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How cross-disciplinary is bionanotechnology? Explorations in the specialty of molecular motors

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Nanotechnology has been presented in the policy discourse as an intrinsically interdisciplinary field, requiring collaborations among researchers with different backgrounds, and specific funding schemes supporting knowledge-integration activities. Early bibliometric studies supported this interdisciplinary vision (MEYER & PERSSON, 1998), but recent results suggest that nanotechnology is (yet) a mixed bag with various mono-disciplinary subfields (SCHUMMER, 2004). We have re-examined the issue at the research project level, carrying out five case studies in molecular motors, a specialty of bionanotechnology. Relying both in data from interviews and bibliometric indicators, we have developed a multidimensional analysis (SANZ-MENÉNDEZ et al., 2001) in order to explore the extent and types of cross-disciplinary practices in each project. We have found that there is a consistent high degree of cross-disciplinarity in the cognitive practices of research (i.e., use of references and instrumentalities) but a more erratic and narrower degree in the social dimensions (i.e., affiliation and researchers' background). This suggests that cross-disciplinarity is an eminently epistemic characteristic and that bibliometric indicators based on citations and references capture more accurately the generation of cross-disciplinary knowledge than approaches tracking co-authors' disciplinary affiliations. In the light of these findings we raise the question whether policies focusing on formal collaborations between laboratories are the most appropriate to facilitate cross-disciplinary knowledge acquisition and generation.

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Introduction

Nanotechnology has been identified by many as a key future technology area, with economic growth potential (e.g., WOOD et al., 2003). Governments have invested or earmarked substantial financial resources to further research and development (R&D) and to translate research results into commercial applications. These programmes are often associated with the idea of broadly converging technologies and 'interdisciplinary' research. The effort surrounding NBIC (Nano-Bio-Information-Cognitive) technologies in the US can be seen as an example of this kind of convergence activity. Led by the National Science Foundation (NSF), the NBIC mission is to explain the 'mind and human behaviour by understanding their physico-chemical-biological processes at the nanoscale' (ROCO & BAINBRIDGE, 2003: p. 1). NBIC supporters argue that the impetus for convergence is driven by the integration and synergy of the four technologies (nano-bio-info-cogno) that originate from the nanoscale, where the building blocks of matter are established (ROCO & BAINBRIDGE, 2003: vii). Also in Europe, increasing attention has been given to the 'importance of interdisciplinary approaches' in nanotechnology (e.g., MALSCH, 1997).

The debate about 'interdisciplinarity' (or, more accurately 'cross-disciplinarity')[1] is not restricted to nanotechnology. In recent years there has been a sharp increase in the number of policies and the amounts of funding aimed at promoting cross-disciplinary collaborations among different scientific and technological fields, under the assumptions that cross-disciplinary research generates a higher rate of breakthroughs, is more successful at dealing with societal problems and fosters innovation and competitiveness. In other words, cross-disciplinarity has become the 'mantra of science policy' since the mid 1990s (METZGER & ZARE, 1999; BRUCE et al., 2004).

These efforts have been paralleled by the publication of several normative studies highlighting the benefits, in scientific as well as in socio-economic terms, of more cross-disciplinary modes of knowledge production (GIBBONS et al., 1994; LEYDESDORFF & ETZKOWITZ, 1998) and to an exponential increase in the number of scientific papers (self-)labelled as 'multi-' or 'interdisciplinary' (BRAUN & SCHUBERT, 2003).

The discourse on cross-disciplinarity has been particularly intense in those scientific and technological areas of economic and political importance (environment, biotechnology, ICT, nanotechnology, etc.) that are viewed as emerging at the boundaries, or through the convergence of traditional scientific disciplines. The rhetoric is that collaboration among researchers from several disciplines, will result in *new ways of thinking* that will eventually *catalyze revolutionary new science*.

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[1] Following GRIGG et al. (2003), we use the term *cross-disciplinary* to denote all forms of research that cut across disciplinary borders in some way; *interdisciplinary* is reserved for very integrated cross-disciplinary research.

But is this so? Does the rhetoric match up to the empirical evidence? Bibliometric studies contribute to this debate. In the case of nanotechnology, some analysts have characterized the ensemble of nanotechnology as more cross-disciplinary than general science (e.g., MEYER & PERSSON, 1998), while others have taken a more sceptical view of nanotechnology as an intrinsically cross-disciplinary endeavour. Recently, for example, SCHUMMER (2004) argued that most nanotechnology journals are organized along disciplinary lines, i.e., with each receiving contributions from mainly one discipline. The issue of how to measure or track cross-disciplinary activity has always been rife with diverging observations and interpretations.

In addition to the existing numerous conceptual and normative approaches to interdisciplinarity (e.g. see bibliography in KLEIN, 1990), in the last 10–15 years a range of empirical studies based on bibliometric data has emerged. However there is a worrying lack of consensus even about how cross-disciplinarity should be measured (VAN RAAN, 2000; BORDONS et al., 2004). Some cross-disciplinary practices, such as citations, appear to be very frequent between related disciplines but extremely rare among unrelated ones (PORTER & CHUBIN, 1985; VAN LEEUWEN & TIJSSEN, 2000; MORILLO et al., 2001).

This study seeks to contribute to this methodological debate by exploring cross-disciplinary exchange in detail in case-studies at the research project level in an increasingly prominent area of nanotechnology – *bionanotechnology*. Bionanotechnology is a case in point of an emerging cross-disciplinary field. The UK’s Biotechnology and Biological Sciences Research Council (BBSRC) (2005) begins its definition by asserting that it “is a *multi-disciplinary* area that sits at the interface between engineering and the biological and physical sciences” (emphasis added), whereas the briefer OECD definition states that bionanotechnology “covers the *interface* between physics, biology, chemistry and the engineering sciences” (emphasis added) (OECD, 2005).

Drawing on case studies in molecular motors, one of the specialties of bionanotechnology, we seek to describe different dimensions of cross-disciplinary knowledge acquisition and generation and to explore which aspects of cross-disciplinarity can be traced by (which) bibliometric means, and which are best explored by other approaches.

The specialty studies the motor proteins (myosin, kinesin, dynein, F_1-ATPase and others), which generate force at the intra-cellular level using the chemical energy stored in biomolecules. One would expect the research in this specialty to show some form of cross-disciplinarity since it involves aspects of biophysics (such as force and energy), biochemistry (such as binding sites), structural biology (protein structure) and cell biology (effects of motors on cytoskeleton functions), and the frequent use of molecular biology techniques (SCHLIWA, 2003).

The results from this study suggest that even similar research projects present different degrees of cross-disciplinarity depending on what aspects of research are examined: the cognitive aspects showing more consistent behaviour, and the social aspects displaying less disciplinary diversity and more disparate profiles for each project investigated.

Studying cross-disciplinarity

The definitions of discipline and cross-disciplinary research are in themselves problematic and controversial. Here, we will follow the sociology of science literature on the dynamics of research and disciplines, which was developed mainly in the 1970s (see reviews within WEINGART & STEHR, 2000; BECHER & TROWLER, 2001), and sees *disciplines* as social constructs with tightly associated cognitive dimensions (”tribes with territories” as Becher put it), but highlights that the actual arena of research is the *specialty* (i.e., the invisible college as defined by CRANE, 1972) and that the platform for the research is the individual *laboratory*, which plays a crucial role as the provider of resources, in particular instrumentalities and the tacit knowledge associated with them.[2] Our unit of analysis is the *research project*, which is defined as a scientific contribution made through a series of publications that show some coherence in terms of the topics addressed and the main researchers involved over a limited time span (2–5 years). The conceptual framework has four levels of analysis (discipline, specialty, laboratory and research project) which should not be seen as a rigid hierarchical set like Russian dolls, but as constructs that are in constant flux allowing for a plurality of overlaps – a project may include one or more laboratories and various specialties and disciplines.

The research project was chosen as the unit of analysis to capture the degree of cross-disciplinarity at the level at which knowledge is generated. Since in the biosciences, a laboratory or principal investigator often works on several problems and projects that are not necessarily closely related, taking the laboratory or the individual researcher as the unit of analysis would generally over-estimate the intensity of disciplinary interactions, and analysis of isolated journal articles may under-estimate the diversity of a project’s contributions, given that each article may address a particular audience. In order to overcome the possible arbitrariness of defining a research project from a set of publications (ex-post), the publications chosen to represent a project were selected or checked after analysing the researchers’ narrative of their contributions to the research specialty.

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[2] In this paper, we limit the use of the more generic term *field* to areas of knowledge production, such as nanotechnology, that do not fall into the category of discipline or research specialty.

As mentioned above, since the 1980s bibliometric tools have been used as the most straightforward method of assessing the extent of cross-disciplinarity (PORTER & CHUBIN, 1985), although there has not been the same degree of consensus about the most appropriate method of categorizing knowledge into disciplines or the most appropriate indicators (BORDONS et al., 2004). One reason for this lack of consensus could be that cross-disciplinarity is intrinsically a multi-dimensional concept, and in consequence, it cannot be properly represented by one single indicator. This is what SANZ-MENÉNDEZ et al. (2001) proposed and developed in a seminal study.

Here we adopt a multi-dimensional approach, looking at various aspects of research (affiliation, researchers' background, references, instrumentalities, citations) triangulating information from interviews, publications and other complementary sources (e.g. CVs, personal and laboratory homepages) first, to construct a narrative of case studies (not shown in this paper; see the Appendix for short summaries) and second, to conduct a cross-case analysis based on the research dimensions examined, which is presented below. We believe that the main novelty of this approach is that the analysis is fine-grained and based on a detailed scientific and technical investigation of the research specialty. This degree of detail allows for the inclusion of a dimension to examine instrumentalities (i.e., the use of methods, materials and instrumentation), which have often been portrayed as playing a crucial interstitial role among disciplines (PRICE, 1984; SHINN & JOERGES, 2002) and between the various subfields of nanotechnology (MEYER, 2007).

Given the diversity of specialties that independently contribute to bionanotechnology, we argue that cross-disciplinary practices can only be compared by focusing on similar projects within a given specialty and, less crucially, within a given national system. Otherwise, the variety of the practices observed in a project might be contingent on the particular specialty and national institutions to which it belongs. The cases presented here were selected from a group of important contributions made by Japanese researchers on the mechano-chemistry of biological molecular motors. The five case studies include all (four) of the Japanese keynote speakers at an international conference on molecular motors held in Cambridge in September 2005, plus one particularly successful project. The choice of Japan reflects this country's relative strength in this specialty.

For each case, the practices for the different dimensions of research examined (affiliation, references, etc.) were assigned to a particular discipline – biochemistry, biophysics, cell biology or structural biology. Since molecular biology appears to be an instrumental discipline that cuts across the disciplines listed above, the practices related to molecular biology were either not used or were assigned to its next closest discipline. The contribution of other related disciplines, such as genetics and theoretical biology, were found to be negligible in the research projects considered.

It should be mentioned that the topic of molecular motors is covered by various research specialties or invisible colleges (SCHLIWA, 2003). We chose case studies from the community that developed from a research tradition of muscle physiology with contributions from biochemists, structural biologists, biophysicists and cell biologists. This community aims to understand how biological molecular motors function, whereas other communities are focused on: (i) complex theoretical/mathematical modelling; (ii) technological applications of biological molecular motors; and (iii) design of synthetic motors, respectively. An important caveat to this exploratory investigation is the extent to which the results obtained may be contingent on the particular scientific community examined (HICKS, 1992). Thus, even within molecular motors, the disparities in the degrees of cross-disciplinarity among various dimensions may be related to the community examined.

Findings

A variety of bibliometric studies has developed different measures of cross-disciplinarity (reviewed in BORDONS et al., 2004). Following the multidimensional approach of SANZ-MENÉNDEZ et al. (2001), here we conduct an exploratory analysis of the following dimensions for the five case studies: (i) affiliation; (ii) researchers' background; (iii) referencing practices; (iv) instrumentalities; (v) citations. We present a summary of our findings in Table 1. The sections below discuss the findings in more detail.

Affiliations

Table 2 shows the interviewees' institutional affiliations[3] at the time that the research projects were carried out (the shaded cells). These are very diverse, and include electronic chemistry, medicine and an information and communication technology institute. Even more varied are the affiliations of researchers along their careers, ranging from physics and engineering to physiology and medicine, including cell biology, zoology, neurobiology and a number of cross-disciplinary centres. Three of the researchers (A-1, A-2 and D-1) have always worked within the specialty of molecular motors yet they show as much a diversity of institutional affiliation as the other three, whose work has included other specialties. This result, in agreement with a previous large scale analysis of disciplinary publication by departments (BOURKE & BUTLER, 1998), challenges studies that rely on disciplinary affiliations to measure cross-disciplinarity, which assume that "the disciplinary affiliation of co-authors corresponds to their disciplinary knowledge contribution" (SCHUMMER, 2004: 438).

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[3] By 'institutional affiliation' we mean the disciplinary labels given to the organizations (institutes, university departments or laboratories) where the researchers worked.

Table 1. Summary of empirical findings: share of disciplines in various research dimensions

	Research project versus	Project A				Project B				Project C				Project D				Project E			
	Dimension	Stru	Chem	Phys	Cell	Stru	Chem	Phys	Cell	Stru	Chem	Phys	Cell	Stru	Chem	Phys	Cell	Stru	Chem	Phys	Cell
Social dimensions	Affiliation			(100%)			100%						(100%)			(100%)					(100%)
	Background		10%	90%			100%						100%		30%	70%				50%	50%
	Affiliation including collaboration			(90%)	10%		50%	(50%)		15%			(85%)	25%		(75%)				15%	(85%)
	Background including collaboration		10%	80%	10%		50%	50%		15%			85%	30%	30%	40%				75%	25%
Cognitive dim.	References	5%	40%	50%	5%	5%	55%	35%	5%	55%	25%	20%	10%	20%	45%	15%	20%	25%	30%	40%	10%
	Crucial instrumentalities	5%	35%	60%			65%	35%		50%	35%	15%		25%	50%	25%			35%	65%	
	Citations		35%	55%	10%	10%	55%	30%	5%	30%	30%	25%	15%	15%	25%	40%	20%	10%	20%	55%	15%

Notes: Legends for disciplines: Stru: Structural biology. Chem: Biochemistry. Phys: Biophysics. Cell: Cell biology. Brackets indicate that the disciplinary affiliation lies outside the four disciplines – the one selected is the closest approximation.

The percentages shown in this table are rough estimates (rounded to 5%) of the relative importance or share of a discipline (columns: Stru, Chem, etc.) for a given dimension of research (rows: affiliation, references, etc.). The first four rows, displaying data concerning the social dimensions of research (affiliation and background) show much less disciplinary spread than the rows concerning the cognitive dimensions (references, instrumentalities and citations). Moreover, whereas the dominant discipline is contingent on each case in the social dimensions, in the cognitive dimensions biochemistry and biophysics consistently capture an important share, as would be expected in projects focused on the mechano-chemistry of molecular motors. However, in all cases but one, there is a correlation between the dominant disciplines in the social aspects and the main disciplines in the cognitive dimension. These observations together with the narratives of the case studies, suggest that indicators based on the cognitive dimensions are more reliable than indicators of the social dimensions for estimating the generation of cross-disciplinary knowledge in a research project.

Table 2. Institutional affiliation of the researchers interviewed

Post	Res. A-1	Res. A-2	Res. B-1	Res. C	Res. D-1	Res. E
BSc	Dept. Physics	Dept. Physics	School of Bioscience and biotechnology	Medical School	Dept. Biology (Zoology)	Arts & Sciences (multi-disciplinary)
MSc	Dept. Physics (Biophysics)	Dept. Physics (Biophysics)	School of Bioscience and biotechnology	----------	Dept. Zoology	Arts & Sciences (multi-disciplinary)
PhD	-------	Dept. Physics (Biophysics)	*Dept. Electronic Chemistry*	Medical School (Dept. .Anatomy & cell biology)	Dept. Zoology	Arts & Sciences (multi-disciplinary)
Post 1	Medical School (Physiology)	Dept. Physics (Biophysics)	*Institute for Integrative Bioscience*	Medical School (Dept. Anatomy & cell biology)	Medical School (Physiology)	*Medical School (Cell. & Mol. Pharmac., US)*
Post 2	Dept. Physiology (US)	**Institute of Physiology**	Institute of Industrial Science	Dept. Physiology	**ICT Institute (Biomaterials)**	Dept.Engineering (Physical Engineering)
Post 3	*Non-affiliated Project*	*Non-affiliated Project*	Inst. of Science and Industrial Research	Dept. Physiology and Biophysics	**ICT Institute (own lab)**	
Post 4	Dept. Metallurgy (own lab)	Dept. Physics (own lab)		Medical School (Dept. Anatomy neurobiology)	**Institute of Medical Research (UK)**	
Post 5	Centre for Interdisciplinary Research	Pharmacology (Bioanalysis chemistry)		*Medical School (Dept.Anatomy & Cell Biol)*	***ICT Institute (own lab)***	
Post 6	Biomedical Engineering Research Org.	Dept. Engineering (Bioengineering				

Note: **Bold** type denote the institutions where the examined research projects were conducted. *Italic* type indicates public research organizations other than higher education institutions. For Project A, two researchers were interviewed.

Thus it can be seen that molecular motors research is carried out within many disciplinary affiliations. In some cases the relation between the organizational affiliation and research is understandable on disciplinary grounds. In other cases, it seems purely circumstantial.

Background of researchers

The second and fourth rows in Table 1 present researchers' backgrounds before and after collaboration, respectively. These estimates of researchers with a particular disciplinary background in each project team were based on information obtained from the interviews, triangulated with the other available data on the researchers – mainly previous laboratory affiliations, and publications. This background, thus, does not represent the formal academic training of the researchers, but only their main discipline in terms of practice (attendance at meetings, techniques used, etc.). The rationale for using this classification criterion rather than initial academic training, is that it is a better indicator of the main disciplinary expertise of the team. For example, researcher D stressed that he views himself as a biophysicist in spite of the fact that his PhD was nominally in zoology. The main drawback to this classification method is that it assigns one researcher to only one discipline and thus it does not allow for multi-assignments –

although very often the researchers in this specialty use techniques and publish in journals of disciplines other than their main niche.

Table 1 shows that, within a given research project, the researchers' background is fairly mono-disciplinary in many cases. The only clear-cut case of cross-disciplinarity is Project E, which was conducted in a laboratory with an established policy of taking on similar numbers of postdocs and graduate students from biophysics and cell biology. The other case that shows some interdisciplinarity is Project D, which involved a small team of biophysicists and an important contribution from a biochemist. In cases B and C, the mono-disciplinarity of the laboratory was determined by their location in particular university departments; in case A it was the result of a decision by the project leader to recruit experts in the biophysics of molecular motors. This high degree of mono-disciplinarity in affiliations is often alleviated through external collaborations, which, rather surprisingly, occurred in three of our five cases once a breakthrough was achieved. In all cases except Project E, external collaborators brought technical expertise that was not related to the main discipline of the lab.

In summary, the backgrounds of the researchers in the five cases were quite different in each case and were more mono-disciplinary than might have been expected.

References

We assume that the references in project publications capture the sources of knowledge used in the research,[4] and are a good indicator of the diversity of disciplines involved in the research process. For each project, we selected up to three of the most important articles based on the authors' narrative of the research process and prestige of the journal. Each of the references cited in these key articles (between 60 and 120 references per project) was assigned to a unique discipline after examination of title and abstract. Since many papers touched upon various disciplines, the criterion used was to assign each paper to the discipline in which or from which it made its original contribution. Given that the community of molecular motors examined is focused on experimental research, in the majority of cases this meant assigning the paper to the disciplinary tradition of the key experimental methodology. Around 10% (20% in one case) of the referenced publications were not classified because either the title or the abstract was missing or because they could not be allocated to only one discipline.

This classification method is more accurate than the more widely-used approximation based on journal classification to disciplines. The latter approach has two important problems: (i) many journals are assigned to two or more related categories, not allowing a precise disciplinary distinction to be made for an important

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[4] Here we assume that the emphasis on other functions of referencing, such as legitimation, is small compared to the identification of knowledge-source.

part of data; (ii) the main contribution of some articles does not fall into the same disciplinary category as the journal in which they appear. In this case, we found that journal-based classification underestimated the contribution of structural biology, overestimated cell biology and could not be used for the 35% of the references published in multidisciplinary journals.

The fifth row in Table 1 presents the percentage of references among the main disciplines. It displays a wide spread of referenced disciplines in all projects, with 45% to 60% of the references to journals outside the dominant discipline. This spread might be interpreted as indicating that molecular motors is indeed a particularly cross-disciplinary specialty. However, these percentages may not be higher than those found in 'normal' journals in the life sciences: for example, using the ISI subject categories of journals, VAN LEEUWEN & TIJSSEN (2000) found that 54% of the references in biochemistry and molecular biology publications and 92% of those in biophysics journals were to other disciplines. Since this assignment method allows multiple categories for each journal, it tends to over-estimate the number of cross-disciplinary references. Other studies have obtained percentages of outside-discipline references varying between 35% to 60% (PORTER & CHUBIN, 1985) and of around 65% (SANZ-MENÉNDEZ et al., 2001). The current results, therefore, suggest an important, but not necessarily exceptional, degree of cross-disciplinarity in this dimension.

Instrumentalities

Techniques, instrumentation and materials, i.e. instrumentalities, following De Solla Price's terminology, are thought to be a major driver of cross-disciplinary research (PRICE, 1984; HOLLINGSWORTH & HOLLINGSWORTH, 2000, p. 237; SHINN & JOERGES, 2002). We examined the use of instrumentalities in each project. In the case of collaboration, the expertise for some instrumentalities is in the laboratory of the collaborators (e.g., optical microscopy in case B, electron microscopy in case D). Relying on the information obtained from the articles and the interviews, we assigned each main instrumentality to its parent discipline and a degree of expertise to each laboratory in the moment of the project.

The results are presented in Table 3. It should be remembered that this degree of expertise is ephemeral and changes quickly as the frontier of science moves forward. The first point to notice is that all the research projects involved mastering a remarkable diversity of techniques, irrespectively of their disciplinary ascription. This diversity was manifest in the narratives of the projects, which described the different contributions made by the various researchers. To cite two examples: (a) in Project A, success in visualizing and manipulating single fluorescent ATP benefited from the previous experience of researchers A-2, A-3 and A-leader in fluorescence microscopy; A-1 and A-2's expertise in electron microscopy; A-4's experience in synthesizing ATP-fluorescent probes; A-5's in micro-needle manipulation; A-1's in laser tweezers; and A-5's expertise in protein preparation. It should be noted that although all these researchers were biophysicists, some had expertise in instrumentalities generally linked to other disciplines; (b) the studies of Project D on dynein relied on the skills of researcher D-2 and his expertise in the very laborious purification of this protein, on D-1 and D-2's skills in nano-manipulation and fluorescent microscopy, on D-3 and D-4's expertise on electron microscopy and on D-5's capabilities in image processing.

The data from Table 3 are presented in numerical format in Table 1, using an exponential weighting procedure followed by normalization.[5] The choice of an exponential scale for the weighting is based on the idea that the extra effort needed to acquire an extra degree of expertises increases as the technology moves closer to the frontier. There is an unexpectedly good agreement between this estimate and the share of disciplines among references, given that both measures are the result of independent methodological approaches. However, we should emphasize that the quantification of instrumentality use per team is merely indicative.

Table 3. Main instrumentalities used in the research projects

Instrumentalities	Associated discipline	Proj. A	Proj. B	Proj. C	Proj. D	Proj. E
Genetic and protein engineering	Molecular biology	Best	**Frontier**	**Frontier**	-----	**Frontier**
Biochemical protocols for protein preparation	Biochemistry	Standard	**Frontier**	Standard	**Frontier**	Standard
Synthesis of fluorescent probe	Biochemistry	**Frontier**	**Frontier**	Standard	**Frontier**	Best
Nano-manipulation	Biophysics	**Frontier**	Best	Best	Best	Best
Fluorescent microscopy	Biophysics	**Frontier**	Best	Best	Best	**Frontier**
Electron microscopy	Structural biology	Standard	----	**Frontier**	**Frontier**	----
X-ray crystallography	Structural biology	----	----	Best	(Standard)	(Best)

Note: Legend: **Frontier**: technique still under development. Its success deserves publication as a technical breakthrough. Best: recently developed, state-of-the-art technique. Standard: technique that has become widely used. This implies a good level of reproducibility. The cases in brackets indicate that the technique was available in the laboratory, but was not used in the project under study here.

In summary, all the projects on molecular motors research needed a wide diversity of instrumentalities from different disciplinary traditions, and it seemed that it was essential for the success of the project either to recruit, to learn and become, or to collaborate with users or experts in these instrumentalities.

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[5] The exponential scale used is: 1 point for Standard techniques, 2 points for Best techniques, 4 points for Frontier techniques. The choice to use a base 2 exponential (rather than e or 10) was arbitrary.

Audiences (citations)

Whereas references allow us to assess the sources of knowledge used in the research projects, analysis of the citations provides information about the audience that reads and exploits the scientific contributions examined here. For each project, we constructed a random sample set of a hundred citations equally distributed along time and among key articles, and each assigned to a unique discipline based on title and abstract using the same criteria as in the assignment of references. It was not possible to classify some 5% to 15% of the citations.

The pattern of distribution of citations among disciplines (see Table 1) was similar to that for references, with biochemistry and biophysics generally taking the largest shares. Case D is the only instance of a different dominant discipline in references and citations. Our interpretation is that the high share of references in biochemistry reflects the centrality of protein purification techniques in this project, whereas the high share of biophysics in citations shows the significance of the results for the study of dynein and flagella dynamics. We could argue that there is a general tendency for structural biology and biochemistry to have a lower share in citations than in references, and for biophysics and cell biology to have a higher share in citations than in references. These tendencies could be explained in cognitive terms, as the use by more integrative disciplines of the results obtained by those more reductionist disciplines. This trend, which needs further confirmation, can be observed in matrices of citing versus cited disciplines obtained in larger bibliometric analyses (e.g. see RINIA et al., 2002).

Discussion and conclusions

The research projects we analyzed on the mechano-chemistry of molecular motors were carried out with very diverse affiliations and significantly diverse researchers' backgrounds, in each case within a narrow disciplinary base (upper rows in Table 1), but involved a rather similar set of references, instrumentalities and citations, spread across various disciplines (lower rows in Table 1).

Since we can relate organizational affiliations and researchers' backgrounds to the social aspects of research, and references, instrumentalities and citations to the cognitive aspects, we would argue that the cognitive dimensions of research show a high and consistent degree of cross-disciplinary activity while the social aspects present a lesser and more erratic degree of cross-disciplinarity, even when collaborations are considered, with the main disciplines being contingent on the specific projects. These findings suggest that cross-disciplinarity is an eminently epistemic characteristic, i.e., that it pertains to the cognitive rather than to the social dimensions.

Nevertheless, it can be seen that there is a positive correlation between the dominant type of (cognitive) expertise contributed by a team and its dominant disciplinary (social) ascription – in other words there is a link between *tribe* and *territory* though it is much looser than in ‘normal’ (‘mainstream’, ‘disciplinary’) research (BECHER & TROWLER, 2001). This is not surprising, as cognitive processes and flows occur through social interactions, and the boundary between the social and the cognitive is blurred.

Although we focused on only five cases and only one specialty of bionanotechnology, we think that the evidence presented in this study does demonstrate that nanotechnology is not necessarily cross-disciplinary in the way that is often assumed in ‘nano-visions’: involving research teams with researchers from various backgrounds or formal collaborations between laboratories affiliated to different disciplinary departments. The cases illustrate clearly that even in the case of collaborations, the affiliations and backgrounds of project teams were less boundary-crossing than the cognitive aspects of research, such as citations, references, or instrumentalities.

In light of this, we contend that bibliometric indicators based on citations and references can capture the generation of cross-disciplinary knowledge, whereas approaches tracking co-authors’ disciplinary affiliations may be problematic. As we have shown, analysis of researchers’ underlying careers clearly illustrates that for researchers working on molecular motors the current affiliation is often unrelated to the original disciplinary training or to the actual research being conducted. For instance, one researcher (A-1) had started his career in a physics department, moved to a medical school, then was employed in a metallurgy department and finally was in a position in a bioengineering organization, at the same time always maintaining a research agenda ‘narrowly’ focused on molecular motors. Another researcher had moved from a zoology department to a laboratory in a national ICT institute. While the career histories of researchers display diversity and disciplinary variation, it is difficult to conceive how departmental affiliations at a given time can correspond to a scientist’s particular knowledge contribution.

A second aspect that was investigated is the *extent* to which molecular motors is cross-disciplinary in cognitive terms. The 45% to 60% of citations outside of the dominant discipline (and 45% to 70% of received citations) is high, but not extraordinary. For example, VAN LEEUWEN & TIJSSEN (2000) reported shares of from 54% up to 92% in similar disciplines, using less stringent, journal-based criteria for cross-disciplinarity. Our interpretation is that the data obtained in this study reflect not an exceptional degree of cross-disciplinarity in molecular motors, but rather normal referencing practice for a research specialty within this broad area of the biological sciences. The fact that our analysis was at the level of the research project confirms that cross-disciplinarity practices occur during the knowledge generation process, rather than being a bibliometric artefact of the aggregation of various research subfields under one category.

Finally, the narratives of the case studies show that mastering a broad set of the instrumentalities is crucial to conduct successful research in molecular motors. Given that expertise in instrumentalities is often aligned along disciplinary traditions (e.g. protein purification with biochemistry or single molecule manipulation with biophysics), we propose that the need for a broad set of instrumentalities is one of the main drivers of cross-disciplinarity. Other studies on nanotechnology have pointed to instruments as the main links between research subfields (MEYER, 2007). Our findings are in line with evidence from a number of historical case studies on the key role of instrumentalities as connectors between otherwise independent research specialties and/or disciplines (SHINN & JOERGES, 2002).

This leads us to another issue: how do scientists in the research specialties of bionanotechnology garner knowledge from various disciplines? Which knowledge-acquisition strategies do they adopt? Our results regarding affiliations challenge the vision of cross-disciplinarity as arising from formal collaborations leading to joint-publications. Preliminary analysis of the interview data suggests that each research project has its own particular strategy designed to accommodate its particular needs and resources: in some cases through *recruitment of* researchers with complementary skills, or through the development of instrumentalities *in-house*, or through *collaboration*. The case study evidence points to the existence of various (equally) valid strategies, with PRICE's (1984) notion of 'instrumentalities' at the heart of the knowledge acquisition and exchange processes among different disciplines. These findings raise the question of whether policies focusing on formal collaborations between laboratories are the most appropriate to facilitate cross-disciplinary knowledge acquisition and generation. Complementary policies, such as instrumentation platforms or small grants for short term technical exchanges, might play a positive complementary role for knowledge-transfer between disciplines. Further research on knowledge-sourcing strategies and the role of instrumentalities will be carried out and presented elsewhere.[6]

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[6] Preliminary results available in the SPRU Electronic Working Paper Series (SEWPS): http://www.sussex.ac.uk/spru/documents/sewp152.pdf

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Appendix: Summary of case studies

Project A

In the late 1980s the leader of Project A had developed fluorescent techniques to visualize single filaments of actin, and micro-manipulation techniques to measure the forces exerted by myosin. In 1992-1997, he received a grant of about $10 million (enormous for this specialty) to visualize and measure forces and displacement at the level of a single molecule. He gathered a team of about ten researchers (among them the postdoctoral researchers A-1 and A-2 who we interviewed) plus around 15 graduate students. In spite of sharing a common biophysics background, the researchers assembled had know-how in techniques from other related disciplines, acquired from their previous projects and work in other laboratories. The project was successful in perfecting a number of already existing techniques of microscopy and nano-manipulation to great accuracy, and combining them to eventually achieve the synchronous manipulation and visualization of single molecular motors on nano-scale.

Project B

In the 1990s, the laboratory of B-1 studied the enzyme F1-ATPase using biochemical techniques. In 1995 a new PhD student, B-1, was given the task of studying the conformational changes of this enzyme and proving the lack of rotation in F1-ATPase. The failure of his research strategy brought him to think that rotation might indeed be occurring. In the absence of any suitable biochemical techniques to show rotation, and being aware of the experiments conducted on single molecule detection by biophysicists in Lab A (above), student B-1 contacted a biophysics group that was using visualization techniques on actin-myosin. In close collaboration with PhD student B-2 from this biophysics lab, he succeeded in showing the rotation of F1-ATPase by binding fluorescent actin to the rotating enzyme. The research, combining biochemical and biophysical techniques, introduced F1-ATPase to the molecular motors community (more focused on biophysics) and single molecule detection to the bioenergetics community (centred on biochemistry).

Project C

Researcher C first used electron microscopy and later molecular biology techniques in the 1970s and 1980s to study the cytoskeleton and neuron transport activities (cell biology). In the 1990s, through molecular biology he began to study the cellular functions of a family of kinesins which led to major contributions on the relation between the kinesin genes, molecular structures and dynamics. Given that researcher C had been professor at a medical school since the early 1980s, until very recently all his graduate students and research staff, like him, had a training in medicine. Although, researcher C's laboratory was initially based on cell biology, in the project studied, a couple of PhDs conducted experiments using techniques from biophysics and structural biology, learning from one-off contacts with researchers from other laboratories. It was only in the last part of the investigation that they engaged in a formal collaboration with a US group at the leading edge of cryo-electron microscopy and X-ray crystallography.

Project D

Since researcher D-1 is a member of a national laboratory, he does not have a large research team, but is well endowed with equipment. The research contribution we examined started with the purification of a new type of dynein by lab member D-2 who is a specialist in the biochemistry of protein purification and engineering. Researcher D-1's expertise in optical microscopy and nano-manipulation showed that this dynein was a *single headed* processive motor (a surprising result since processive motors had been assumed to need two heads). In spite of having in-house electron microscopy, they collaborated externally in Japan to improve image quality. After the publication of their results in a major journal, they were approached by the British researcher D-3 who offered to improve the images further, using computer enhancement, and this approach brought about the collaboration of his colleagues, researcher D-4 in the electron-microscopy and senior researcher D-5 in the composition of the paper. The success of the project was primarily due to D-2's expertise in protein purification and was enhanced by D-3's and D-4's improvements to the resolution of electron microscopy images.

Project E

After completing a cross-disciplinary PhD involving cell biology and biophysics (using laser tweezers to study membrane proteins), researcher E joined one of the leading molecular motors labs. This laboratory had accumulated expertise in state-of-the-art molecular biology techniques for biophysics and cell biology by recruiting researchers and students from both biophysics and cell biology. During the project we analyzed here, researcher E learnt molecular biology techniques and theoretical notions of structural biology and applied protein engineering and fluorescent microscopy to study how the motility of kinesin is related to its structure. Once he had published these important results, his research gained more prominence through collaboration with a biophysics group which had just developed a new microscopy fluorescence technique with improved spatial resolution.