they deal with the university [to negotiate for profit-sharing matters]. Then there is a rule that the inventor can take no more than 5 percent of the price . . . 3 percent, 2 percent or even 0 percent" (interview 49, March 2005).

Besides, this scientist came to know that he needed a basket of patents, not singular ones, to make profits: "According to concepts acquired in Japan, only a group of patents can [guarantee you to] make money. A single patent might not protect the technology enough. To take over the market, you need a bunch of patents for protections . . . . One patent doesn't have enough protective strength, so we need a group of patents" (interview 49, March 2005). His network ties were useful ongoing, rather than one-time, resources. In this sense, network ties provided my informants learning opportunities, and the benefits of such opportunities could be absorbed and felt only gradually (Leung 2009).

5.4 Clarifying (2005–Present)

After the redefining/restructuring stage, Chinese science institutes entered the "clarifying" stage in the nanotech journey. While the focus on nanomaterials (Fig. 2) has already enabled many Chinese science institutes to gain influence in the nanotech world, they recognize that continuous improvement is necessary to sustain high productivity. Now that "quantity" has been achieved, it is time to upgrade the quality of nanotechnology research products (Kostoff, Barth, and Lau 2008; Leung 2009).

Policy makers emphasized quality improvement in official documents. For example, the *Medium- and Long-Term National Plan for Science and Technology Development 2006–2020* put a great emphasis on increasing the quality of high-tech projects in China. This was regarded as the critical step to turn China into an "innovation-oriented society"—a mission to be accomplished by the year 2020 (State

Fig. 2 Nanomaterial products

Council of China 2006). In this policy document, indigenous innovation occurred as a central theme throughout. Among other science and technology fields, nanotechnology remained an area of high perceived prospect. It was identified as one of the "megaprojects" to advance the innovation visions and goals of the plan (Cao et al. 2006).

At this stage of the nanotech journey, overseas networks continued to have great significance in terms of resources, knowledge, and motivations. But networks now also helped Chinese science actors "clarify" nanotechnology development in China. One important thing was about clarifying the strength of China in the global landscape of nanotechnology. To do so, government-sponsored organizational entities and science institutes invited foreign scientists to witness and testify to China's progress in nanotechnology. One international networking event hosted by National Center for Nanoscience and Technology was ChinaNano2005 in Beijing.[3] The event was the first of its kind, dedicated to bringing in prestigious scientists, important attendees, and keynote speakers from around the world. An important function of this type of event was to show the world how much China had advanced in nanotechnology.

Clarifying also involved network consolidation and expansion. According to my informants, referral was quite common in their networking experiences. For example, when a Chinese scientist was interested in contacting a scientist from a foreign institute, knowing someone from the same institute could put them in touch with the

[3] I attended this conference as a paper presenter. As I observed, the conference included many scientists from around the world. The conference also included a tour to visit a microfabrication laboratory at CAS.

targeted scientist. This is somewhat similar to the "multiplier effects" of ethnic networks (see Portes and Sensenbrenner 1993) and "structural holes" in business network (see Burt 1992). In essence, having some ties facilitates additional learning by providing more sources.

More specifically, alumni networks could be useful for referrals. Other times, they also served as "ambassadors" to facilitate mutual adjustment between enterprises and universities. Based on my informants, alumni networks often provided the starting point for an industrial partnership. One of my informants from a prestigious university in Beijing had a previous student working in the enterprise: "I am now collaborating with an enterprise. The one who contacts me is a PhD graduate from this university so we don't have any communication problems. He also gives me lots of sound ideas in many areas. Now, the enterprises become very great. . . . The better enterprises usually have a group of people with strong scientific background so we can communicate with the others very easily. Sometimes, they even think [analyze R&D problems] in a better way than we do" (interview 32, March 2005).

Network ties also helped science actors clarify business interests and facilitated articulation and practice adjustment. Adjustments happen incrementally and improve slowly. One example was about differentiating needs of business enterprises of different scales and located in different regions. The better-connected scientists had repeated exchanges with enterprises. Consequently, they developed a clear understanding about the differences between large and small enterprises, and the advantages and disadvantages of different geographical regions. One of them commented about Shanghai's research environment—one that had many small enterprises—as follows: "[Shanghai's] business environment is very good, and what I mean is Shanghai has a certain technological level and this level is good enough for earning money immediately. However, I agree it is snobbish, as people will only concern whether the product can earn money or not. [Yet], if it [the research] cannot earn money, they [the investors] will look it [the research] down and don't want to [support the research]" (interview 47, May 2005). This scientist was from a less prestigious university in Shanghai. He knew that small enterprises are often eager to see quick economic returns. In a collaborative project, these enterprises did not expect the academic partner to conduct "perfect" research. Rather, something "good enough" to deliver and let the enterprise sell products to the market quickly was sufficient.

On the contrary, larger enterprises—especially multinationals—were more ambitious. These enterprises might give the academic partner more R&D resources and time, but they expected sophisticated research and products. This could translate into tremendous pressures: "Collaborating with the [local] enterprise carries great pressures, because they require you to have very good designs and [still] make economic returns within a short time. Compared with foreign enterprises, [local ones] are still short-sighted. That is, they don't have long-term planning. For this point, I am disappointed. Enterprises like Samsung [which is a Korean high-tech company] will invest a lot in research and development" (interview 47, May 2005). The investment provided by multinational enterprises enlarges the resource endowments of Chinese science institutes. More important, the academic partner assumed increased responsibilities to ensure transparent and accountable institutional arrangements while collaborating with established international partners. In this sense, the process of networking overseas served to improve the Chinese innovation infrastructure.

While many Chinese science actors continued to enjoy international networks, they now had better knowledge about foreign scientists and became more selective in partnering. In patent activities, for example, international collaboration had become less popular. According to Table 5b, 80 percent of collaborative projects with patent applications were international ones in 2002. Yet, in 2003, international collaboration dropped to 77 percent; in 2004, the number dropped much further, to only 48 percent. One possible reason was that Chinese science actors were now more able to identify good domestic partners. In particular, division of labor between geographical regions became much clearer now, and domestic collaborations would save the international travel costs (Leung 2009). For example, a Shanghai scientist might have a great commercialization idea but lack strong technical skills. The scientist might turn to a colleague in Beijing to help with the basic science. This is consistent with the theoretical prediction of refining innovation strategies in Rogers's framework.

5.5 Routinizing (2005–Present)

Depending on the level of capabilities, some Chinese science institutes were able to routinize nanotechnology research. According to Rogers (1995), this stage is about assimilating the innovation into organizations so that members would forget that a certain practice was an innovation. The innovation is now taken for granted as beneficial to the long-term interests of the organization, and the innovation sustains.

The *High Technology Development Report* published by the CAS (Chinese Academy of Sciences 2005) documented that the NSFC supported more than 150 scientists and seventeen "innovative teams" in the year of 2004 alone. The funding amount exceeded RMB 600 million in that year. In 2006, Chinese science institutes collectively produced more than 14,000 journal articles in nanomaterials, accounting for 26.2 percent of the world's productivity in this subarea (Kostoff, Barth, and Lau 2008). Several Chinese science institutes in my sample were the world's most prolific institutes (see Tables 6 and 7). According to Jiancheng Guan and Nan Ma (2007), among the fifteen most prolific institutes that produced nanotechnology research as of 2007, five of them were Chinese science institutes.[4] This collective achievement has not only rendered China the most productive country in this specific nanotechnology subarea. In the broader realm of nanotechnology research, China has become the second most prolific country, just behind the United States (Kostoff et al. 2006; Kostoff, Barth, and Lau 2008).

Several research institutes in my sample have attained a consistently high performance in publications and patent outputs. Based on performance records, these institutes have shown a high prospect of sustaining productivity in nanotechnology. Tables 4, 6, and 7 show the top performers in terms of funding, publication quality, and quantity. These top performers—or sustainers—include CAS, Tsinghua University, PKU (in Beijing), Fudan University, and Shanghai Jiaotong University (in Shanghai). Between 1986 and 2006, more than 10,000 nano-related patents had been filed in the Chinese Intellectual Property Office. The top performers continued to apply and

[4] It is noteworthy that Guan and Ma (2007) treated all the CAS institutes as one organizational entity. As a whole, CAS produced 4,541 nanotechnology research papers in 2007.

Table 6 Productivity in nanotech publications by subareas: United States and China

Nanotech area[a]	World productivity (no. publications)	US productivity (percent)	China productivity (percent)	US:China ratio
1	2,028	25.6	11.0	2.33
2	1,053	23.5	12.3	1.91
3	16,432	27.2	11.6	2.34
4	6,319	21.6	17.2	1.26
5	2,251	18.9	19.1	0.99
6	2,509	18.1	16.6	1.09
7	1,752	15.1	14.0	1.08
8	394	20.8	22.3	0.93
9	474	19.6	32.3	0.61
10	1,876	27.6	28.3	0.98
11	447	37.1	14.5	2.55
12	414	47.8	18.8	2.54
13	14,263	18.0	26.2	0.69
14	8,423	17.9	22.6	0.79
15	775	33.3	13.5	2.46
16	5,070	34.9	8.5	4.12

Note: [a] Nanotech areas listed by Kostoff et al. (2006): (1) quantum dots (2,028 records); (2) quantum wells, wires, and states (1,053 records); (3) optics and electronics (16,432 records); (4) magnetism and tribology (6,319 records); (5) properties of thin films (2,251 records); (6) application of thin films (2,509 records); (7) deposition of thin films (1,752 records); (8) diamond films (394 records); (9) applications of carbon nanotubes (474 records); (10) multiwalled nanotubes (1,876 records); (11) single- and double-walled nanotubes (447 records); (12) single-walled nanotubes (414 records); (13) nanomaterials and nanocomposites (14,263 records); (14) polymers, composites, and metal complexes (8,423 records); (15) DNA (775 records); (16) proteins and cellular components (5,070 records). It is not clear why Kostoff et al. used two categories for "single- and double-walled nanotubes" (11) and "single-walled nanotubes" (12).

obtain a large number of nanotech patents. An increasing number of these patents were for biomedical applications. On the other hand, government funding became more evenly distributed. According to Table 4, the top ten institutes provided 35.14 percent of total NSFC for nanotechnology research in 2005 (compared with 54.1 percent in 2000). In 2008, the percentage dropped further to 29.94 percent.

To achieve routinization, my informants told me that improving the research quality was an important item in their "to-do" list. For this matter, overseas networks have significant "prismatic value" (Podolny 2001). That is, if Chinese scientists collaborated with an overseas scientist (especially those from the United States), the impact of their research increased on average. Kostoff et al. (2006) compared nanotechnology research papers authored by Chinese scientists alone ("China-only" papers), American scientists alone ("US-only" papers), and coauthored papers by Chinese and American scientists ("US-China" papers). According to their findings, China-only papers had a median citation count of four (i.e., meaning that only four other scientists

Table 7 Funding, publications, and citation score for the fifteen most prolific Chinese institutes in nanotechnology research, 1999–2003

Institute	Funding in 1999–2003 (million RMB)[a]	Publications in 2003	Highly cited publications in 2003
CAS	72.2	1,893	53
Tsinghua University	17.2	508	23
PKU	13.6	301	15
Nanjing University	10.2	377	5
University of Science and Technology China	7.3	367	12
Fudan University	6.8	173	5
Jilin University	3.9	288	3
Shandong University	3.6	231	3
Zhongshan University	3.2	143	10
Tianjin University	3.1	98	—
Zhejiang University	2.6	238	—
Nankai University	2.4	117	4
Harbin Institute of Technology	2.1	112	—
Wuhan University	1.8	106	3
Shanghai Jiaotong University	1.5	163	—

Note: [a] As of January 2009, 1 RMB (Chinese yuan renminbi) ~ US$0.146; US$1 = 6.835 RMB.
Source: Funding data gathered by the author; publications data from Kostoff, Barth, and Lau (2008).

cite a Chinese paper on average). In comparison, the median citation count was twelve for US-only papers. For US-China papers, the median citation was ten. Collaboration between the American and Chinese science institutes benefited the latter significantly.

Some of my informants gained prestige by collaborating with one or more famous foreign enterprises (including those in Hong Kong and Taiwan). One of the most notable examples was the Tsinghua-Foxconn Nanotechnology Research Center. This center was a partnership between the FoxConn Technology Group, founded in Taiwan in 1974, and Tsinghua University in Beijing. The founder of FoxConn, Terry Gou, was from Taiwan. Tsinghua received more than US$35 million from FoxConn to build the center. The founding of this center—with a large amount of initial capital—had consolidated Tsinghua's status as the most important nanotechnology institute in China. Almost all of my informants in the entire study were aware of the center's director. Other individual scientists told me that they had gained prestige in one way or another as an affiliate of Tsinghua-Foxconn. Since Tsinghua University has been historically regarded as one of the strongest science and engineering universities in China, the partnership increased the reputation of FoxConn as well.

On an individual level, networks reinforced a scientist's reputation and allowed the scientist to exploit his or her advantages further. The experience of two of my informants—from two highly prestigious universities in the United States and China—was illustrative about such an exploitation process (March 1981). In this collaboration, both the American and Chinese scientists were themselves quite competent in their specialized fields. Yet, they believed that collaboration would augment their existing research capacity, particularly in the area of tissue engineering research. The American scientist was not an ethnic Chinese scientist, so his collaboration was not driven by family ties or “cultural reasons” (Leung and Li 2006).

The Chinese scientist produced artificial organs with nanomaterials, which he believed was compatible with the methods in tissue engineering. The American scientist told me that he originally resisted nanotechnology, thinking that there had been too much fanfare and hype associated with nanotechnology. Yet, his Chinese friend convinced him of the potentials of nanotechnology in biomedical applications. Information exchanges between the two were facilitated by the Internet and had become increasingly frequent. Over time, the two of them influenced each other and published joint papers on artificial organs, tissue engineering, and even on China’s latest nanotechnology development.

Later, the Chinese scientist was invited by the American scientist to teach in his university as a visiting professor. The Chinese scientist’s experience of teaching in a highly prestigious university in the United States attracted attention not only from his home university and colleagues in his professional circles but also the media. His reputation was enhanced. On the other side, the American scientist also benefited. With increased knowledge about the research environment in China, he published articles about the development of tissue engineering in China and attracted the attention of other potential Chinese partners and students. The tie between these two scientists has led to collaborative research that involved additional researchers from both countries. Their tie later became a basis of an institutional partnership between the two institutes.

At this point, I have presented various salient issues, obstacles, and coping strategies in each of the five stages of the Chinese nanotech journey. Table 8 summarizes the nanotech journey in China, and Table 9 summarizes the empirical and theoretical findings.

6 Discussion and Conclusion

This research analyzes the emergence of nanotechnology among Chinese science institutes as a collective innovation journey. Applying the process framework developed by Rogers (1995) enables me to discuss the major issues, constraints and opportunities in the Chinese nanotech journey logically and coherently. In further research, this framework might be modified and/or extended to examine innovation in other settings.

Substantively, this research shows that large-scale innovation is possible in contexts where the infrastructure is still developing. In the Chinese case, infrastructural constraints did not prohibit science institutes from pursuing nanotechnology. Instead, the nanotech innovation motivated Chinese science institutes to reform their infrastructures and R&D capabilities. Infrastructure does not have to precede innovation, and the two could go hand in hand. Further studies can examine how such a co-development process operates in other innovation and management contexts.

In this respect, the traditional conception of innovation infrastructure may be revaluated. That is, whether innovation is possible may depend heavily on whether

Table 8 Salient issues, obstacles and solutions during the Chinese nanotech journey

Stages	Salient issues/questions	Obstacles	Coping strategies
Agenda setting	Determining the proper strategies for entering the nanotech bandwagon	Infrastructural underdevelopment	Concentrating resources on selected institutes and R&D areas
	How to establish the goals for nanotechnology	Costs of networking and unclear benefits	Building a network-ready R&D environment
Matching	What existing capabilities can be utilized	Information deficit on nanotech's latest developments	Exploratory learning
	What nanotech subarea is the most applicable	Finding an anchor to handle nanotech's amorphous character	Mobilizing prior and existing ties
Redefining/ restructuring	How to promote the chosen subarea (i.e., nanomaterials)	Inexperience in publishing abroad	Consolidating workforce by building joint research centers
	How to enhance organizational capabilities via the network form	Difficulties in attracting network partners	Institutionalizing university-industry partnerships
Clarifying	How to align research products with business interests	Unfamiliarity with the operation of private business	Mobilizing alumni networks
	How to better distinguish among different business interests	Overly preoccupied with academic research/ business interests	Developing a more flexible mindset through learning by doing
Routinizing	How to improve research quality	Insufficiently talented scientists	Exploitative learning
	How to sustain productivity	Inability to identify additional doable nanotech areas	Increasing international collaborations

Table 9 Major Theoretical and Empirical Findings

How networks compensate for infrastructural constraints
• Shared resources in networks enlarge resource endowments.
• Relational rents provide knowledge for better proprietary activities.
• Unequal power between network partners and science actors propels rapid development of transparent and accountable institutions.
• Better industrialization knowledge facilitates the exploitation of market consumption/opportunities.
• Network-based learning depends on overcoming trust barriers.
Further development of nanotechnology in terms of basic science
• Continuous focus on selected subareas in nanotechnology research, most notably nanomaterials.
• Sustained high productivity in research publications.
• Quality of research products slowly increases.
Further development of nanotechnology in terms of applications
• Sustained increase in nanotechnology applied products.
• Increasing amount of patent applications.
• Strong interests in biomedical applications due to large population demand.
Further development of science infrastructures
• Resources continue to be concentrated in prestigious institutes.
• Increasing amount of international cooperation in research, application, and business endeavors.
• More returnees from industrialized economies.
• More selective in terms of international collaboration and more attention on domestic collaboration.

network structures are available. Based on my findings, networks offer learning materials to foster propriety activities. Thus, my informant learned that single patents were not protective enough; only a basket of patents will do the job. At the same time, the quest for overseas networks motivated Chinese science actors to improve the institutional structures for high-tech activities in China. Finally, external networks could provide actual financial support and/or better management skills for Chinese science actors to handle the problem of low resource endowment. Taken together, external networks have compensated for the industrial infrastructure of China in the nanotech innovation journey.

On the other hand, networks only facilitated Chinese science institutes to a limited extent. After attaining a high publication quantity, there were new challenges to overcome. For example, enhancing research quality through overseas collaborations would hinge on overcoming trust barriers (between collaborators) and other mutual learning difficulties. Otherwise, collaborative networks might remain nominal without any substantive value. Scientists from less prestigious institutes still had few overseas networking opportunities. Based on my observations, scientists from these institutes were still unable to articulate the business potential of their research projects very well. To improve, continuous learning (including learning-by-doing) is necessary (Argote 1999). At the same time, Chinese science actors have become more selective in overseas collaboration. To save transportation costs, more and more Chinese science actors have turned to domestic collaborators in R&D activities.

This research examines one particular innovation journey among many others in China. To be a true "innovation society," there would be more innovation journeys for

Chinese science actors. While this research shows that utilizing external networks can compensate Chinese science actors for infrastructural constraints, there is a downside of the "network strategy." That is, China's dependency on industrialized countries at the national level may continue to persist. Networks may help Chinese science actors identify high-tech bandwagons; yet, in the longer run, Chinese science actors must abandon the "good enough" attitude in new science. Otherwise, they may only remain "great followers" in science and technology.

One desirable approach for further studies is to compare China with other national settings to determine if—and to what extent—the innovation pattern in China is distinct (Salter and Faulkner 2011). Based on this research, the challenges for innovation in Chinese science institutes seem only to differ from other countries by degree, not by nature. For instance, science institutes in any country could take advantage of external networks to augment existing capabilities. It is only a matter of intensity as to how eager science institutes in different national settings were to adopt the network strategy. Comparative research can yield additional insights. Another fruitful research direction is to analyze event sequences and temporal patterns at each stage of the innovation process more rigorously. Following this direction, it is possible to conduct a multilevel study with sufficient data.

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