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I. Rafols and M. Meyer
(SPRU)

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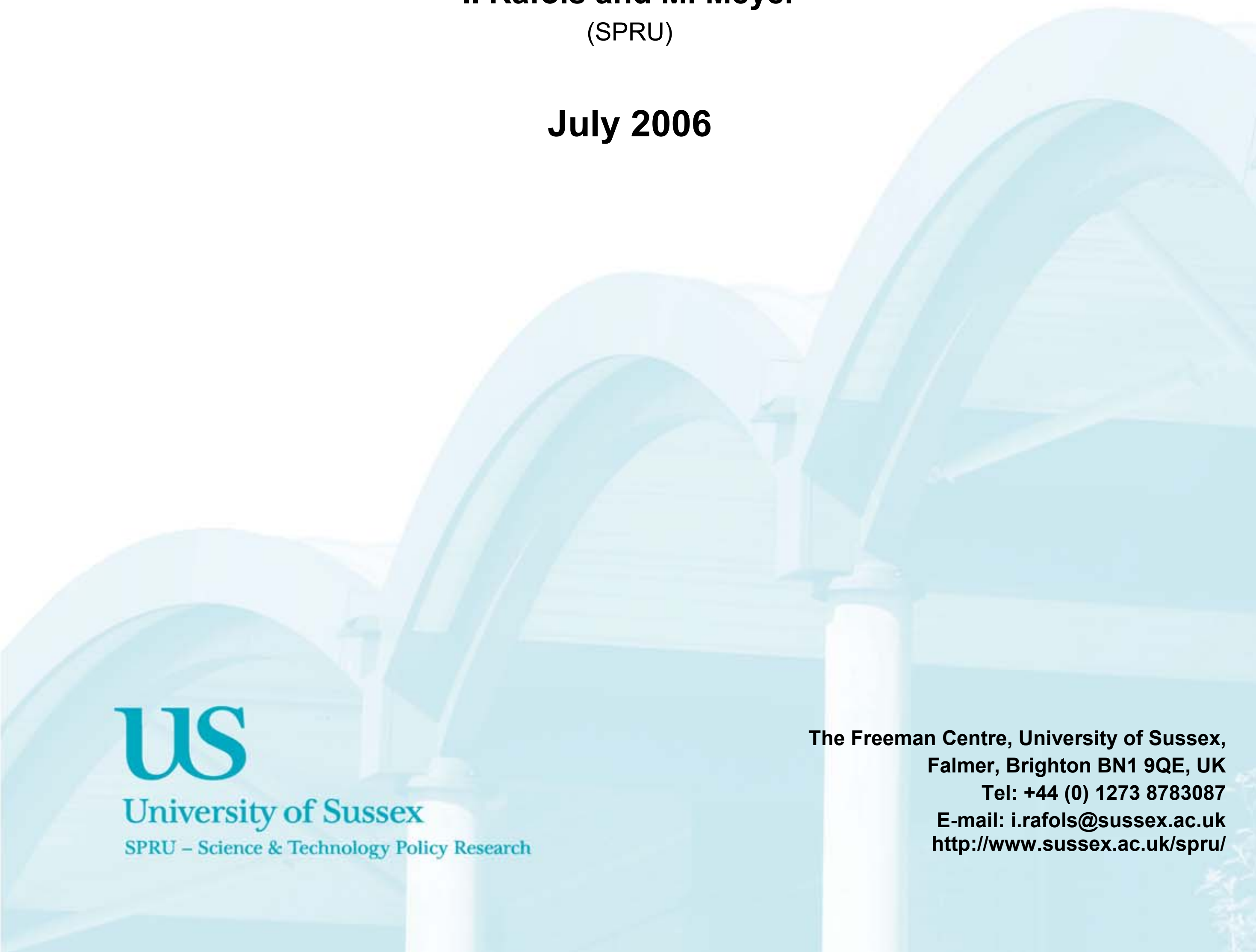

US
University of Sussex
SPRU – Science & Technology Policy Research

The Freeman Centre, University of Sussex,
Falmer, Brighton BN1 9QE, UK
Tel: +44 (0) 1273 8783087
E-mail: i.rafols@sussex.ac.uk
http://www.sussex.ac.uk/spru/

Knowledge-sourcing strategies for cross-disciplinarity in bionanotechnology

ISMAEL RAFOLS[1]
MARTIN MEYER[1,2,3]

1 SPRU, University of Sussex, Brighton, United Kingdom
2 Steunpunt O&O Statistieken, Katholieke Universiteit Leuven, Belgium
3 Helsinki University of Technology, Institute of Strategy and International Business, Finland

Abstract

In this exploratory investigation, we conduct five case studies to look into the extent and types of cross-disciplinary practices in a specialty of bionanotechnology. We found that there is a consistently high degree of cross-disciplinarity in the cognitive aspects of research (i.e. references and instrumentalities), but a more erratic and narrower degree in those dimensions associated with social constructs (i.e. affiliation and researcher's background). Moreover, we observed that research groups engage in a striking variety of strategies for knowledge-sourcing, including collaboration, but also in-house learning and recruitment. We suggest that a trade-off in research costs between cross-disciplinarity and integration may explain the variety of strategies encountered.

1. Introduction

Since the mid 1990s 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, based on 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 (or *interdisciplinarity*, in its loosest sense[1]) has achieved the status of a 'mantra of science policy' (Metzger and Zare, 1999).

This has been paralleled by the publication of normative studies highlighting the benefits, in scientific as well as socio-economic terms, of more cross-disciplinary modes of knowledge production (Gibbons et al., 1994; Leydesdorff and Etzkowitz, 1998) and by a massive increase in the number of scientific papers claiming to adopt 'interdisciplinary' approaches (Braun and 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 are the result of a convergence of traditional scientific disciplines. The rhetoric is that through the collaboration of

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[1] Following Grigg et al. (2003), we use the term *cross-disciplinary* to refer to all forms of research that in some way cut across disciplinary borders; we reserve *interdisciplinary* to describe very integrated cross-disciplinary research.

researchers from several disciplines, *new ways of thinking will emerge* that will eventually *catalyse revolutionary new science*.

Bionanotechnology is an example of an emerging cross-disciplinary field. The UK's Biotechnology and Biological Sciences Research Council's (BBSRC) definition of bionanotechnology claims that it 'is 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).

However, despite the political rhetoric and normative discourses, on the one hand the practice of cross-disciplinary research appears not to be as widespread as claimed, due to countless institutional rigidities (insecure career paths, unfair evaluation, need of longer training), and the other hand the conventional wisdom concerning its benefits is not supported by systematic evidence and remains poorly understood (Weingart and Stehr, 2000; Bruce et al. 2004; Schild and Sorlin, 2005). Although since the mid 1990s there has been a notable output of new empirical studies to add to the more numerous conceptual and normative approaches adopted in the past, there is a worrying lack of consensus even about how to measure cross-disciplinarity (Bordons et al. 2004). Another crucial aspect that still needs to be evaluated is the costs and risks of failure associated with cross-disciplinarity –which, according to anecdotal evidence, may be fairly high.

This investigation aims to make a modest contribution to the relatively scarce empirical data by looking into the cross-disciplinary practices of research in one of the specialties of bionanotechnology, *Molecular motors*[2]. This specialty studies the motor proteins (myosin, kinesin, dynein, F_1-ATPase and others) that generate force at a sub-cellular level using the chemical energy stored in bio-molecules. It would be expected that research in this specialty would show some form of cross-disciplinarity since it involves issues related to 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).

We aim to empirically test the views that claim that cross-disciplinary collaboration is the prevalent form of research in fields such as bionanotechnology. Some initial explorations into nanotechnology found that, compared to 'normal science', the field was very cross-disciplinary (Meyer and Persson, 1998); more recent research, using different indicators, found that most nanotechnology-specific journals are predominantly mono-disciplinary (Schummer, 2004).

In this short paper we investigate two research questions:

1. In which sense are research practices in Molecular motors cross-disciplinary?
2. How do research groups garner the knowledge from the various disciplines?

Our results suggest that even similar research projects present different degrees of cross-disciplinarity depending on the aspects of research examined: cognitive aspects show a more consistent behaviour; social aspects display disparate profiles in each project investigated. We will argue that these differences are due to the diverse strategies for knowledge sourcing followed by each of these projects. Finally, we suggest this use of diverse strategies exemplifies the variety of ways of handling the trade-off between cross-disciplinarity and integration.

The paper is organised as follows: section 2 presents the theoretical assumptions and methodology; sections 3, 4, 5 and 6 describe the case studies and the multidimensional and research strategies' analyses, and summarise the empirical findings; section 7 introduces a conceptual model, and section 8 concludes the paper with a discussion of the theory and policy relevance of the study.

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[2] We indicate the research specialty Molecular motors, with capital initial, as opposed to molecular motor, all in lower case, the molecule.

2. *Conceptual and methodological approach*

The definition of disciplinary and cross-disciplinary research is in itself problematic and controversial. Here we follow the sociology of science literature on the dynamics of research and disciplines that was mainly developed in the 1970s (see reviews within Weingart and Stehr, 2000; Becher and Trowler, 2001), which 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 in Crane's (1972) terms) and that the platform for the research is the individual *laboratory*, which plays a crucial role as a repository for tacit knowledge. In our study the 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)[3].

This conceptual framework has four levels of analysis (discipline, specialty, laboratory and research project) which should not be seen as a rigid hierarchical set but rather as constructs that are in constant flux allowing for a plurality of overlaps: a project may include one or more labs, and various specialties and disciplines.

Since the 1980s, bibliometric tools have been used as the most straightforward method to assess the extent of cross-disciplinary interactions (Porter and Chubin, 1985), although there has been little agreement over the years about the appropriate categorization of knowledge into disciplines, or the most appropriate indicators to use (Bordons et al., 2004). One reason for this lack of consensus could be that cross-disciplinarity is intrinsically a multi-dimensional concept, and as a consequence it cannot be properly represented by a single indicator, as proposed and developed in Sanz-Menéndez et al.'s (2001) seminal study.

Here we have adopted this multi-dimensional approach by looking at various aspects of research (affiliation, researcher's background, references, instrumentalities and citations) triangulating information from interviews, publications and other complementary sources (e.g. CVs, personal and lab homepages) first to construct a narrative of case studies (not included in this paper) and, second, to conduct a cross-case analysis of the dimensions of research examined, which we present below. We believe that the novelty in our approach is the inclusion of one dimension to examine instrumentalities (i.e. the use of methods, materials and instrumentation), which have often been portrayed as playing a crucial interstitial role between disciplines (de Solla Price, 1984; Shinn and Joerges, 2002).

Given the disparity of specialties that contribute independently to bionanotechnology, we argue that cross-disciplinary practices can only be compared by focusing on similar projects within a given specialty and – but not so crucially - a given national system. Otherwise, the diversity of 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 important contributions made by Japanese researchers on the mechanistic dynamics of any of the biological molecular motors. This selection criterion did not prove to be stringent: the five case studies involve the (four) Japanese keynote speakers at an international conference on Molecular motors held in

[3] The choice of the research project as the unit of analysis is to reflect the dynamics of the research. In order to assess cross-disciplinarity we need to look at the *creative* or positive interactions between disciplines. Since in this field, one laboratory or principal investigator may work on several problems and projects that are fairly unrelated, taking the laboratory or the individual researcher as a unit of analysis would generally over-estimate the intensity of disciplinary interactions that have an impact on the research process. Defining a research project based on a set of publications (ex-post) may produce problems of arbitrariness. Here, the selection was made or re-examined after the researchers' narratives of their contributions in the field had been examined.

Cambridge in September 2005, plus one other particularly successful Japanese project. The choice of Japan is a reflection of this country's relative strength in this specialty.

For each case, the practices of the different dimensions of research examined (affiliation, references, etc.) were assigned to a given discipline among biochemistry, biophysics, cell biology and structural biology. Since molecular biology appears to be an instrumental discipline cutting across those disciplines previously listed, the practices related to molecular biology were not used or were assigned to its second closest disciplines. 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 currently by various specialties or invisible colleges (Schliwa, 2003). Among these, we have chosen case studies from the most relevant and biggest community, which has developed from a research tradition of muscle physiology with contributions from biochemists, structural biologists, biophysicists and cell biologists. Whereas this community aims to understand how biological molecular motors function, others are concerned respectively with complex theoretical/mathematical modelling, technological applications of biological molecular motors, and creation of synthetic motors. 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 between the degree of cross-disciplinarity among various dimensions may depend on the community examined.

3. *Summary of case studies*

3.1. Project A

In the late 1980s the leader of Project A had developed fluorescent techniques to visualise single filaments of actin, and micro-manipulation techniques to measure the forces exerted by myosin. In 1992-1997, he received a grant of some $10 million (enormous for this field) to visualise and measure forces and displacement at the level of a single molecule. He gathered a team of about 10 researchers (among them the postdoctoral researchers A-1 and A-2 who we interviewed) plus some 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 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 visualisation of single molecular motors on the nano-scale.

Interpretation: This is a case in which there is little diversity in terms of disciplinary training of the researchers (mostly biophysicists), but breadth in the number of techniques that those researchers had mastered in their former cross-disciplinary careers. As a consequence external collaboration was not necessary.

3.2. Project B

In the 1990s, laboratory 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 the 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 visualisation 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 biophysics community and single molecule detection to the bioenergetics (biochemistry) community.

Interpretation: This is a classic tale of successful research through deep collaboration between two specialties and two fields: one collaborator B-1 brought the biochemistry of bioenergetics and the other B-2 introduced the biophysics of linear molecular motors.

3.3. Project C

In the 1970s and 1980s, researcher C first used electron microscopy and later molecular biology techniques 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, their 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 had, like him, a background in medicine. However, most of his publications have been based on experiments conducted in his own laboratory (in-house development) by PhD students who later became experts in techniques from various disciplines and specialties, such as fluorescent microscopy or electron microscopy, sometimes after learning via on-off collaborations.

Interpretation: In this case, the lack of disciplinary diversity within the laboratory was compensated for by punctuated external collaboration plus excellence in in-house development of learned techniques.

3.4. Project D

Since researcher D-1 is a member of a national laboratory, he does not have many researchers but is well endowed with equipment. The research contribution we examine here started with the purification of a new type of dynein by lab member D-2who 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 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 a 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.

Interpretation: Although laboratory D is quite focused in biophysics, the researchers in D-1's lab had mastered a wide portfolio of instrumentalities. For the project examined the recruitment of a researcher with expertise in biochemical techniques was crucial and the later external collaboration increased the quality and impact of laboratory D's research.

3.5. 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 labs in Molecular motors. This was a laboratory that had achieved 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. Here researcher E learnt molecular biology techniques and theoretical notions of structural biology. He applied protein engineering and fluorescent microscopy to study how the motility of kinesin is related to its structure. Once he published these important results, his research gained even more impact through collaboration with a biophysics group which had just developed a new fluorescence technique with improved spatial resolution.

Interpretation: This is a case where expertise in various techniques is acquired as a result of the cross-disciplinary background of the researcher combined with a cross-disciplinary recruitment policy. Collaboration brings about a new technique and greater impact, but not an increase in disciplinary diversity.

4. Multidimensional analysis of cross-disciplinarity

There is a range of bibliometric studies that have 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 introduced above: (i) affiliation; (ii) background; (iii) referencing practices; (iv) instrumentalities; (v) citations.

4.1. Affiliations

Table 1 shows the institutional affiliations in the careers of the researchers interviewed. It shows some striking differences, despite six of the researchers having pursued coherent professional careers. Three (researchers A-1, A-2 and D-1) have always worked within the specialty of Molecular motors yet the pattern of their affiliations shows as much diversity as those for the other three researchers, who also worked in other specialties. The list ranges from physics and engineering to physiology and medicine, including cell biology, zoology, neurobiology and a number of cross-disciplinary centres. This result challenges those studies that rely on affiliations to measure cross-disciplinarity, assuming that 'the disciplinary affiliation of co-authors corresponds to their disciplinary knowledge contribution' (Schummer, 2004, p. 438).

In summary, Molecular motors research is carried on in many disciplinary affiliations. In some cases the relation between the affiliation and the research is understandable on disciplinary grounds; in others, it seems purely circumstantial.

Table 1: 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)**	Dt.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				

Shaded cells denote the institutions where the examined research projects were conducted. Bold type indicates public research organisations outside of higher education institutions. Two researchers were interviewed in relation to Project A.

4.2. Background of researchers

The second and fourth rows in the table show the percentage of researchers, within the project teams under investigation, with a given disciplinary background, before and after collaboration, respectively. It should be stressed that the figures are very rough estimates. The research background of each lab was constructed from a question in the interview, triangulated with other information on the researchers –mainly details of past affiliations and publications. Thus, the background does not represent the formal academic training of researchers; only their main discipline of practice up to the time of the project. The rationale for using practice, rather than academic training, is that it represents better the disciplinary expertise and self-perception of the interviewed researcher. For example, researcher D emphasised that he considers himself 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, not allowing for multi-assignation – although very often the researchers interviewed used techniques and published in journals in disciplines different from their main niche. Thus, the researchers' backgrounds indicated provided here have to be understood more in social terms as constructions of disciplinary identity, rather than in terms of expertise.

Table 1 shows that the backgrounds of researchers within a given laboratory are mono-disciplinary in many cases. The only clear-cut cross-disciplinary case is the lab in Project E, which appears to have a clear policy of taking postdocs and graduate students from biophysics and cell biology in similar numbers. The other case that shows some interdisciplinarity is Project D, which involves a small team of biophysicists and an important contribution from a biochemist. In case of Projects B and C, the mono-disciplinarity of their labs was determined by their location in a university department, with the addition that in case A there was a policy of recruitment of experts in Molecular motors who could understand the very focused goal of the project leader. This high degree of mono-disciplinarity was alleviated to an extent through external collaborations, which in three of the five cases occurred after a breakthrough has been achieved. In all cases except Project E, external collaborators brought technical expertise that was unrelated to the lab's main discipline.

Thus, the background of the researchers was quite different in each case and much more mono-disciplinary than might have been expected.

4.3. References

For each research project, we selected the 2-3 most important articles according to journal prestige and/or authors' narrative of the research process. Each of the references 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 several disciplines, the criterion for assignation was the type of methodology used in the key contribution of the paper. 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 a single discipline. We consider that this classification method is more accurate than the more widely-used approximation based on journal classification to disciplines. We found that journal-based classification underestimated the contribution of structural biology, overestimated cell biology and could not be used for the 35% of articles published in multidisciplinary journals.

The fifth row in Table 4 presents the percentage of references among the main disciplines. It demonstrates the 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 a particularly cross-disciplinary specialty. However, these percentages are only slightly higher than those found in 'normal' journals in the life sciences,[4] and there are extremely few instances of broad cross-disciplinarity, i.e. citations from very disparate disciplines. Therefore, our results suggest an important, but not necessarily exceptional, degree of cross-disciplinarity in this dimension.

4.4. Instrumentalities

Techniques, instrumentation and procedures, i.e. instrumentalities in de Solla Price's terminology, are thought to be a major driver of cross-disciplinary research (de Solla Price, 1984; Hollingsworth

[4] e.g., percentage of references outside-discipline varies from 35% to 60% in Porter and Chubin (1985) and is around 65% in Sanz-Menéndez et al. (2001);

and Hollingsworth, 2000, p. 237; Shinn and Joerges, 2002), Here we examined the use of and expertise involved in the instrumentalities applied in each lab at the time of the project, and assigned each main instrumentality to it's a parent discipline. The results are presented in Table 2. It should be noted that the degree of expertise is ephemeral and changes rapidly as the frontier of science advances.

The first point to note is that all the research groups had mastered a remarkable diversity of techniques, irrespective of their disciplinary ascription. This diversity was manifest in the project narratives, which described the various researchers' different contributions. To cite two cases: (a) In Project A, success in visualising and manipulating single fluorescent ATP benefited from the previous experience in fluorescence microscopy of researchers A-2, A-3 and A-leader, A-1 and A-2's expertise in electron microscopy, A-4's in synthesising ATP-fluorescent probes, A-5's in micro-needle manipulation, A-1's in laser tweezers, and A-5's in protein preparation. It should be noted that although all these team members were biophysicists, some of them had expertise in instrumentalities from other disciplines; (b) Project D's work on dynein relied on researcher D-2's expertise in the very laborious purification of this protein, on D-1's and D-2's skills in nano-manipulation and fluorescent microscopy, on D-3's and D-4's know-how about electron microscopy and on D-5's capabilities in image processing.

Table 2: 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)

The cases in brackets indicate that the technique was available in the lab, but was not used in the project under study. ***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 data in Table 2 are presented in numeric form in Table 4, using the following weighting procedure based on normalisation procedures: 20 points for Frontier, 10 points for Best, 5 points for Standard. The choice of an exponential scale for this weighting is based on the idea that the extra effort needed to acquire an extra degree of expertise becomes greater the closer the technology is to the frontier. There is an unexpected agreement between this estimate of the relative importance of instrumentalities and the share of disciplines among references, given that both measures are the result of completely independent methodological approaches.

In summary, all groups engaged in Molecular motors research had mastered a diversity of instrumentalities that originated from different disciplinary traditions. However, the projects differed in the strategy followed (recruitment, learning or collaboration) to garner expertise in these instrumentalities.

4.5. Citations

While use of references allowed us to assess the knowledge sources of the research projects, citation analysis indicates who read and used the scientific contributions being examined here. For each project, we constructed a random sample set of a hundred citations equally distributed across time and key articles, each of which was assigned to a unique discipline after examination of title and abstract. Between 5% and 15% of the citations were impossible to classify.

The distribution of citations among disciplines (see Table 4) shows a similar pattern to that for references, with biochemistry and biophysics taking the largest shares in most cases. Case D is the only case with different dominant disciplines for references and citations. Our interpretation of this is that the high share of references in biochemistry reflects the centrality of the 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. It could be argued that there is a general tendency for structural biology and biochemistry to have a lower share in citations, and for biophysics and cell biology to have a higher share. This tendency could be explained in cognitive terms, as the use by more integrative disciplines of the results obtained by the more reductionist disciplines. This trend, which needs further confirmation, can be observed more clearly in matrices of citing versus cited disciplines obtained from larger bibliometric analyses (e.g. see Rinia et al., 2002).

5. Strategies for knowledge-sourcing and summary of empirical findings

Section 4 addressed the first research question concerning *how* Molecular motors research is cross-disciplinary. Here we look into the strategies that teams developed for acquiring knowledge from different disciplines, and particularly expertise in the diversity of instrumentalities. From the project narratives, we identified three main strategies:

Recruiting: In order to diversify instrumentalities know-how, the group incorporates researchers with complementary skills.

Learning: Given a group of researchers with similar skills (typical of a disciplinary graduate school), some need to build expertise in new instrumentalities from scratch, sometimes helped by intermittent or non-formal collaborations.

Collaborating:[5] In order to acquire or improve certain instrumentalities, the group relies on the contributions of an external collaborator.

Each of these strategies can be implemented by researchers from the same or different specialties and the same or different disciplines. The combination of these options gives rise to up to twelve different single strategies. Although most research groups combine several strategies, for the selected projects it was relatively easy to identify the dominant sourcing strategies, as shown in Table 3.

From the five cases studied, we can identify five different main strategies and three complementary strategies. We do not think that this diversity is an artefact due to a bias in the choice of cases, given that the selection of researchers was made based on (keynote speakers at a prestigious conference).

The central columns in Table 3 show that most collaborations occur within the same specialty and across disciplines. The preponderance of within specialty collaborations highlights the importance of the invisible college as the main *agora* or *arena* for knowledge exchange. Within the invisible

[5] Here we limit the use of the term collaboration to cooperative activities between researchers from different laboratories, typically leading to joint publication.

college, researchers from different disciplines can build the social relations and common language that facilitate collaboration.

A second important observation is that collaborations tend to play a complementary role. In three of the five cases examined (A, C and E), collaboration only occurred after the main laboratory had made a new major contribution to the field, a contribution that was extended by the techniques of another team. In case D, the contribution of a collaborator was an essential part of the project from the beginning, but was less important than one technical development in-house. Only in case B was collaboration the main driver of the breakthrough that was achieved.

Table 3. Strategies for knowledge sourcing

STRATEGY	Recruitment		Collaboration		In-house learning	
	Specialty	Discipline	Specialty	Discipline	Specialty	Discipline
Project A	SAME	SAME	Same	Differ.		
Project B			DIFFER	DIFFER	Differ.	Differ.
Project C			Same	Differ.	SAME	DIFFER
Project D	SAME	DIFFER	Same	Differ.		
Project E	DIFFER	DIFFER	Same	Same		

Shaded cells with words in upper case indicate the main strategy followed in a particular research project. Words in the non-shaded cells indicate the most relevant complementary strategy.

6. *Summary of empirical findings*

Table 4 presents a summary of the empirical findings of this exploratory investigation. It shows that the cases studied have very diverse affiliations, significantly diverse researcher backgrounds, but comprise a rather similar set of references, instrumentalities and citations, spread over various disciplines. Since we may relate affiliation and researcher's background 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 lower and more erratic degree of cross-disciplinarity – even when collaborations are considered - with the main discipline being contingent on specific laboratories. Nevertheless, there is a clear positive correlation between the dominant type of (cognitive) expertise contributed by a team and its dominant disciplinary (social) ascription – in other words there is still a link between *tribe* and *territory* though much looser than in 'normal' research. The disparity between the degrees of cross-disciplinarity in the various dimensions supports the need for a multi-dimensional approach in evaluation exercises.

Table 4. 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**
Affiliation			(100%)			100%						(100%)			(100%)					(100%)
Background		10%	90%			100%						100%		30%	70%				50%	50%
Affiliation includ. Collabor.			(90%)	10%		50%	50%		15%			(85%)	25%		(75%)				15%	(85%)
Background includ. Collabor.		10%	80%	10%		50%	50%		15%			85%	30%	30%	40%				75%	25%
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%
STRATEGY		Rec	REC	Col		COL Lear	COL Lear		LEAR Col				Col	REC	Rec				REC Col	REC

Legends for discipline: ***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. Legends for stragegy:* **Rec**: *Recruitment.* **Col**: *Collaboration.* **Lear**: *Learning. Cells are shaded on a linear grey scale according to the discipline's share in each dimension. Dominant strategies are shown in upper case letters and shaded cells.*

The percentages shown in this table represent a rough estimate (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 a much narrower disciplinary spread than the rows related to the cognitive dimensions (references, instrumentalities and citations). Moreover, whereas the dominant discipline is contingent in each case on the social dimensions, in the cognitive dimensions biochemistry and biophysics consistently capture an important share, as might be expected from projects focused on the mechanistic understanding 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 case study narratives suggest that indicators based on cognitive dimensions are more reliable than indicators associated with social dimensions for estimating the disciplinary spread of a research project.

The last row in Table 4 allows us to compare cross-disciplinarity and the knowledge-sourcing strategies. From the case study narratives it emerged that mastery of many of the instrumentalities used in Molecular motors was crucial for the conduction of successful research in this field. The consistent disciplinary spread in references corroborates the importance of cognitive diversity. However, the top four rows (social aspects) and the last row (strategies) in Table 4 do not show any congruent pattern, suggesting that research groups can enter this specialty from different disciplinary backgrounds and affiliations and may pursue a variety of knowledge-sourcing strategies in order acquire the knowledge required to work in the specialty – which is mainly related to the diversity of instrumentalities required.

In all the cases studied formal collaboration is used as a means to increase the cognitive diversity of the project, but in only one case was collaboration the main strategy pursued. In the other cases, in-house learning and recruitment of researchers both from the same and from different disciplines were the main strategy. In particular, the strategies adopted in Projects A and C (recruitment of researchers from same background and in-house learning, respectively) challenge the conventional wisdom that in fields such as bionanotechnology successful research involves collaboration between researchers or laboratories from different disciplines. What are the unexpected advantages of the mono-disciplinary practices used in Projects A and C?

7. A trade-off between cross-disciplinarity and integration

Building on Llerena and Meyer-Krahmer (2004) and Hollingsworth and Hollingsworth (2000), we propose that the variety of knowledge-sourcing strategies encountered supports the idea of a trade-off between the benefits of disciplinary diversity and the costs of integration.

The first cost of integration is extra effort devoted to coordination and communication, given that disciplinary diversity is useless unless the body of knowledge brought together can be properly articulated through a fluid understanding between the various researchers in the team. In the case of teams with researchers from several disciplinary backgrounds, this communication will require ‘interpretative learning’ (Grigg et al. 2003), which we here tentatively term *conversant capacity*, i.e. the capacity to interact with various disciplinary knowledge sources, based on an already attained understanding of the essential terms, implicit assumptions and observational classes of disciplinary frameworks. *Conversant capacity* would play the role in a research group that according to Cohen and Levinthal (1990, p.) *absorptive capacity* plays in a firm: it allows researchers ‘to recognize the value of new, external information, assimilate it, and apply it’ to specific goals. Given that the acquisition of *conversant capacity* involves an important investment, groups that manage to access the same diversity of knowledge sources while sharing some basic commonalities, either in terms of specialties or disciplines, will benefit from lower integration costs. Or, as Cohen and Levinthal put it, there may be ‘a trade off in the efficiency of internal communication against the ability of the subunit to assimilate and exploit information originating from other subunits or the environment’.

The second cost lies in the problem of attributing research authorship in collaborations. Owing to the importance in the reward system of science of recognition, researchers need to receive credit for their contributions. The downside of carrying out research through external collaboration or as a member of a large lab is that the credit tends to go to the principal investigator, who may belong to a community outside the scope of some of the collaborators. As one interviewee put it:

> It’s very, very hard to get going as a young person in this field. […] Because you need so much of an establishment, really, to make a difference, to actually do something original.

> […] there is this whole business of building your apparatus and getting people who are competent to do the experiments, combining that expertise [in apparatus use] with the expertise of the protein chemistry and so on. That is really hard to do when you are in your own. *And then you finish collaborating and then you finish up disappearing under someone else's umbrella*.

We interpret the diversity of knowledge-sourcing strategies in the various research projects presented as the result of the variety of possible 'solutions' to the trade-off between disciplinary diversity and integration. How each project meets the need of diverse knowledge sources depends on the funding and institutional settings but also on contingent factors such as researchers' personal inclinations. In Project A, for instance, the group leader had a large grant which allowed him to garner a wealth of cross-disciplinary expertise in instrumentalities by hiring only biophysicists who were familiar with specific techniques from other disciplines. This strategy brought diversity without need for special integration efforts. In the case of Project B, lack of cognitive diversity in the initial lab was solved through collaboration, whereas the cost of integration was minimized thanks to the absolute commitment and enthusiasm of two postgraduate students. In the case of Project C, the cost of 'losing' some right to attribution in full-blown collaboration was viewed as higher than spending some extra effort on in-house development of the instrumentalities that were acquired through punctuated collaboration.

In a seminal study Katz and Martin (1997, p.17) vindicated the need to adopt a 'more symmetrical approach' to assess the costs and benefits of collaboration. Similarly, these results suggest that it is more than time that the widely flaunted benefits of cross-disciplinary research should be evaluated in the light of the costs of integration, which appear to be equally high.

8. Discussion

To summarise, in this exploratory study we found that although cognitive diversity is crucial in Molecular motors, social cross-disciplinary practices (e.g. in organizational affiliations) are less common than might generally be expected. We argued that the reason for this is that there are various possible strategies for achieving cognitive diversity, and some research groups find ways to garner it without having to bear the costs of disciplinary integration. Although these results need to be considered with caution as they maybe specialty contingent,[6] we believe that the conceptual model used for their analysis would be generalizable.

From a radical interpretation of the findings it might be concluded that ultimately cross-disciplinarity matters very little. On the one hand, the differences across projects in affiliations and researchers' backgrounds suggest that current or historical disciplinary labels are not relevant. On the other hand, an essential ingredient seems to be *cognitive diversity*, starting from excellence in a variety of instrumentalities and probably including a sound and broad – but not necessarily complex or sophisticated - grasp of the basic concepts in the fields involved.

These observations suggest that the term cross-disciplinarity is a misnomer (Gläser, personal communication) and in much of the policy discourse, inter- or transdisciplinarity are used to implicitly refer to knowledge diversity either in relation to disciplines, specialties, technologies or the stakeholders concerned. In contexts, such as academia, where disciplines happen to be the (overrated) unit of categorization, cross-disciplinarity in some dimensions may arguably be an (imperfect) proxy for cognitive diversity. However, in contexts outside of academia, where there are other forms of group ascription and categorizations of knowledge (e.g. in industrial research),

[6] Hicks (1992) for instrumentation, and Fujigaki (2002) for cross-disciplinarity, showed that close knowledge domains presented a very different structure in relation to the issues they examined.

disciplines are known to be irrelevant, whereas knowledge diversity is still considered an asset (Cohen and Levinthal, 1990). This lack of applicability of the concept of cross-disciplinarity at the technological and industrial level is a major obstacle in fields such as nanotechnology where significant interactions between science and technology have been reported (Meyer, 2000).

In the face of the problems outlined above, we would advocate for a change in focus from cross-disciplinarity to cognitive diversity. Diversity is a concept used across a range of scientific fields, from ecology to economics, to refer to three different attributes of a system composed of different elements and/or categories (Stirling, 1998):

- **Variety**: number of distinctive elements/categories.
- **Balance**: relative distribution or share of elements/categories.
- **Disparity**: degree to which the elements/categories examined can be distinguished.

However, most studies of cross-disciplinarity (including ours) have examined variety and balance of disciplines as indicators of degree of diversity, and either ignored or carried out a separate analysis of the disparity between fields, for example in bibliometric mapping (see references in Bordons et al., 2004). The challenge lies in creating a 'measure' of cognitive diversity that is robust (or at least transparent and predictable) to changes in categorization methods (be it top-down disciplinary classification or bottom-up clustering), and which includes the three attributes listed above (Stirling, 1998).

Our critique of the term cross-disciplinarity should not be interpreted as a denial of the role played by disciplines. The empirical results have shown that there is an important correlation between the predominant cognitive areas and the social disciplinary ascription. This is understandable because Molecular motors research is - so far - basic science, and as such, it is mainly conducted, debated and published in an academic setting, where disciplinary structures rule. Returning to Becher's tribes and territories (Becher and Trowler, 2001), it is through the interplay between the social and the cognitive that disciplines become an issue in knowledge production: even when social cross-disciplinarity is not strictly a cognitive need, it becomes useful as a means, a social instrument, for accessing across the scientific community the diversity of skills necessary to tackle a given problem.

While acknowledging that this is a pilot study, we believe that these conclusions are relevant for the evaluation and design of research policies aimed at fostering emergent fields, which currently focus on the facilitation of cross-disciplinary collaboration between laboratories. First, evaluation exercises looking into cross-disciplinarity should focus on the cognitive indicators (e.g. references), which have been shown to be more accurate proxies for knowledge diversity than social indicators (e.g. affiliation). Second, this investigation demonstrates that social cross-disciplinarity is valuable as a *route or means* to achieve the *goal* of cognitive diversity, but that there are other routes which, under some conditions, may offer higher chances of success. In fact, some of the current policies, such as investment in shared platform technologies, or those fostering the migration and acquisition of generic technologies (instrumentalities), may already be performing this function.

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