Dynamics of Nanosciences and Technologies: Policy Implication

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ABSTRACT
Whatever the country, nanotechnology features as a key priority of most national research and innovation policies. This focus on nanotechnology is due to the promises of this general purpose technology, this new technological wave. As 'one size does not fit all', policies supporting its development cannot just adopt the 'best practices' of the preceding wave. We argue that specific on-going dynamics of nanoscience and technology production justifies the existence of dedicated nanotechnology policies. It also questions the portfolio of instruments mobilized and their balance. In this article, we discuss policies developed for the preceding technological waves and, based on the characteristics of nanosciences and technologies, propose five dimensions of policies to be taken into consideration for their governance at the country and cluster levels.

KEYWORDS: presearch policy, nanotechnology policy mix, knowledge dynamics, general purpose technology

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1. INTRODUCTION

Whatever the country, nanotechnology features as a key priority of most national research innovation policies. This is also visible through the specific working group created at OECD, the growing importance of the ISO technical committee on nanotechnology and the new international initiatives, such as the IDRRDN[1], that bring together the heads of most national nanotechnology programmes. In Asia, the recent United Nation APCTT-ESCAP Consultative Workshop on Promoting Innovation in Nanotechnology[2] and the 2004 Asia nano forum demonstrate that the momentum is global and covers most countries in the globe.

We interpret this as the emergence of a new technological wave following preceding ones organized respectively around physics (after the second world war), information and communication technology (from the seventies) and biotechnology(from the mid eighties). These waves exhibited very different characteristics and drove to very different institutional frameworks and policies (Laredo

2006 and 2009 following Bonaccorsi approach of 'search regimes, 2008). As recently highlighted by, both, on-going academic works and policy reports[3] , 'one size does not fit all'. Meaning that each wave drove to different policies, particularly, in dealing with the portfolio of policy instruments mobilized. It has also been a recurrent phenomenon (possibly reinforced by the development of benchmarking exercises) to adopt for the next wave what was considered as the 'best practice' of the preceding wave: the French "Plan Calcul" to address the development of IT or Nixon's "War against Cancer" at the birth of biotechnology are striking examples of such isomorphous forces (DiMaggio and Powell, 1983, Cruz-Castro and Sanz-Menendez, 2007). The central argument of the paper is that on going dynamics of nanoscience and technology production both justifies the existence of specific nanotechnology policies and questions their content, that is, the portfolio of instruments mobilized and their balance.

For doing so, we shall first put in perspective existing portfolios (section 2), briefly present why experts consider nanotechnology as a new technology wave, and review the central features of first generation 'National Nanotechnology Initiatives' (NNI) (section 3). We shall then mobilise the French 'Nanobench' database on publications and patents worldwide to discuss key features of nanodynamics and their implication for policy[4]. Section 4 demonstrates that the high rate of growth observed in nano S&T production justifies the existence of NNI. In section 5, markers gathered make us consider that the observed dynamics does not drive to a new specific industry, but rather that nanotechnology will be embedded in multiple industries at the R&D stage, making it a "general purpose technology". This questions both centralised initiatives (rather than sector driven) as support tools for the development of nanotechnology, and the emphasis on start-up firms as a major component of future mass commercialisation. Section 6 then addresses the locus of such developments, showing that the world is not flat and that we face a high concentration in a limited number of clusters worldwide. The concluding section (section 7) sums up the specific features of nanotechnology dynamics and the corresponding policy issues raised, as a demonstration of the specificity of each technological wave and as a source of reflection about the challenges faced by the 2010-2020 generation of nanotechnology initiatives.

2. TECHNOLOGICAL WAVES AND CORRESPONDING POLICY PORTFOLIOS

We inherit, from over 60 years of organized governmental interventions promoting research and innovation, a rich portfolio of instruments for implementing new priorities. What is striking, however, is how different these have been depending on the technological waves and how difficult it has

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[1] International Dialogue on Responsible R&D in Nanotechnology.

[2] Colombo, December 2-3, 2009.

[3] For on-going research developments see the ERA dynamics project of the PRIME network of excellence (www.prime-noe.org) and in particular the 2007 Bonn workshop and 2008 Toulouse session). For policy reports see the report of the European Commission expert group chaired by L. Georghiou (2008).

[4] Nanobench/Nanotrendchart is a research project (2008-2011) funded by the French research agency (ANR) bringing together teams from Université Paris-Est and Grenoble school of Management (GEM).

been for most countries and policies to adjust from one wave to the other [5]. The following section recalls, very briefly and grossly, the conditions under which the different instruments developed. It sets the landscape for discussing the main components of what we call the first generation of nanotechnology policies.

Since the early times of OECD, "leading edge sectors" have been a specific focus of scientific and technical policies [6]. Politiques scientifiques et techniques were coined by OECD (1963 Piganiol report) at the same time the Frascati manual (initiated by C. Freeman) was adopted and promoted a measure of national inputs into science and development. These policies were based on two pillars: (i) developing what we call today excellence, that is basic science, through bottom-up driven mechanisms [7] and the funding of the large facilities (and the corresponding 'big science'), and (ii) 'large programmes' dedicated to leading edge sectors (aeronautics, space, nuclear power were the key focus) [8]. These large programmes were linked to the post World War II physics revolution and focused on heavy equipment industries characterized by few industrial producers and a limited number of large users worldwide (most of them nationally grounded utilities in transport, communication and energy) [9]. Depending upon countries (and in particular in Germany and France), these were complemented by a third feature, the support to industry specific "technical centres" (e.g. mechanical industries or tiles and bricks industry): funded by all actors in the industry (often through a special levy on their turnover), they were dedicated to tailoring new techniques to the specific requirements of their industry, to promoting skilled labor and to supporting actors in adopting new production techniques.

As it is classical in policies, recipes that had worked earlier were selected again for the next technological revolution based on computer science and information technology. This was the case for instance in France with the Plan Calcul. But, as will be witnessed later, some countries did not follow established paths and promoted new approaches. This was the case of the UK where the concept of 'technological programme' (Callon et al., 1997) was elaborated through experimenting.

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[5] Some analysts would argue that choices are more linked to 'national systems of innovation' and their past trajectories. We argue that differences between countries lie more in the ways the different policies have been implemented than in their definition and choice of main instruments. This is reinforced by recent work done on the role of OECD evaluations in driving countries to share similar approaches in priority handling (Henriques, 2006).

[6] The shifting names of these policies are revealing. They were first labelled 'scientific and technical policies', then technology came in at a time where a distinction was established between the knowledge base to make new products and the ability to develop such new products. Later the focus shifted from the product (science) to the process (research), and finally this move also applied to technology dimensions, focusing on the ways they were produced and inserted into effective new products and services. Innovation thus became central.

[7] may these be professional bodies – academies like in the then USSR, or fundamental science dedicated labs, like CNRS in France, Max Planck Gesellschaft in Germany or Riken in Japan) – or funding agencies, like NSF in the US, the British research councils or the DFG in Germany(the sole country then to have a balanced approach).

[8] It is not without interest to recall the governance structure of such large programmes since they are again on the forefront when discussing how to tackle new 'global issues' such as climate change. These programmes had one central coordinating body (most often a dedicated agency). This was complemented by one or more mission oriented government laboratories in charge of developing the science, the technics and of training the required capabilities. Key industrial actors (which often turned out as national industrial champions) were in charge of industrial development while the home market (again most often organised around one nationalised user –e.g. a utility or the national airline) was reserved and served as a springboard to exports and international competition. A later step, at least in Europe was amalgamation and mergers around industrial capabilities, building in all the corresponding fields world leading production firms.

[9] This period is also associated with the boom of plastic based industries largely focused on mass markets. It is revealing to see that no OECD country developed specific programmes or supports for these industries.

The Alvey programme for advanced information technology was based on a collective analysis of all concerned actors (through the report produced by Lord Alvey). The focus of the programme was on the 'strategic technologies' that were perceived as central to the future of information technology. And the central implementation mechanism was through collaborative programmes between firms (the justification being that the danger does not lie in sharing a given technology, but in being barred from accessing it if it turned crucial for the firm's new products), and between industry and university. The latter became the central feature and motto of most R&T policies in the 1980s and beyond. The justification for it mixes three complementary arguments. The first one is purely quantitative: public capabilities represented then more than half total R&D capabilities in developed countries (around one third today) and firms not collaborating would loose in investment capacity. The second one is linked to the respective roles of actors: while firms found it more and more difficult to invest in longer term and 'frontier' science, this was the main focus and driver for public research. Finally, the third argument is linked to the notion of 'absorption capacity' (Cohen and Levinthal, 1990) facing the tacit dimensions of new knowledge (Polanyi, 1968): in new or 'frontier' science or technology, collaboration is central for firms to master internally the new technologies and to be able to integrate them in their new products. 'Technological' or 'collaborative' programmes have since then become a central policy instrument.

Information technology soon appeared as central to nearly all industries. It was also clear that most IT policies focused on technological offer while the debate on the influence of market demand upon innovation was growing (Mowery and Rosenberg, 1979). OECD again pushed a review which drove to the famous article by H. Ergas (1986) and the interest in diffusion policies. There was, however, little direct connection between the concept and new policy instruments, and this drove to diverse implementation routes. Following Vernon cycle (Vernon, 1966), and in the wake of works on dominant designs [10], Ergas made a strong difference between emerging and mature industries. We focus here on the former while the latter have been the focus of multiple developments[11]. Following Winter and Nelson's seminal work on evolutionary economics (1982), the central idea was to generate diversity. No one instrument could do it alone. Ergas put forward two central principles: a friendly environment (which has recently witnessed multiple new developments[12]) and 'decentralised' approaches. Two central mechanisms were highlighted: the multiplication of offer and the support to new technology based firms[13] that would be better fit to relate to users (Von Hippel 1988) and develop new uses; the agglomeration of capabilities in key nodes, following the US models of route 128 and Silicon Valley (Saxenian, 1994).

Start-up policies (from incubators to funds supporting seed and venture capital) and cluster-

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[10] In particular Abernathy and Clarck (1985) or Tushman and Anderson (1986) on breakthrough innovation and the emergence of new dominant designs. It was also the time when, studying innovation in agriculture, Rogers published its famous model on 'the diffusion of innovations' (first edition in 1968).

[11] Two are worth mentioning. The first one was to support small firms in integrating the new technologies in their products. This was taking over a classical support mechanism warranted on a market failure argument with, for instance, French 'aides à l'innovation' (started in 1968 and later taken over by a specific agency, ANVAR) or the US 'Manufacturing extension programme' (developed under the Clinton administration, based upon long lasting state interventions, Shapira, 1998). The second one followed the path proposed by Becattini reviving Marshall's second option (besides large firm vertical integration) that is to switch policies from industrial sectors to industrial districts (Becattini, 1990). This has generated numerous developments until Porter's notion of cluster (1998) became the reference

[12] See in particular European developments around demand driven innovation policies, dealing with standards, procurement and the notion of 'lead markets' (e.g. the EU Aho report, 2006).

[13] See the review made by Bollinger, Hope and Utterback (1983).

based policies (Porter, 1998) that were initiated then, became the central vectors for policies supporting the biotechnology wave. Revisiting the biotech revolution (e.g. Rothaermel and Thursby, 2007), we can, in retrospect, see how important start-up firms have been as a link between the new science base created and existing incumbent (mostly pharmaceutical) firms. They acted as a bridge and, when successful, translated the new science produced into new drugs that established pharmaceutical firms could then develop and market. These biotech firms developed mostly where 'frontier science' was developed, that is, for the US, in the few places where strong research universities are located, driving to a strong concentration in a limited number of clusters as highlighted by the collocated biotech networks analysed by Owen-Smith and Powell (2004). This articulation between start-up firms and clusters highlighted the importance of the science base. It drove, within less than one decade, to a rebalancing of efforts within public policies, putting back on the agenda the importance of 'fundamental research' and of its central performing place, universities[14].

Thus, we face a situation where each new wave developed new instruments that complemented preceding ones and drove to a new balance in resource allocations. Showing the central role of these new institutions and instruments does not mean fully discarding preceding ones. For example, policies that fund large facilities (and not only for physics, e.g. the large cell and genome data banks for biotechnology), technological and collaborative programmes have been central to the implementation of the European biotech policy. Some say that these choices are context dependant, linked to the different 'national systems of innovation' and their past trajectories (Nelson, 1993). Our assumption is different: each technological wave has witnessed the progressive adoption by countries of similar instruments, and even a similar policy mix (Bach and Matt, 2005). However, the ways in which these instruments have been implemented is highly dependent on past trajectories and on a country's 'national preferences of structure' (Weiller, 1949). In this article, we focus on the former issue, the shared portfolio of instruments.

3. FIRST GENERATION NANOTECHNOLOGY NATIONAL INITIATIVES

Nanotechnology deals with "the understanding and the control of matter" at the level of the nanometer. At this level, "unusual physical, chemical, and biological properties can emerge in materials". "These properties may differ in important ways from the properties of bulk materials and single atoms or molecules". These "unique phenomena enable novel applications" (NNI, 2007). Nanotechnology research covers diverse scientific and technological fields (physics, chemistry, molecular biology, information and communication technology, engineering) and its potential value lies as much in the new possibilities offered in each of these fields as in their convergence (Nordmann 2004). "The interest in nanotechnology arises from its potential to significantly impact numerous fields, including aerospace, agriculture, energy, the environment, healthcare, information technology, homeland security, national defence, and transportation systems" (NNI 2007-2010 Strategic Plan). A key dimension of nanotechnology R&D lies in the fact that working at the nanoscale requires developing shared concepts, capabilities and instruments for "imaging, measuring, modelling and manipulating matter" (NNI, ibid.).

Research in nanotechnology has long and deep roots (most papers go back to the famous 1959 speech by Feynman: 'there is plenty of room at the bottom'). Nanotechnology actions by funding agencies can be tracked since the early 1990s. The development of an encompassing policy is associated with the inclusion in the 2001 US budget of the "nanotechnology national initiative", confirmed in 2003 by the US 21st century nanotechnology R&D act. The US NNI was rapidly followed by Japanese and Korean ones, while the European Union developed a nanotechnology programme[15]. Within 2 years, most OECD countries had their own initiative or programme. This has been a lasting movement and at the end of this first decade, as demonstrated by the analyses of the OECD working group on nanotechnology, nanotechnology research is a major national priority in all OECD countries and beyond.

An in depth analysis of these policies shows that they share similar aims, with 5 main goals: mixing research, facility building, education, transfer and societal aspects (so called 'responsible development')[16]. For the purpose of this article, three are central to discuss resource allocations.

- As in previous technology waves, but in a minor mode as compared to the physics wave, one policy dimension deals with the development of facilities. These facilities resemble very much the "technological platforms" of the biotechnology wave (Peerbaye & Mangematin, 2005), being rather an articulated set of mid-size instruments rather than a very large telescope or a synchrotron radiation facility. They are decentralized and organized in networks (e.g. Dutch, French and British initiatives).

- Transfer is warranted on a 'friendly ecology' (US and German initiatives) while most discourses about these policies focus on nanotechnology start-up firms (Bozeman et al. 2007 for positioning the issue). This is especially visible in the UK where all documents emphasize exemplary new firms.

- Research is the realm of programmes. These national programmes exhibit important differences. They differ depending upon the inclusion, or not, of bottom-up based exploration (present in the US and French programmes, but not in the German initiative). Some initiatives include the national labs as key dimensions of their own (e.g. the US NNI and DoE labs, Japan with a systematic dual implementation of priorities, through national labs and through funding agencies), while others consider them as performing entities (e.g. Germany, the Netherlands or France). However, their major difference lies in the overall approach selected. Either the approach focuses on the common abilities required, and then most nanotechnology funding is gathered under one central programme, as in Japan, France, Korea or the EU. Or the focus is on different potential applications fields, driving to 'targeted programmes' managed by the different technical ministries or agencies. The latter are then assembled under an overall coordinating body with more or less impact on individual trajectories. The US NNI is exemplary of this second approach with a coordinating mechanism at the President's level and, following the 'mission oriented' tradition of the country (Bozeman and Dietz, 2001), implementation by the

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[14] Europe is exemplary of such developments with the creation of new funding agencies (ERC at European level, ANR in France) and policies to nurture excellence in Universities (see the German excellence initiative or the French Campus policy).

[15] In fact a sub programme since it was common with the new materials programme.

[16] Facing public debates and controversies at an early stage, all national policies have developed a dual component dealing with 'environmental, health and safety' (EHS) aspects (with an important focus on toxicology and on standardisation issues) and with 'ethical, legal and societal implications' (ELSI) focusing on public dialogue and R&D practices – the European code for responsible nano R&D, the international dialogue on responsible R&D in nanotechnology (IDRRDN) or the International risk governance council (IRCG) are illustrations of the shared issues faced by countries.

different sectoral federal agencies in charge of supporting research and development. Germany, though having one central programme, has organized it around the different industries, driving them to define 'lead innovation' projects dedicated to speeding up the inclusion of nanotechnology in their capabilities and new products.

Though very striking at the beginning of the decade these differences are less and less relevant and we witness a convergence around three poles (as exemplified by the French case, see Textbox 1): (i) supporting 'frontier science' and a wide exploration of potential new concepts, (ii) developing an articulated nanoprogramme on the instruments, methods and processes to work at the nano level (nanoimaging, nanocharacterisation, nanosimulation, nanomanipulation and nanofabrication), and (iii) focusing collaborative projects and public-private partnerships on given applications and sectors considered as strategic (energy, health and environment on the side of 'public goods', microelectronics, new materials and biotechnology as privileged industries).

Overall this gives a very converging image whereby the core of the activity lies in targeted 'technological programmes', complemented by support to frontier science and facilities and accompanied by the mobilization of existing tools to support the emergence of start-up firms (and at a lesser, but far more important level than in preceding waves an accent on standardization, Delemarle 2009).

Our ambition is to confront this portfolio with the observed dynamics in nanoresearch and technology worldwide. Many observers have spoken of the hype around nanotechnology (Rip, 2006): do we observe a real focalization of scientific and development activities? Technological programmes have up to now been associated with the emergence or consolidation of one industry. Do we face such an emergence? Or do nanotechnology dynamics drive us to consider it as a 'general purpose technology'? Does the latter mean a wide diffusion in sectors? And if this is the case, what type of geographical developments are observed? Is the world of nanotechnology 'flat', as one would expect when a technology pervades all sectors and industries? The three following sections look at these aspects in turn.

[BOX 1] SOME NOTE ON THE EVOLVING FRENCH PROGRAMME

Initiatives on nanotechnology started at the ministerial level in the second part of the 1990s. It was organised in two programmes: a nanoscience action incitative based upon the bottom-up development of mono or multi-PI projects, and a network approach favoring cooperative public-private partnerships in different domains (mostly in nanoelectronics).

In 2004 all ministry-based project funding was gathered in one autonomous funding agency, ANR, which was in charge of funding disciplinary-based fundamental research through programme blanc and application-oriented strategic cooperative research through thematic programmes. Nanotechnology featured high in the latter with the programme PNano. This programme witnessed an interesting development: it was one of the few thematic programmes to have an important 'basic science' component (which could be developed without industry partners); it had two core components based upon 'shared dimensions' and the exploration of new concepts. But it also had an application dimension with support to nanoelectronics developments, health and environmental applications.

Looking at de facto fund allocation by all ANR programmes (2005-08, nearly 300 million euros not including facilities, ANR data), it became clear that the programme PNano represented only half of this total and programme blanc only one sixth. One third came for targeted programmes on energy (especially solar), materials, information and communication technology and biotechnology. Within the programme PNano, it became clear that the exploration and the instrumental components were faring well while the 'demonstration' and 'application' ones were less and less attractive. The analysis made by the Programme Committee explained it by two dimensions: (i) the difficulty to co-fund at significant levels the demonstrations proposed, and (ii) the need for a stronger connection with application oriented programmes, meaning a better inclusion of "nano demonstrators" in these programmes.

These considerations, associated to the wider political environment, drove to a complete reshuffling of the ANR nano policy in 2010 (with elements of it initiated in 2009 as part of the government recovery plan). The policy is now organised around three components: (a) a nanoscience programme (which appears as such for the first time in programme blanc which was until then only disciplinary driven); (b) a nanotechnology programme, called P2N, organised around characterisation, modelling, simulation, fabrication and around the feasibility of new concepts; (c) a nanoinnov programme concentrated on given sectors and their new applications (while nanodimensions of other application programmes are more clearly identified).

4. EXPLOSIVE GROWTH IN SCIENCE AND WIDE EXPLORATION IN TECHNOLOGY JUSTIFY THE POLICY PRIORITY GIVEN TO NANOTECHNOLOGY

This section and the following ones build upon the construction of a new data set of nanotechnology publications and patents[17]. Textbox 2 presents the main methodological choices and developments made.

A clear image emerges from the publication data which gathers some 538,000 articles (Figure 1) corresponding to 1.1 million different addresses of authors: an explosive growth, of some 14% per year, well above the average growth of publications accounted for by the Web of Science (3%) or dealing with the emergence of new fields, such as Human Genetics in the 1990s (around 8%, OST 2003). Following analysis of previous waves, part of the explanation for such a growth could lie in 'relabelling' (Rip, 1983). This would mean that there is a cumulative and iterative movement between the creation of targeted funding programmes to answer observed growth and the ability of academics to 'relabel' on-going work around new priorities or fashionable topics. This may well exist, but Figure 1 shows that the share of articles that do not contain the string 'nano' and that have been included still represents over half of the papers at the end of the period under observation (2006).

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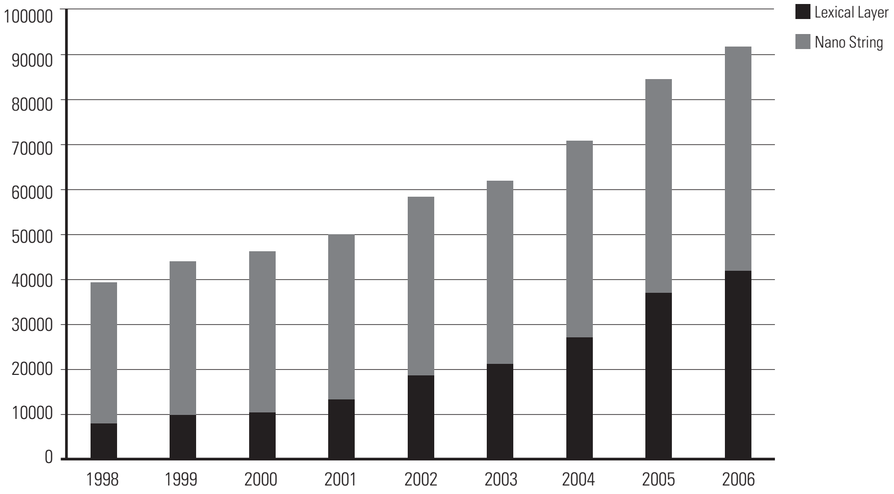
[17] This development has been supported by CEA (2006-07), the EC through the PRIME network of excellence (2007-2008) and is now supported by ANR (2008-2011), through the Nanobench project (see note 4).

This explosive growth is not fully mirrored in patents (Figure 2): some 176,000 priority patents have been taken during the same period, but the pattern is very different. We have witnessed a doubling of patenting activities from 1998 to 2002 and since then limited variations worldwide around 21,000 patents per year. To give an order of magnitude, this is more than renewable energies together (wind, solar and fuel cells)[18]. This shows the already relative importance of inventive activities. At the same time, it demonstrates that after an initial anticipation of rapid market development, downstream applications driving to deepening and complementing initial patents remain 'limited', explaining the observed world 'plateau'. This drives us to consider that we are still, mostly, in an exploration phase[19]. This hypothesis is further supported by the results of Bonaccorsi and Thoma (2007) which show that nearly 70% of patents include academic authors[20].

FIGURE 1. NUMBER OF PUBLICATIONS IN « NANO » BY YEAR AND DATA LAYER



Source: Nanotech/ Nanotrendchart project, 2008

Explosive growth in science, wide exploration in technology: this clearly justifies the existence of targeted programmes. Gathered data even shows that programmes have followed a first 'scientific' explosion. Since then, we can assume that these public investments fuel this rapid growth. Furthermore, the vast presence of academic authors in patents is an indicator of the importance of 'collaborative dimensions' and, thus, also confirms the relevance in the public funding mix of 'technological programmes'.

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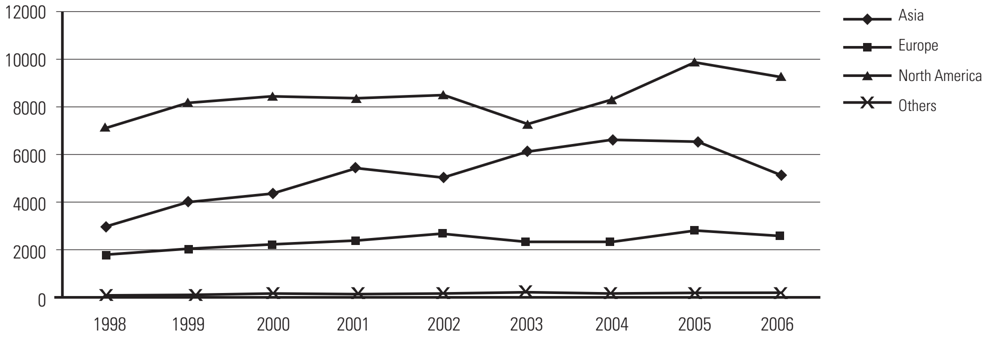
[18] Own treatments done using the OECD queries on 'clean technologies'.

[19] We use it following March (1991) between exploration and exploitation.

[20] Meaning authors that publish articles in journals included in the WoS, irrespective of their institutional affiliation.

FIGURE 2. EVOLUTION OF PRIORITY PATENTS PER GEOGRAPHICAL AREAS



Source: NanoBench/ Nanotrenchart, 2009

[BOX 2] METHODOLOGICAL NOTE ON DATABASE CONSTRUCTION AND ENRICHMENT

This box explains the methodological choices made to characterize the dynamics of nano S&T production. We use two datasets: the Web of Science for publications and Patstat for patents.
A central issue deals with delineation. Mogoutov and Kahane (2007) explain the choice made to use an automated lexical modular methodology. This method does not use experts, it is based on an initial nano string that is progressively enriched by other keywords selected using an intercitation network density method. New keywords are tested for their specificity and added up to form the final query. This approach was first employed to extract publications between 1998 and 2006. The database contains 538,000 articles, and is considered by Huang (2008) as one of the largest database so far in the bibliometrics field.

This approach was also used to extract patents from the EPO Patstat database which is being built as the database of all national patent offices. The query gave 66,000 patents. A specific issue lies with the numerous extensions an initial patent (called a priority patent) gives rise to. Being dedicated to trace new knowledge, we decided to focus only on these priority patents, taking as the relevant date of production, the filing date and not the date the patent was granted (which comes generally between 2 to 6 years later). Thus, the final database, including patents up to 2006, contains some 220,000 entries.
Three major enrichments have been made dealing with localization (of authors and inventors), institutional affiliation and thematic focus.

For thematic affiliation (publications only), the choice was made to use existing In-Cites Essential Science Indicators. To examine the distribution of publications along the three main areas recognized by nanoscientists (physics and microelectronics, chemistry and nanomaterials, life sciences and nanobiotechnology), we have examined the distribution of the papers in the database and built the categories by aggregating In-Cites categories (see Delemarle et al. 2009 for a detailed explanation).

Geolocalization and the construction of clusters built a major second enrichment. A full presentation of the methodological developments made for allocating geographical coordinates to each address can be found in Delemarle et al. (2009). 97% of all articles and 94% of addresses were geocoded. To construct clusters, we selected all cities with 1000 addresses or more over the observed period (a rather low threshold, just over 100 publications per year, on average). We, thus, identified 293 'core cities'. To move from cities to 'clusters' we chose a geographic distance (50 kilometers after sensivity tests[21]) because in many countries there is no equivalent to the US 'metropolitan areas'. We used a statistical method to assess overlapping between clusters, aggregating smaller ones into larger ones when duplication was over 20%. This gave 203 clusters, regrouping 85% of total publications and 77% of all addresses.

The third enrichment dealt with categorizing organizations in "firms" (identifying large world R&D players within it), "universities" (including institutes of technology like MIT or Georgia Tech and university hospitals), "public research institutes", and "others" (mostly other hospitals, foundations and not for profit research organizations). Parsing techniques were used to separate names of organizations from addresses in publications while Patstat standardised names of assignees were used and checked against original names. Working on publications we were able to build a reference database on higher education institutions, using a combination of automatic techniques based on harmonized WoS labels, the presence of 'Univ' or 'institute of technology' or of 'department', and a manual check at the level of clusters. This was fed into the patent database and compared to assignees' names. A similar approach was used for public research organizations (where the WoS list is more elaborated and where markers such as academy and research institute enable to trace most of them). For firms, automatic techniques based on harmonized WoS names, markers of firms (AG, SA, ltd…) and a comparison with the DTI list of the largest firms in term of R&D (2006) enabled us to build a database, which was manually checked at the level of clusters (using internet sites as a source). What was left gave rise to the others category (once more, manual control at the cluster level enabled us to re-allocate those corresponding to the 3 previous categories).

5. A NEW MAJOR NANOINDUSTRY, RATHER A GENERAL PURPOSE TECHNOLOGY

The presence of an important patenting activity enables us to address issues about future economic developments. Will we witness the emergence of a new industry, as was the case in aerospace (with the aeronautics industry), or in information technology with the development of the computer industry, and more widely in the electronics sector? Will it follow the pattern of biotechnology, where start-up firms have played a catalytic role in its initial development[22]? We can expect that major incumbent R&D players will play a marginal role in the latter case or be focused on one specific industry in the former case. Table 1 drives to a very different conclusion: a majority of world largest R&D players (as accounted for by the DTI scoreboard) are present, and this covers all fields.

We take this as a very clear marker of potential pervasiveness (remember that we are still in ex-

TABLE 1 The Presence of Large R&D Industry Players in Inventive Activities (DTI scoreboard)

Field of firms	Total Firms	Firms with Nano Patents	%
Electronic & electrical equipment	103	70	68%
Technology hardware & equipment	226	150	66%
Chemicals	96	84	88%
Pharmaceuticals & biotechnology	153	73	48%
Health care equipment & services	53	39	74%
Automobiles & transport	86	59	69%
Aerospace & defence	35	24	69%
Materials & construction	55	42	76%
Oil, Gas & Electricity	53	39	74%
Food producers inc. Beverages)	32	16	50%
General industrials	38	24	63%
Household & personal goods	40	21	53%
Industrial engineering	70	35	50%
Telecom & media	32	14	44%
Software & computer services	110	14	13%
banks, insurance, retail, leisure	49	6	12%

Source: DTI scoreboard and Nanobench/ Nanotrenchart project, 2009

ploration). Linking this to the above mentioned explosive growth drives us to wonder whether we do not face a "general purpose technology" (GPT)[23]. Bresnahan and Trajtenberg (1995) characterize general-purpose technologies "by the potential for pervasive use in a wide range of sectors and by their dynamism" (83). They further underline that there has been a 'prevalent' general purpose technology in each 'era' (85). Their reference to Griliches (1957) and his study of hybrid corn, highlighting the invention of a new method of inventing, "a method for breeding superior corn for specific localities" (86), drives them to focus on 'innovational complementarities'—"that is the productivity of R&D in a downstream sector increases as a consequence of innovation in the GPT technology" (84).

This approach warrants a dual interest both in technology generation and in the ways diffusion takes place. In further work done on GPT, both dimensions are articulated through the emergence of dedicated industries: new equipments (like the Corliss engine, Rosenberg and Trajtenberg, 2001), new utility companies (like electricity, Moser and Nicholas, 2004) or a new sector producing mass intermediary goods (Jovanovic and Rousseau on IT and semiconductors, 2005).

The hypothesis we derive from the above mentioned patent data might offer a different articulation between production and diffusion. What we witness is that incumbent players in multiple fields develop nano R&D. Pervasiveness, as was the case for hybrid corn, happens directly at the research and development phase in the different industries. Thus, there should not be a new specific industry, unless we consider that the development of instruments and software for undertaking R&D at the nanoscale level warrants a new industry segment.

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[21] Except for 3 very dense countries (Japan, Taiwan and Korea where the distance was reduced to 30 kilometers).

[22] Even if this is being reconsidered for its maturation. See Rothaermel and Thursby, 2007.

[23] This hypothesis has been recently discussed by Youtie et al. (2008).

This has strong policy implications: in term of new economic activities, the objective is no longer to build an IT or a biotech like industry, but to insure that different existing industries and different firms within these industries master these new R&D competences and can integrate them in their new product development. The focus will then clearly be on 'diffusion policies' at the R&D stage, with three main policy options to be considered. One option is to revive the industry-specific 'technological centres' from the physics wave (see section 2) for developing tailored tools (especially simulation models) and 'technological platforms' gathering in adapted facilities the set of equipments required (working at the nano level is costly).

A second one, which seems to prevail in the second generation of NNI, is to develop industry-targeted programmes. A third one focuses on capability building, considering that the main barrier lies in firm absorptive capacity (especially small firms). This has a dual meaning: (i) there is a need for higher education to provide the necessary trained manpower; (ii) firms must be incited to recruit and integrate these new engineers and researchers (and there are here clear examples of such policies in the 1980s in Germany and France).

These policies imply the existence of a strong and diversified public research and training capability, focusing less on applied dimensions than on the "ways of doing nanoresearch" and the corresponding understanding. Here, we face what was typically labelled as 'strategic science' by Georghiou and Metcalfe (1990), and implies focusing on development of devices within public research funding.

Such results also question the de facto importance given to start-up policies. However, there could be two important reasons for mobilizing such policies. One is that the new instrumentation segment is mostly made of such firms. The other is that societal uncertainties about nano 'acceptability' (e.g. Siegrist et al, 2007) are so high that large firms, while still developing R&D activities, prefer to leave the role of demonstrating the value of new products to smaller firms. This would then drive to similar dynamics as in biotechnology, whereby the successful trajectory of a start-up is not to become a new large firm, but to be bought by one existing large firm (Rothaermel and Thursby, 2007). There are wide discussions about the benefits for a country or a region to support such firms when most are bought by global players that locate the corresponding economic activities in other regions or countries (Phil Cooke, 2006, coined the term 'decapitation' to discuss this phenomenon).

6. EXPLORATION CONCENTRATED IN A LIMITED NUMBER OF CLUSTERS WORLDWIDE

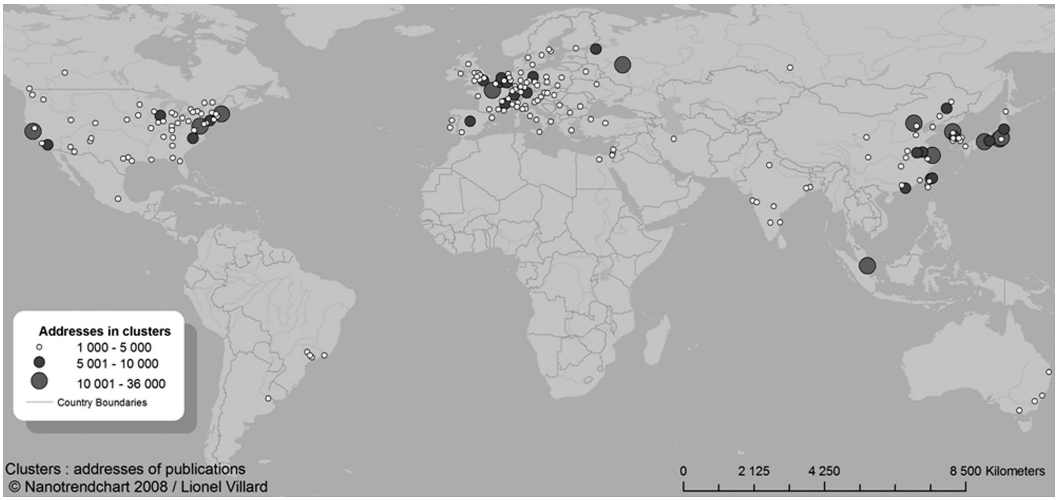
We, thus, face a first challenge whereby policies need to develop generic capabilities and to focus on their diffusion within existing industries. These are not new issues per se. But, the last two decades, at least in Europe, have highlighted that the performance of such policies were, in great part, linked to their delivery mechanisms. More than effectiveness of implementation structures, the issue has been on appropriateness of such structures. We have witnessed de facto specializations between levels, that is, national policies being complemented even superseded both by regional and European ones. While the first IT policy initiatives were mostly national (following the UK Alvey programme), we have observed a growing role of the EU in supporting ICT to the point that it is now taken for granted that the support to new, fast-growing technologies should include an important European component (as nanotechnology demonstrates). At the same time, the national level has been more and more challenged as being adequate for diffusion policies. Following the Italian districts (Becattini, 1990), multiple policies have focused on the local level of articulation as being central to the effective circulation and absorption of knowledge by firms. We have witnessed both a transformation of central policies and a growing role of regional ones. France is a good case in point for both, with the shift, since the beginning of the 21st century, of central policies towards pôles de competitivité (Delemarle and Larédo, 2005) and with the growing role of regions in supporting firm innovation capacities. This is mirrored in academic work, regional innovation systems being by far the most popular topic within systems of innovation (Carlsson, 2005).

Most of these works, however, focus on mature industries and technologies. This is well exemplified by Porter's famous wine cluster. However, biotech development in the US also witnessed a high concentration of biotech firms and public capabilities in a limited number of central clusters (Powell et al., 2002). Similar analyses have been made for nanotechnology, Zucker et al. (2007) contending that this phenomenon is cumulative, whatever the technology wave. Shapira et al. (2008) confirm this trend for nanotechnology in the US. This partly contradicts both academic work (e.g. mode II by Gibbons et al., 1994, that argue about a changing paradigm based on distributed capabilities) and the fashionable sentence and book by T. Friedman (2005): 'the world is flat'.

One of our aims has, thus, been to test this notion of concentration in a limited number of places, which we confirm with just over 200 clusters, representing 80% of total publications in nanoscience and 75% of inventors of nanopatents. A second question was to see whether what is true in the US (a geographical pattern that is in continuity with existing hierarchies) also applies worldwide. The answer is clearly no, and this applies both at global and European levels. Much like Japan's emergence as a central player in the 1970s, other Asian countries (China first but also Korea, and to a lesser extent India, Taiwan and Singapore) have become central to the on-going knowledge dynamics, though more often in publications than in patents (Map 1).

Differentials in rates of growth (Figure 2) drive us to anticipate a radically different hierarchy within less than one decade. In an econometric analysis, Mangematin et al. (2009) propose a synthesis of both phenomena by showing that two main criteria explain overall growth: past trajectory and location (the latter referring de facto to Asia, as opposed to the US and Europe). Even within

MAP 1. LOCALIZATION OF THE 203 NANOCLUSTERS WORLDWIDE

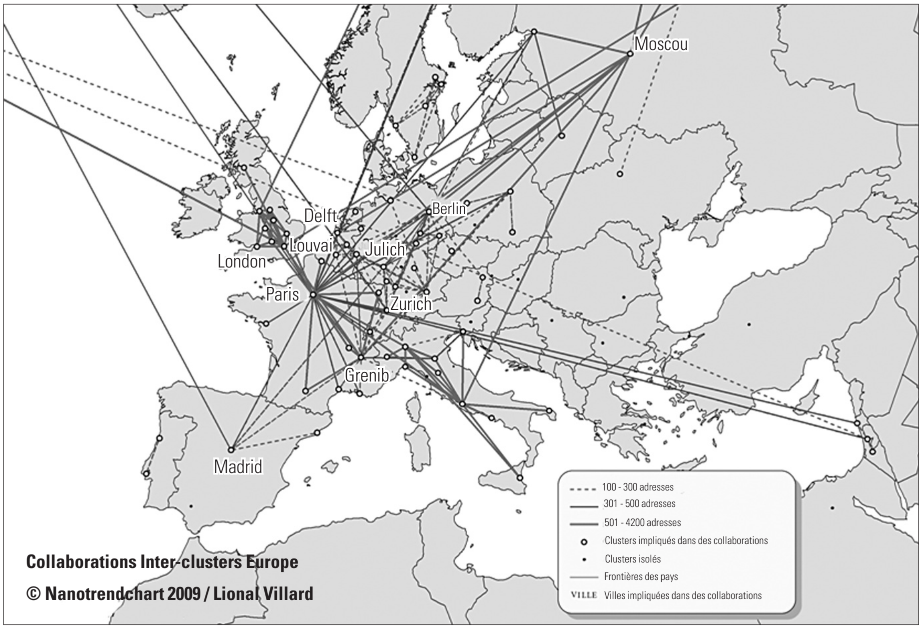


Clusters : addresses of publications
© Nanotrendchart 2008 / Lionel Villard

Europe, the classical views on inherited hierarchies no longer prevail: Oxford and Cambridge do not drive Europe any longer (even in the UK, London plays a bigger role); places like Leuven in Belgium or Grenoble in France have now reached a high degree of centrality[24], while cities like Madrid or Jerusalem[25] have become important players. Within the 80 European clusters, those from 'new member states' and from Southern Europe, though on average smaller in size, have become significant players. (Map 2).

Once more this entails strong implications for public policies. What does the concentration on a limited set of clusters tell us? Probably two central aspects for policy development:

MAP 2. CLUSTERS IN EUROPE AND INTERCONNECTIONS BETWEEN CLUSTERS



One is that this concentration enables us to rethink diffusion policies by engineering linkages at both industry and geographical levels. There are two consequences: one is classical, that is to develop policies for engineering relations within nanoclusters, and, in particular, between actors in nanoscience and technology and the other existing industries of the cluster, in order to foster the targeted production and diffusion of nano-based knowledge. The other is to consider the fact that most clusters are concentrated on one industry only: this drives us to organize specific actions tailored to reinforce bilateral actions between one 'nano' cluster and other industry-oriented clusters to enable the diffusion of nanotechnology and its exploitation within these other industries. Such policies are still in their infancy.

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[24] Centrality is based on the number of incoming and outgoing links between one cluster and the other ones.

[25] Europe for research includes EU members and members specifically associated for research activities (e.g. Norway, Switzerland or Israel).

The other aspect, complementary to above-mentioned developments, is that policies devoted to ‘strategic research’ should have both a thematic and a geographical component. National nanotechnology initiatives have mostly focused on the former. And the latter has mostly been covered by infrastructure policies only (around nanotechnological platforms). In France, the importance of bottom-up initiatives (and regional policies) has been central in this second direction (Delemarle 2007 on the emergence of Minatec in Grenoble). However, these policies have remained focused on infrastructure while other dimensions remain to be explored.

7. MANAGING TENSIONS: TOWARD A RENEWED POLICY MIX?

Nanotechnology dynamics face governments with a unique tension, even a paradox. On the one hand, it should become a general-purpose technology of a new kind, with its penetration being linked to “ways of doing R&D at the nanoscale”, and not to a new equipment, goods industry or to a mass-produced, intermediary goods. Thus, it should entail strong diffusion policies addressing the R&D capabilities of firms. And on the other hand, supply is more and more concentrated in a limited number of clusters worldwide. How both trends can be simultaneously accommodated is the difficult question that policies have to address.

The analysis offered a number of arguments, which question directions taken, and even more, the effective balance of the policy mix (Bach and Matt, 2005). We identify five dimensions before discussing the challenges raised by the governance of such policies.

A first dimension deals with capability building. In a knowledge base economy, human resources are a key dimension[26]. At the same time, curricula remain mainly grounded in established disciplines, while “doing R&D at the nanoscale” entails crossing boundaries (e.g. electronic engineers requiring quantum physics). Thus, a critical effort for policies is to focus on training curricula. Work done by P. Stephan (2007) shows that wide diffusion will require more than doctoral level education and that master level programmes of significant enough size are as (and even more) important. Looking at present day policies, these dimensions are always mentioned, but their implementation remains limited to, at best, a few supports to doctoral programmes. We believe that second generation NNI should make this dimension a key element with adequate programmes and procedures that directly address the support of curricula at the master level and of doctoral schools (concerning both the functioning of these costly training programmes and including significant numbers of grants).

A second dimension lies with strategic research associated with the instruments, concepts, and models needed to work at the nanoscale, as well as the exploration of new concepts that derive from those new capabilities. This revives the notion of ‘strategic research’ mentioned earlier, which was developed at the end of the 1980s. This is what justifies the quasi-systematic presence in funding agencies of dedicated nanoprogrammes. However, looking at the high concentration of science in clusters, we derive the fact that the latter play a critical role in being the hosts of the projects funded. But, as observed before, this support has many chances to focus only on the strong points of the cluster, limiting the coverage of available ‘bricks’ for application oriented R&D. This is why we suggest that programmes focused on nano strategic research entail both a thematic and a geographical

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[26] This aspect is well mirrored by the increasing share of an age class entering higher education.

component. Such aspects are still in their infancy and we know very few cases where the governance of clusters and means available for fostering research may cover this. This is indeed an important dimension on which policies need to experiment!

A third dimension lies in the capacity to integrate and tailor this knowledge base for application oriented R&D. We have seen the wide coverage of fields and the important involvement of the largest world R&D players. If policies wish to accelerate the wide diffusion of these new ways of inventing and developing new products, it is critical to go beyond this stage and ensure a wide enlargement of these capabilities within concerned industries. The present dominant answer is to develop targeted programmes around major societal dimensions (mostly energy, health and the environment). But, our data shows the dynamism of new materials, and we all know nano-enabled products in textiles or agro-food. The German option of 'leading edge innovation projects' might provide one answer to this broad diffusion stake. But, the German case also reminds us of the power of the post World War 2 'industrial collaborative centres' (also called 'technical centres' in France, see section 2) in promoting the tailorization and diffusion of new techniques. This provides a second option for diffusion-focused policies. Furthermore, our recent work on microelectronics (Kahane et al., 2009) shows the critical role played by dedicated government laboratories in the development, standardization and promotion of firm chip development capabilities, as government laboratories are the usual hosts of costly facilities funded by the government. Since what is at stake here is the R&D capabilities of firms, this might provide a third model for enlarging the number of firms with adequate nano-absorptive capacities.

Numerous works have, however, told us that such new knowledge is 'sticky'. Meaning that, when the knowledge is not cumulative, most sources mobilized by firms are found in a limited geographical radius (Audretsch and Feldman, 1996, Von Hippel, 1994). Clusters, thus, play a critical role in this diffusion process. The options mentioned above should, therefore, take this into account. Policies should also develop incentives that favor intra-clusters relationships. However, account must also be taken that many existing industries, though gathered in clusters or industrial districts, will not be located in the 203 nanoclusters identified. Thus, a new issue for policies is to foster privileged, application-oriented linkages between nanoclusters and clusters already specializing in existing industries (to give an example France has some 60 clusters specialized in one existing industry).

A final dimension lies with the role that start-up policies might play. We see a clear role for developing instruments, software and even test or limited-batch production for supporting the R&D effort of incumbent firms. This is far from creating new mass markets and new industries. Governments should, thus, thoroughly review their programmes and proportion them to the nature of the stakes, focusing more efforts to support the transformation of R&D capabilities of existing firms. For the latter, 'targeted' or 'oriented' tax credits might be a powerful instrument.

These five dimensions cannot all be implemented from one unique central place. As advocated some 25 years ago by Ergas (1986), this mix of supply and demand policies require a decentralized approach, or to say it in present day terms, at least for Europe, multi-level governance. Scholars working on the dynamics of the European Research Area, have arrived to the conclusion that this

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[27] See the ERA dynamics project of the EU funded PRIME network of excellence, www.prime-noe.org, and the pending special issue to be published in 2011. See for a policy expression the EC expert group report chaired by Luke Georghiou: Challenging Europe's research, rationales for the ERA (2008), available on Cordis website.

multi-level governance cannot be generic or shared for all R&D problems, but it should be tailored to each problem[27]. We argue that the rapid pace of development of nanotechnology associated with its role as a general-purpose technology requires that this problem be urgently addressed. The US, with the NNI and its special legislative arrangement, has proposed one centralized approach, which enables horizontal coordination between Federal departments. In Europe, the EC has supported the emergence of new tools which enable the coordination of different national funding agencies and research institutes, the ERA NETs. Similarly, member states speak of developing 'joint programming' on key shared issues. What is clearly missing is the inclusion of regions (states in Federal countries) and of clusters in that governance scheme. We consider the development of productive second generation of 'nanotechnology initiatives' to be a clear challenge.

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