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STRATEGIES FOR KNOWLEDGE ACQUISITION IN BIONANOTECHNOLOGY
Why are interdisciplinary practices less widespread than expected?

Ismael Rafols

Discourses on convergent technologies claim that fields such as bionanotechnology are interdisciplinary and, therefore, require specific organizational forms, such as laboratories with researchers from many different disciplinary backgrounds. However, empirical investigations challenge the intrinsic interdisciplinarity of these emergent fields, and some analysts criticize the discourses as prescriptive. In order to investigate actual laboratory practices in bionanoscience, this article explores the dynamics of knowledge integration and the knowledge acquisition strategies of 10 research projects in two research specialties, namely biomolecular motors and lab-on-a-chip. The research shows that knowledge integration is, in fact, very asymmetrical: typically, a project will use materials and techniques from various disciplines at a standard level of know-how, but focus its research effort on the unique expertise of the home laboratory. Furthermore, projects use various strategies to acquire knowledge: interdisciplinary practices involving deep collaborations and exchanges between distinct disciplines at either the personal or institutional level are only one strategy to acquire knowledge and, indeed, not the most common. The majority of projects combine different strategies, including service collaboration, limited recruitment and in-house learning. These observations can be explained by a trade-off between the benefits of cognitive diversity set against the costs of team cohesion and learning.

Introduction

One of the central tenets of the current discourse on innovation is that the most important scientific and technological breakthroughs are the result of interdisciplinary endeavours and, therefore, innovation policies should facilitate and foster interdisciplinary research. However, a quick look at interdisciplinarity 'in practice' shows that the latter is extremely diverse: interdisciplinary research is carried out in a variety of ways. What are these practices and how do they differ? This article deals with this question by investigating the strategies that laboratories use in order to acquire bodies of knowledge beyond their domestic expertise. The scope of the research is bionanoscience.

The idea of interdisciplinarity as a source of creativity and innovation has become particularly relevant in those areas of science and technology (S&T) that have emerged as a result of technological convergence, such as nanotechnology (Malsch, 1997) or NBIC

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technologies (nano-, bio, info-, and cognitive-based) (Roco & Bainbridge, 2002). The growing importance of interdisciplinarity is also one of the central claims of a number of policy studies arguing that the science and technology system is undergoing major structural changes (e.g. Gibbons *et al.*, 1994; Leydesdorff & Etzkowitz, 1998; see Hessels & van Lente, 2007 for a recent review). In parallel with these discourses, since the early 1990s, there has been a boom in the (self-reported) adoption of interdisciplinarity by both scientists and policy-makers (Braun & Schubert, 2003). In both discourses and policies, interdisciplinarity is presented as the result of particular strategies of knowledge acquisition: (i) research collaboration among two or more laboratories affiliated with different disciplines; or (ii) the recruitment in one laboratory of researchers from many different backgrounds (Gibbons *et al.*, 2004, pp. 4–6, 147–150). Jerry Salomon of the Caltech Beckman Institute expressed this view as follows:

> You know Beckman's idea was to put chemists and biologists together and throw in some computing stuff and see what came out. I think [interdisciplinarity] it's really no more, no less than that (Salomon, quoted in Scerri, 2000, p. 202).

Nevertheless, social studies of science suggest that the practices that lead to interdisciplinary research are more diverse. It is widely acknowledged that interdisciplinary research 'does not necessarily imply collaboration between researchers from different disciplines' (Bordons *et al.*, 2004, p. 440), and even when it does, it encompasses a variety of practices (Laudel, 2001, 2002).

Moreover, the strong normative component of much of the discourse on interdisciplinarity suggests that this 'is, in effect, a discourse on innovation in knowledge production' (Weingart, 2000, p. 30) that 'provides a means for steering and coordinating strategic investment in research across a range of partners (Lowe & Phillipson, 2006, p. 167). In other words, the rhetoric on the benefits of interdisciplinarity is a convenient tool to foster reform in scientific institutions (e.g. tenure track, see Fuller, 2003) – whereas generally the argument is presented in the reverse sense: that organizational reform is necessary to support interdisciplinarity. This reversal is what, in his critique of Mode 2, Godin refers to as performative discourse: 'suggesting a new organization of knowledge and participating in its realization' (Godin, 1998, p. 465).

These arguments about the difference between discourse and practice in interdisciplinarity received some support from the results of a bibliometric study on nanotechnology conducted by Schummer (2004): although nanotechnology has been presented as an intrinsically interdisciplinary endeavour, most nanotechnology-specific journals publish articles by authors from one single disciplinary affiliation. For instance, *Nanotechnology* used mainly to publish articles written by physicists. Bibliometric studies reveal only one strategy for interdisciplinary knowledge acquisition, namely, collaboration between departments from different disciplines. However, the question must be whether, in everyday research practice, laboratories rely on other strategies. In an earlier paper, the degree of interdisciplinarity in the field of biomolecular motors was analysed using bibliometric indicators *and* laboratory practices (Rafols & Meyer, 2007). In some cases the contents of research were found to be interdisciplinary even when the projects were affiliated to or carried out by researchers from a single discipline. But then, how did these projects manage to gather different bodies of knowledge?

In order to understand the variety of interdisciplinary practices, this article explores the knowledge acquisition strategies used by academic laboratories in 10 projects running under two known research specialties in bionanotechnology, that is biomolecular motors (BM) and lab-on-a-chip (LOC). What are the practices for knowledge integration and acquisition? In what way are these practices interdisciplinary? How and why do they differ between research fields?

The findings presented suggest that the practices that tend to be associated with interdisciplinarity in science policy, such as deep collaboration between laboratories or the transient recruitment of a whole mix of researchers from diverse backgrounds, are much less common in reality. Instead, laboratories rely on their core expertise and the combination of various strategies, such as limited recruitment, service collaboration or in-house development. The choice of strategy depends on the laboratories' goals (more educational or more research-focused), institutional conditions (such as funding or student availability), and capabilities to absorb knowledge from other areas. This choice can be understood in terms of a trade-off between the benefits of cognitive diversity and the costs incurred by maintaining the cohesion of a team or achieving the desired learning (Llerena and Meyer-Krahmer, 2004; Hollingsworth, 2006).

Conceptual and Methodological Framework

The definition of disciplinary and interdisciplinary research is problematic and controversial. This study follows the sociology of science literature on the dynamics of research and disciplines (Weingart, 2000; Becher & Trowler, 2001), which sees disciplines as social constructs with tightly associated cognitive dimensions ('tribes with territories' as Becher puts it), but highlights that the actual arena of research is the research specialty, i.e. the body of knowledge constituted around specific objects, problems, methodologies and/or concepts that advances through the contributions of an identifiable community (the invisible college in Crane's (1972) terms). In line with other scholars (Klein, 2000, p. 17; Porter *et al.*, 2006, p. 3), interdisciplinarity is here defined as a mode of research that integrates different bodies of knowledge, i.e. as a cognitive characteristic of the research process.[1]

Since we are interested in the practices[2] that lead to interdisciplinarity, we need to define the units of analysis for both the (potentially integrative) research outcome and the social spheres mobilized. For the research outcome, I take as unit of analysis the research project, which is defined as a set of persistent practices aimed at solving a scientific or technological problem. The research project is then identified (or 'operationalised') via a sequence of publications that show coherence in terms of the topics addressed and the main researchers involved, over a particular time span (2–5 years).[3] The 'individual laboratory' is the unit of analysis for social space: it represents that platform in which research is conducted based on 'domestic' knowledge embedded in instruments, researchers and local interactive networks. In line with this perspective, I use the term collaboration to refer to investigations that involve researchers based in different laboratories.[4]

The goal of this paper is to provide an understanding of how in a given project a laboratory acquires knowledge from different sources. Or, in other words, to investigate the mobilization of social resources in order to gain the cognitive diversity needed for a research objective. I want to uncover the knowledge acquisition strategies (social processes) through which knowledge integration (a cognitive process) is achieved. Based on previous studies (Palmer, 1999; Sanz-Menéndez *et al*., 2001; Laudel, 2001), I hypothesize that there are various possible forms and rationales for knowledge acquisition.

Although a research project is tightly associated with the technical and human resources available in the laboratory (which are dependent on previous achievements), the distinction between the laboratory and the project is helpful to capture knowledge integration accurately. This is because in biosciences laboratories there are often various lines of research being pursued by different intra-laboratory teams, without this always leading to synthetic efforts among them.

The choice of bionanoscience as the empirical object of study reflects its current funding importance and perception as a particularly interdisciplinary field. The UK's BBSRC (2006) defines bionanotechnology as 'a multi-disciplinary area that sits at the interface between engineering and the biological and physical sciences', while the OECD defines it as an area that 'covers the interface between physics, biology, chemistry and the engineering sciences' (OECD, 2005). Within bionanoscience, I have focused on the research specialties of biomolecular motors and lab-on-a-chip, given their explicit interdisciplinary character and relevance for the NBIC vision.

The BM research specialty studies the motor proteins (myosin, kinesin, dynein, F_1-ATPase and others) that generate force at sub-cellular level using the chemical energy stored in bio-molecules (Schliwa & Woehike, 2003). BMs are essential for the movements in living beings, for example in muscle contraction, transport of vesicles in neurons or the propulsion of bacterial flagella. Given their size and source of energy (small chemical molecules), BMs are viewed as potential 'engines' or actuators for nano-devices, as well as being of interest for understanding a variety of diseases. LOC research investigates the construction or use of devices that integrate microfluidic and analytical functions in a small chip (Whitesides, 2006). LOC devices typically consist of a chip of solid material (glass, polymers or others depending on applications) carved or moulded with micro/nano channels through which liquid solutions or suspensions are flowed in order to control their delivery and/or to carry out chemical or genetic analyses. BM and LOC are a fundamental part of the NBIC vision as connectors between biological systems and the NBIC-engineering devices that will combine ICT, nano- and bio- technologies to enhance, substitute or repair biological functions.

For each research field, five case studies were conducted, each corresponding to a specific research project. The cases were selected among the contributions by Japanese researchers in two international conferences in very specific topics: mechano-chemistry of BM, and LOC devices for cells. The selection of projects from only one country working on narrowly defined topics was deliberate: it was designed to ensure that variety among the practices employed was not due to differences related to national settings or scientific or technological needs. A caveat to this investigation is the extent to which the results may be contingent on the particular specialties and period examined.

For each of the 10 case studies, I conducted one interview (in some cases two) of 1–2 h with the principal investigator and/or main contributors to the project, inquiring about the affiliations and background of the research teams, experience, main instruments, techniques and concepts used, and where they had been acquired. This data was complemented by information from scientific publications, miscellaneous documentation and homepages. A special feature of our method is that the project's most relevant research articles were analysed prior to the interviews, feeding into the latter's preparation. This allowed me make specific and technical inquiries into 'who' had contributed to a given piece of research, and 'how', in order to complement and contrast the narratives offered by the interviewees. This strategy proved particularly valuable for understanding the synergies and division of labour among researchers.

Dynamics of Knowledge Integration

Before looking at the research strategies adopted in each project, it is important to first examine the characteristics of each field to establish how they influence the knowledge integration processes; and second, to examine the key role of instrumentation and techniques in both fields.

The current research community of BM can be traced back to the early 1980s, with some of the leading incumbents already active at that time. The field progressively emerged in the 1960s and 1970s as a result of seminal research on muscle physiology conducted during the 1950s. The designation of the field as 'molecular motors' only became widespread in the late 1990s. The latter's high scientific impact led to BM research diffusing to other scientific areas, such as engineering of actuators for nano-devices (or nano-engines) or applications in medicine, developmental biology and/or neurology.[5] Since BM transform energy stored in chemical bonds into work, their study involves aspects of biophysics (such as force and energy), biochemistry (binding sites), structural biology (protein structure) and cell biology (effects on cytoskeleton functions) and the use of molecular biology techniques (Schliwa & Woehike, 2003). Hence it is viewed as needing interdisciplinary efforts.

The LOC research specialty developed over the last two decades, boosted by demands in molecular biology (e.g. high-throughput DNA sequencing) and defence (biological and chemical weapons; Whitesides, 2006). Research on LOC combines techniques from microelectronics and micro-electro-mechanical systems (MEMS; e.g. photolithography), analytical chemistry (e.g. capillary electrophoresis), microscopy (e.g. scanning probe microscopes), and, depending on the samples being analysed, knowledge from various biology fields. There have been regular conferences held since 1994 (annually from 2000) and a specialist journal was launched in 2001.

Although both research specialties clearly fall into bionanoscience/technology, their dynamics, over the periods analysed (1992–2003 for BM and 2000–2006 for LOC), were remarkably different. First, research in BM was aimed at understanding a natural phenomenon whereas LOC is by definition a technological problem, the goal being the fabrication of devices. Second, whereas the research community for BM was well established, the LOC community, even in the early 2000s, appeared socially more fragmented with less coherent lines of research.[6] Third, whereas the search space for new techniques or approaches in BM was within a broad area of related biosciences, which are often in contact and may share at least part of their epistemologies (e.g. biophysics, biochemistry and cell biology), LOC needed to combine knowledge from usually unrelated areas of science (e.g. electronics, cell biology and analytical chemistry), the joint development of which poses major challenges (see Figure 1). A recent science map of hot research areas highlights the central and detached position of the 'chemical and bio-systems with microchips' research area, between the life sciences and physico-chemical areas, filling a large gap between 'post-genomics' and 'nanomaterials/devices' (NISTEP, 2007, p. 55).

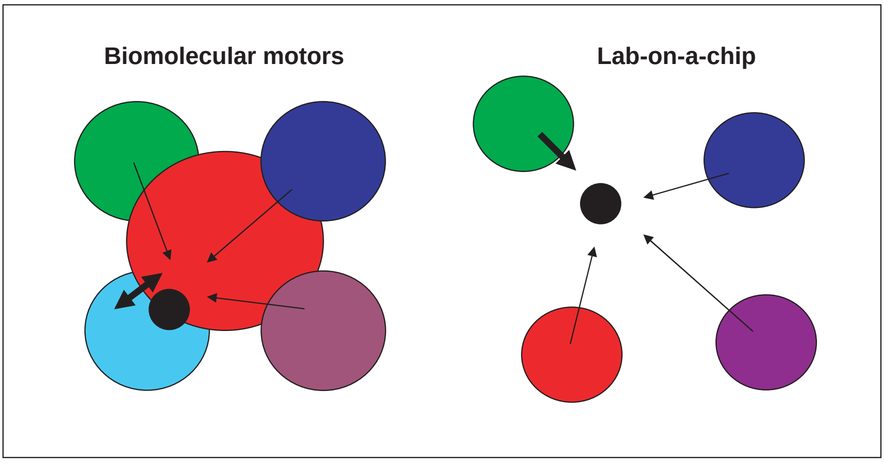

FIGURE 1
Differences in the knowledge search of research specialties. The black spot represents the research specialty under study. Left: in biomolecular motors, a research project combines related, overlapping areas of knowledge, generally with a dominant base of expertise. Right: lab-on-a-chip research uses techniques from unrelated areas of science. One project also draws on one main source of expertise

Finally, in both research fields the development of technology plays a central role,[7] but in different ways. In BM, new measurement and visualization techniques (e.g. single molecule microscopy and nano-manipulation) needed to be developed *in depth* in order to tackle a scientific problem – hence this was a case of science-driven technological development. In LOC, on the other hand, some of the most central techniques (e.g. nanofabrication and cell culture) were very well established, and the challenge was to integrate the *breadth* of techniques into a single chip. This integration process created new problems, which, in turn, gave rise to new technological demands (e.g. biocompatibility or cell attachment to surfaces).

Both research fields are similar with respect to the breadth and asymmetry in the portfolio of expertise used within one project. In all the projects examined, researchers used a wide range of techniques with distinct disciplinary bases, but with various degrees

TABLE 1
Differences in research dynamics between biomolecular motors and lab-on-a-chip

	Biomolecular motors (92-03)	**Lab-on-a-chip (00-06)**
Type of problem	Scientific (understanding nature)	Technological (engineering devices)
Research community	Long and well established	New and forming
Combination of knowledge	From related fields (biophysics, biochemistry, cell biology)	From distant, unrelated fields (electronics, MEMS, analytical chemistry, cell biology, biochemistry)
Research challenge	Development of new technologies to tackle scientific problems	Integration of existing technologies for new applications

of expertise. Projects were built around one to three techniques or instruments, in which the home laboratory excelled, with complementary contributions from other instruments or techniques, in which they had a much lower degree of expertise. For example, one BM research laboratory made a breakthrough in nano-manipulation and single molecule microscopy while using protein preparation techniques that were very common among the BM research community. Several laboratories in LOC used standard cell culture techniques while focusing their attention on the integration of their own microscopy technique (e.g. thermal lens microscopy or scanning electrochemical microscopy) given the constraints of the chip. The use of some of these techniques requires today less expertise than in earlier times, because of the availability of standard protocols, kits and instrumentation. According to Fujimura (1992), these can be viewed as standardized packages or 'grey boxes', which greatly facilitate knowledge 'translation' among research specialties.

In summary, the laboratories developed and operated one to three techniques or instruments by making important and consistent investments of time and/or capital, but they also applied many other techniques at much lower level of sophistication, without making efforts to achieve technical excellence. Through this combination of specialized and standard expertise, laboratories progressively created new research lines that built on previous achievements.

Strategies for Knowledge Acquisition

Although policy discourse often assumes that interdisciplinary research is achieved through collaborations between researchers from different backgrounds, scholarly investigations have demonstrated that there is a rich variety of practices or research modes involved in interdisciplinary outcomes. Palmer (1999) identified four modes of interdisciplinary research (which are not mutually exclusive):

i. a leader recruiting a diverse team;
ii. a collaborator consulting colleagues;
iii. an individual researcher pursuing an integrative agenda;
iv. problem-oriented research combining the first three modes, in an ad-hoc manner.

Palmer suggests that each mode involves three main knowledge acquisition strategies: (i) recruiting, (ii) consulting and (iii) learning. Using similar categories to analyse interdisciplinary fields, Sanz-Menéndez *et al.*, (2001) found that laboratories with less diverse research expertise tended to collaborate more than laboratories with very mixed expertise.

Laudel (2001, 2002) showed that there are different types of collaborations, with different associated reward and communication practices:

i. collaboration involving division of labour;
ii. service collaboration;
iii. transmission of know-how;
iv. provision of access to research equipment;
v. trusted assessorship;
vi. mutual stimulation.

The above typology of collaboration was used to analyse the practices for knowledge acquisition employed in the projects investigated here. Given that the time period of the analysis was 2–5 years, most case studies revealed the use of more than one strategy during the project's lifetime. For the sake of parsimony, Palmer and Laudel's frameworks are simplified into a four-fold typology of knowledge acquisition strategies as follows:

i. service collaboration, which includes provision of research materials, but also access to equipment and the transfer of know-how;
ii. collaboration with division of labour but jointly developed research goals, thereafter referred to as 'deep collaborations';
iii. recruitment of researchers with complementary expertise; and
iv. in-house learning efforts, which often follow some form of collaborative strategy allowing the transmission of know-how in the short term.

When comparing these strategies we have to remember that, in this article, we define as collaborations only the interactions between laboratories; knowledge exchange between researchers within an individual laboratory is considered the result of the recruitment strategy.

Service Collaboration

In service collaboration one laboratory supports the research of another by providing materials, access to and use of instruments, data and analyses, or general know-how. Although these activities can be considered separately, as in Laudel (2001), in the cases investigated here, they were often intertwined (e.g. a medical doctor providing cells for a LOC experiment explained how to culture them and helped check their viability in the initial stages of the research). The providers of the service side of the collaboration may or may not be co-authors of the eventual paper. This depends on personal relations and/or the norms in that particular field.[8] But independently of whether they are granted the co-authorship or not, the researchers providing the services act only in a supportive or advisory capacity and do not participate actively in the design and final interpretation of the results.

Service collaboration seems to have been extremely important for getting the LOC studies started. This is because, in the initial stages, researchers had little or no expertise in some of the materials and instruments they wanted to 'try out'. The service part of the collaboration generally did not spend time trying to understand the details of the research project, but could quite easily help design, demonstrate how to follow routine experimental procedures and give advice on the application of techniques.

In one example of service collaboration in LOC, a professor in a graduate school of environmental sciences with a background in electrochemistry and expertise in scanning electrochemical microscopy (SECM) wanted to create a microchip to monitor cell reactions to specific chemical environments (possible application in pollution or pharmaceutical testing). Since all the students and researchers in his laboratory had backgrounds in applied chemistry, he needed two external sources of expertise: one in microchip fabrication, and the other in cell culture. Over the years, this specific laboratory progressively acquired the expertise, and later proceeded to buy the equipment required for micro-fabrication from a large MEMS laboratory at the same university, which had it and was willing to provide expert guidance on its use through its PhD students. In addition, PhD students acquired knowledge and expertise in cell culture and simple molecular biology techniques with the help of a medical doctor, who was a member of a cross-departmental programme. This is a case of one rather focused and homogeneous laboratory building on its expertise (SECM) and gradually acquiring materials, instrumentation and know-how through service collaboration with colleagues within the same academic institution. Although the contributions of the collaborators were essential, their investment of time and resources was limited – as shown by the fact that they were not co-authors of, or even acknowledged in, the eventual publications of the research.

In the case of BM, service collaborations did not play a major role. The only important exception is the case of a mixed cell biology–biophysics laboratory that provided a molecular engineered protein to a biophysics-based group that had developed a new type of fluorescent microscope. Other instances of service collaborations were complementary, less relevant contributions to the projects. Obviously, in BM, the research community already shared a body of knowledge, and the types of expertise that might lead to service collaboration had either been absorbed internally in the laboratories or could be more easily transmitted through informal contacts. Also, BM research did not generally require the use of large and expensive equipment.[9]

Deep Collaboration

Deep collaboration takes place in a research project that is jointly formulated and interpreted by the collaborating laboratories, but where each of the groups involved makes an essential contribution to different stages of the research process; hence it involves division of labour, and, at the same time, strong (hence deep) collaboration among researchers. This is the type of collaboration 'conventional wisdom' tends to associate with interdisciplinary research. It was present in all BM research instances and contributed to a broadening of the cognitive base (as would be expected) by increasing the diversity of researchers' backgrounds and the expertise in instrumentation. However, this represented the most important strategy only once. In all other instances, the 'home' laboratory first made a new major contribution to the field, and this was followed by a phase of deep collaboration contributing additional techniques and expertise from other teams.

Another feature of the deep collaborations found in BM is that they generally occurred between laboratories belonging to the BM research community, but based on different disciplines (e.g. biophysics and structural biology). This pattern suggests that the previous sharing of interests, scientific language and social networks that occur within research specialties, are important for facilitating the mutual understanding necessary for deep collaboration. It is furthermore telling that, when deep collaboration can and does take place, as in the case of the project on bioenergetics in linear BM, its impact (measured in terms of citations) is significant. This (but only this) instance supports the widespread view that deep collaborations that manage to bridge large cognitive distances have the potential to bring about path-breaking contributions, even if entailing, at the same time, a higher risk of failure.

To my surprise, I did not identify any examples of deep collaboration in LOC research in the period studied, but this is changing as the field gains maturity. A professor of electronics explained the evolution: when he first moved into bionanotechnology in the late 1990s, he lacked the prestige to catch the attention of biologists. Only after he had succeeded in creating some LOC prototypes (and was successful in accruing a large grant), did biologists become interested in his work and in joint collaboration. This example illustrates a common pattern, namely that deep collaborations involve the extension of the area of application of specific techniques.

Recruitment of Researchers with Distinct Backgrounds

Recruitment of researchers with diverse backgrounds is a way of introducing 'external' knowledge into a laboratory. In BM, I found this to be an important strategy in three of the five cases under investigation. Researchers were recruited to fill in specific disciplinary gaps, and in order to complement existing expertise. Examples include a biochemist, with experience in BM, joining a biophysics laboratory to contribute his protein purification expertise; a laboratory recruiting both biophysicists and cell biologists; and another one comprising only biophysicists, albeit with diverse technical expertise.

A different picture emerged in the LOC research environment. One of the case studies was located in a new centre for biomedical applications (opened in 2005) with a large laboratory shared by researchers with different backgrounds, and engaged in different lines of research. Most of these researchers were based at the centre, but some also had their own laboratories in other departments within the same university. The project involved a young researcher (biochemist by training), who had previously worked on the development of molecular biology techniques, and was now developing an LOC for cell analysis working together with an analytical chemist with expertise in electrophoresis and a neuro-scientist interested in neurite navigation. Their combined expertise was allowing them to develop most of the research on their own, with the exception of the microchip, which was provided through service collaboration with another colleague from the centre, who had micro-fabrication equipment in his own laboratory. This case fits with the vision of nanobiotechnology as developing through interdisciplinary teams. Interestingly, this was the most recent of all the projects studied, and was institutionally based in an organization that was trying to create a 'new' institutional culture, which also had other Mode-2 features (e.g. an emphasis on patenting and secrecy).

In the other four cases of LOC, however, there was much less mix, and more similarity with the findings for BM. The teams of the various projects included:

i. a 'pure' biology PhD student in a biophysics laboratory;
ii. a professor in analytical chemistry hiring a post-doctoral researcher with a background in biochemistry at a food science department;
iii. an electronics team with all key contributors belonging to this discipline, but working in different areas of application (sensors, polymer coating, experimental setup);
iv. an electro-chemistry laboratory that did not recruit researchers from different backgrounds.

A professor of electronics in one of the LOC projects highlighted the importance of having both overlap and complementarity in recruitment. At the onset of his career in LOC, he avoided hiring biologists because of his own lack of understanding of this field, which implied that he had no criteria for selecting candidates. But there were also no young researchers with adequate hybrid backgrounds to whom he could relate. But the situation had recently changed, he argued: he was now more capable to judge biologists in LOC, and, moreover, there are now many more young researchers with knowledge of both engineering and the biological aspects of LOC.

The downside of recruitment as a strategy is that it is highly dependent on funding. Two of the LOC laboratories had only recruited researchers with complementary expertise (a cell biologist in an electronics-based laboratory and a pharmacologist in a biophysics-based laboratory) after receiving large grants following initial successes in the field. A third one wanted to, but did not have the funding.

In-house Learning

The search, identification, acquisition and integration of 'external' knowledge into a laboratory involve important learning efforts. In the innovation literature, these processes have been conceptualized as 'interpretative learning' (Grigg *et al.*, 2003), or as the acquisition of *absorptive capabilities*, allowing laboratories 'to recognize the value of new, external information, assimilate it, and apply it' to specific goals (Cohen & Levinthal, 1990, p. 125). The importance of these in-house learning processes should not be underestimated.

In service collaborations, when researchers use materials or instruments obtained from collaborators, their degree of conceptual or theoretical engagement with those materials may be limited, but they often have to acquire the minimum knowledge to set up an experimental base for their application. For example, two electronics laboratories in LOC used cells provided to them through service collaboration, but in order to do so, they had to learn how to make their own cell cultures. Thus, they developed in-house standard expertise, and now each of these laboratories has a room that houses incubators, microscopes, autoclaves, shakers and centrifuges, and at least one researcher who is familiar with the protocols for preparing cells.

In the case of deep collaboration, the participating laboratories also needed to be familiar with each other's contributions and procedures. This can be quite difficult when tacit knowledge is involved. In one of the cases of deep collaboration in which one laboratory prepared an engineered protein motor and the other carried out the X-crystallography, after repeated failures, a researcher from Tokyo had to be flown to San Francisco to learn *in situ* how to prepare the protein sample. In the case of recruitment, there are learning processes resulting from the interactions among recently hired researchers and the researchers embodying the domestic expertise of the hosting laboratory. Finally, researchers can also learn from codified knowledge sources, such as publications and conference presentations.

The degree of in-house learning seems to depend on laboratory goals and institutional factors. Those laboratories with an educational focus that are well established and funded, and/or can work towards long-term objectives, are in a better position to engage in development and internalization of new expertise. A BM project in the medical school of a very prestigious university illustrates this point. This laboratory was well funded and relied almost exclusively on students with a medical background, yet it dealt with a surprisingly wide diversity of topics and disciplines. This cognitive diversity could be achieved because the leading professor was willing to provide time and support to students to learn state-of-the-art techniques in fields in the neighbourhood of his 'domestic' cell biology base. Thus, in the project I looked at in this centre, one PhD student collaborated briefly with an expert on cryo-electron-microscopy and then went on to conduct his own research using the expertise he had acquired, while another post-doctoral researcher spent a long-time developing fluorescent microscopy (at single-molecule resolution) with the help of informal consultations with a major microscope maker. The professor's view was that, although the learning processes were lengthy, the incorporation of these techniques into the laboratory would pay off in the long term, both for the laboratory and for the young researchers involved.

Discussion and Conclusions

Summary of Empirical Findings: Various Strategies for Knowledge Acquisition

This paper looked at the interdisciplinary practices of 10 projects in two different specialties in bionanoscience, namely, biomolecular motors and lab-on-a-chip. It analysed the dynamics of knowledge integration and the strategies of knowledge acquisition by the laboratory in charge of the project.

First, knowledge integration in a research project was found to be asymmetrical. In both research areas, projects were carried out with contributions from different bodies of knowledge, and hence the laboratories involved needed to use a breadth of techniques from various research traditions. However, the depth of expertise was very unequal: a project typically focused on the unique know-how of its home laboratory in a particular research method or instrument, but used standard expertise in many other techniques. This asymmetry was more prominent in LOC, where the bodies of knowledge being integrated were more distinct. Some of these sophisticated but well-established techniques transferred between laboratories may be viewed as 'standardized packages' (Fujimura, 1992).

Second, various strategies were used to acquire expertise from different bodies of knowledge (see Table 2). Although deep collaboration (between laboratories from different disciplines), or mixed laboratories (with researchers from many disciplinary backgrounds) are presumed to be the essential strategies in convergent technologies, in only two of the 10 projects examined were these strategies found to be dominant. In all other cases, other strategies turned out to be more important: (i) service collaboration (particularly in LOC), (ii) recruitment of a limited number of researchers with complementary expertise (but not necessarily from a different discipline) and (iii) in-house learning. Projects generally relied on more than one strategy for knowledge acquisition.

In BM, a long established research specialty, recruitment and collaborations were common and occurred mainly between researchers and laboratories that were part of the same or related research communities but had different core expertise (e.g. nano-manipulation vs electron microscopy). In LOC, however, three of the five case studies did not show either deep collaboration or recruitment in the period under examination. Nevertheless, two out of three began to use these strategies as they accumulated 'hybrid' knowledge and the field itself became more mature. These observations suggest that, although both recruitment and deep collaboration are adopted with the objective of acquiring complementary expertise, they are difficult to establish without the existence of an overlapping body of knowledge. Service collaboration, which does not require this common knowledge base, was crucial in the early stages of LOC research.

TABLE 2
Summary of strategies for knowledge acquisition observed, and conditions facilitating their occurrence (as inferred from case studies).

Strategies	**Definition**	**Observations from case studies**		**Conditions that facilitate occurrence**
		Biomolecular motors (five cases)	**Lab-on-a-chip (five cases)**	
Service Collaboration	Provision of materials, access to instrumentation or transmission of know-how	**NOT significant in four cases** Relevant in one case (one lab sends engineered protein to microscopy-focused lab)	**Very important in ALL cases** Laboratories borrow cell lines, nanofabrication facilities, etc. and need associated know-how	Large cognitive distance between labs. Existence of standardized packages of methods and materials. Lack of costly access to materials or instrumentation
Deep Collaboration	Projects jointly formulated and interpreted by the collaborating labs, but typically carried out with division of labour	**One case where it is essential for breakthrough** In three other cases, it is relevant, but it follows major achievements developed in-house	**NOT present in this period** It begins to occur ONLY after the labs achieve some expertise beyond their domestic knowledge base	Short to middle cognitive distance between collaborating labs in order to keep coordination costs low. Labs belong to the same research community/research problem, but with a different disciplinary focus
Recruitment	Employment of researchers with backgrounds that differ from the lab's knowledge base	**One case of mixed lab** but among related disciplines **Important in three cases**, but to a limited degree. 'External' recruits not only complement but also **overlap** the knowledge base of the hiring lab	**One case with recruits from many disciplines** In three other cases, also present to a limited degree (just one 'external' recruit or complementary skills within same discipline). It becomes more frequent in later periods	Short to middle cognitive distance between hiring lab and recruit. Access to funding. Recruit has both overlap and complementary skills
In-house Learning	Development of practices previously external to the lab's domestic knowledge base	**Essential in two cases**, in which the labs are based mainly in one body of knowledge **Relevant in all cases**, as a requisite for collaboration	Relevant in all cases, given that service collaboration requires some understanding of 'external' materials and methods	In-house learning is needed so as to adopt the materials and methods received from collaborators (absorptive capacity)

Finally, knowledge practices are highly dependent on the goals and institutional settings of the laboratory such as type of funding and the presence of post-graduate students. The main issue is whether it is possible to invest time and human, technical and social resources in in-house learning, recruitment and collaboration. For example, a mid-term project with high funding relied on recruitment, while some laboratories with many post-graduates tended to internalize new knowledge through short-term collaborations followed by in-house development. The effect of institutional constraints on laboratory practices is an aspect that was only tangentially touched upon in this study and deserves further exploration.

A Trade-off Between Cognitive Diversity and Cohesion

In light of these observations, one may ask: why are the knowledge acquisition strategies not as 'fully' interdisciplinary as might be expected from the policy discourse? And under what conditions are some knowledge acquisition strategies more appropriate than others?

To answer these questions, I follow Katz and Martin's (1997), p. 17) suggestion of adopting a 'symmetrical approach' when assessing the benefits and costs of interdisciplinarity. Hollingsworth (2006) provided some evidence that major biomedical discoveries have occurred in organizations that combined moderately high cognitive diversity with high social cohesion. However, the literature on scientific and inter-firm collaboration has argued that there is a tension between cognitive diversity and coordination, i.e. between 'the benefits to innovation of working across disciplinary and organizational boundaries versus the risks that arise from the costs of coordination and relationship development in these collaborations' (Cummings & Kiesler, 2005, p. 704). Llerena and Meyer-Krahmer (2004) advance a similar argument in terms of a trade-off between the benefits of cognitive diversity, and the costs of learning and cohesion. As a result of this trade-off, the performance of projects is thought to be higher at moderate levels of diversity.

This cohesion–diversity trade-off model may explain the practices observed, and, in particular, account for why high and distant cognitive mixes are still rare. In BM, collaboration and recruitment were facilitated by an overlap in the knowledge base between laboratories and researchers, which kept coordination costs low while still providing some gains in cognitive diversity. In LOC, however, deep collaboration and recruitment had to bridge major cognitive distances: under these conditions, the costs of cohesion were greater than the cognitive gains from diversity; therefore these strategies were not adopted. I observed, instead, that the LOC laboratories tended to engage in service collaboration, which provided limited knowledge diversification, but required little organizational effort. Moreover the possibilities of establishing service collaborations were enhanced by standardized materials or methods, which facilitated their adoption or translation in new research communities (Fujimura, 1992).

A richer understanding of the choice of knowledge acquisition strategy needs to consider, in addition, the goals and institutional settings of projects: how and why laboratories with many post-graduates may favour in-house learning as part of their education, or how service collaborations are facilitated by funding support from governmental initiatives (e.g. in several countries 'open-door' nanofabrication facilities are publicly funded so that 'external' researchers can use them).

Institutional Frameworks for Interdisciplinary Research

Discourses on new modes of knowledge production claim that fields such as bionanotechnology require interdisciplinarity – meaning knowledge integration – which in turn requires specific organizational forms (e.g. deep collaborations). The findings reported here suggest that the research practices are, in fact, more diversified. Even though bionanoscience does indeed involve knowledge integration, laboratories engage in diverse knowledge acquisition strategies. Furthermore, in most cases, these do not lead to an increase of cognitive diversity, or in the number of disciplinary affiliations. This is mostly to be explained by the high coordination or transaction costs.

This study was a *descriptive* analysis of how research in bionanotechnology was carried out in the late 1990s and early 2000s in two research specialties. The fact that, during these periods, laboratories engaged little in deep collaboration and recruitment across research fields does not mean that under more favourable institutional frameworks they would not have acted differently. In other words, since this research was not prescriptive, it neither proved nor disproved that institutional changes fostering interdisciplinary work have positive impacts in emerging fields. What the findings highlight is that there are various organizational practices that can support integrative efforts. This observation challenges the view that bionanoscience cannot do without specific organizational structures, and lends support to those criticizing the discourses on interdisciplinarity and 'new modes of knowledge production' as performative (Godin, 1998) and normative (Weingart, 2000).

Instead, the research suggests that support for integrative (or convergent) sciences and technologies can be delivered by a variety of policy instruments. Accordingly, one must question current policy instruments that are based merely on formal collaborations between laboratories. Such formal collaborations are not necessarily the most appropriate means to facilitate knowledge integration, or at least not at any or all stages of the research process. Complementary policies, such as instrumentation platforms or small grants for short-term technical exchanges that facilitate service collaboration, may also have a key role to play.

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NOTES

1. The term interdisciplinarity is used here to represent all types of research crossing knowledge boundaries, including multi-, trans- and cross-disciplinarity.
2. Throughout the text we use the term 'laboratory practice' to denote activities developed by researchers in a laboratory to gather and produce knowledge. Our usage is more

organizational and less micro- than in classical laboratory studies, e.g. in Knorr-Cetina's *Epistemic Cultures* (1999).

3. It should be noticed that this practice-based definition of project does not necessarily coincide with one single funding source – typically one project benefits from diverse grants and/or fellowships.
4. Vertical (ie within laboratory) collaborations between principal investigators and various bench researchers (typically postdoctoral or postgraduate), with the associated divisions of labour, were indeed found in all the cases examined (Laudel, 2001, pp. 765–767). They will be addressed as 'recruitment' strategy, when involving researchers joining a laboratory with an 'external' expertise.
5. The research community that is developing nanotechnology applications of BM since *ca* 2000 is different (although with some overlap) from the basic research community presented here. Interestingly it has some of the characteristics of LOC community: more distance between disciplines involved and knowledge transfer through service collaboration of standardized methods and materials.
6. This fragmentation can be seen, for example, in the proportion of common referencing in different research efforts.
7. One issue deserving further exploration that is not discussed here is the apparently dominant role of technological over theoretical contributions in the development of these research specialties.
8. Regarding co-authoring, we have found differences even in projects with very similar topics, where one would have expected the same social norms to apply.
9. This has changed in some areas, in particular in those using micro- or nanofabrication techniques to conduct BM experiments.

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