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Interdisciplinarity in Practice: A Case of a Nanotechnology Research Center

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Abstract

Convinced that the nature of today?s scientific and technological problems demand interdisciplinary solutions, research policy makers and funders are increasingly demanding coordination among academic disciplines. Yet, research on interdisciplinarity has with few exceptions treated it monolithically as a style of research or research outcome rather than considering the coordination as it happens. It is thus difficult to identify mechanisms of coordination and the consequent policy implications. This paper traces the day-to-day activities of researchers in an NSF-funded university interdisciplinary research center, and in doing so, demonstrates how interdisciplinary coordination takes place both on the cognitive plane and in the political economy of research, being neither wholly about the generation of creative ideas across disciplines nor about the breaking down of barriers across departments. Drawing from the history and sociology of science literature on interdisciplinarity and matching it with organizational theories about coordination, we identify the objects (instruments) and boundary spanners (primarily students) who operate at the nexus of disciplines. Our mapping of the research process provides a framework for understanding tensions in interdisciplinary work and identifying the micro- mechanisms by which change in the management of scientific research occurs.

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Interdisciplinarity in Practice: A Case of a Nanotechnology Research Center

Convinced that the nature of today's scientific and technological problems demand interdisciplinary solutions and compelled by arguments that interdisciplinarity can lead to more creative insights, research policy makers and funders are increasingly demanding coordination among members of different academic disciplines. The National Science Foundation (NSF), one of the premier sources of research funding in the U.S., and the National Academies in their joint report on interdisciplinary research (National Academies (U.S.) 2005) define it as "a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice." Implicit in the definition are proponents' arguments that coordination across disciplines produces better solutions to socially-relevant problems.[1]

Evidence suggests that these efforts have achieved only partial success. Bibliometric studies show that the use of the term "interdisciplinary" in journal article titles across a broad range of disciplines has grown exponentially (Braun & Schubert 2003; Jacobs & Frickel 2009). Yet, others (such as, Weingart 2000) have argued that claims about the predominance of interdisciplinary research may be more rhetorical than actual.[2] Indeed, the National Academies, concerned that universities were having difficulty implementing interdisciplinary research programs, recently published a book of recommendations on reducing barriers to coordination (National Academies (U.S.) 2005), suggesting such actions for universities as changing the promotion criteria to include interdisciplinary journals, accounting for longer startup times for interdisciplinary work when judging productivity, hiring faculty with a mixed set of disciplinary training into departments, creating forums for interactions across disciplines, and changing funding evaluation criteria in order to direct resources to interdisciplinary projects.

Recommendations like these for improving interdisciplinarity imply substantial organizational changes in how research is undertaken, yet we know little about how interdisciplinarity operates and, therefore, how such changes might be implemented or even whether they would be useful instigators of coordination. Research on interdisciplinarity to date has with few exceptions (discussed below) treated it monolithically as a style of research or research outcome rather than considering the coordination as it happens.

In this paper, we argue that to understand how and when interdisciplinarity takes place, scholars must first study the day-to-day work of interdisciplinary researchers. We explore the practices of coordinating across disciplines in a field study of the operations of an NSF-funded interdisciplinary research center in the emerging field of nanotechnology (the Nano/Bio Interface Center at the University of Pennsylvania). “Nanotechnology” refers to the understanding and control of matter at the nanoscale (less than 100 nanometers in size). Many experts regard nanotechnology as inherently interdisciplinary, cutting across chemistry, engineering (of multiple sorts), physics, medicine and other disciplines (Wry, Greenwood, Jennings & Lounsbury 2010; Zucker, Darby, Furner, Liu & Ma 2007).[3] With the creation of the National Nanotechnology Initiative in the U.S. in 2000, the government (through many agencies including the NSF) has channeled large amounts of funding into research universities. These resources come with the explicit requirement that the funded research be interdisciplinary. As a result, universities that attract this funding, such as the one studied here, must make changes in how research is managed in order to fulfill their obligations.

By studying this research center, we are able to examine researchers’ efforts to coordinate across disciplines in their daily work. Our analysis is a work of interdisciplinarity itself, drawing substantially from both the history and sociology of science literatures (where most of the research on interdisciplinarity has taken place) and matching it with organizational theories about coordination across other types of boundaries such as those created by professional or functional differences. It is at this intersection that we hope to draw out new insights for both fields as well as for scientific practice and policy. A focus on the activities of researchers highlights how interdisciplinary coordination takes place both in the cognitive domain and in the political economy of research, being neither wholly about the generation of creative ideas across disciplines nor about the breaking down of barriers across departments. A mapping of the research process provides a framework for understanding tensions in interdisciplinary work and identifying the micro mechanisms by which institutional change in the management of scientific research occurs.[4]

The problem of coordination across disciplines – cognitive and political barriers

The problem of interdisciplinary research is fundamentally one of coordination across disciplines. On the one hand, interdisciplinarity is at the heart of the research endeavor. Research problems can ignore disciplines. This is what makes interdisciplinary questions appealing and, as the National Academies (2005) state, what "drives" scholars towards interdisciplinary research. Interdisciplinary projects spring up regularly as specific problems call them into existence. As described by Lenoir (1997, p. 53), "Scientists at the research front do not perceive their goal as expanding a discipline. Indeed, most novel research, particularly in contemporary science, is not confined within the scope of a single discipline, but draws upon work of several disciplines. If asked most scientists would way they work on problems."[5] Some scholars (e.g., Gibbons, Limoges, Nowotny, Schwartzman, Scott & Trow 1994) have argued that interdisciplinary research has already become the primary "mode" of useful knowledge production inside universities (what has become known as "Mode 2" research), having largely replaced the former disciplinary mode ("Mode 1"). Turner (2000) points to the historical record to show that disciplines are not easily formed or assured of their existence. When scholars focus on goals other than perpetuating their disciplines, interdisciplinary efforts are possible. In this sense, interdisciplinarity is a rejection of the ends of the disciplinary system (such as producing more "disciplined" scholars) in the pursuit of other ends (perhaps solving a social problem).

On the other hand, disciplines create boundaries of two basic kinds – cognitive and political – that make coordination difficult. Debates about the apparent stability or instability of the system of disciplines in the past century has, as a byproduct, brought these barriers into relief (see, Abbott 2001; Gibbons, Limoges, Nowotny, Schwartzman, Scott & Trow 1994; Lenoir 1997; Turner 2000). First, disciplines – as embodied in professional societies, textbooks, departments and the like –govern the political economy of research. That is, they mete out the resources and rewards (in terms of recognition, status and promotions) for conducting scientific investigations. Abbott (2001), a proponent of the stability of the disciplines, argues that these disciplinary social structures are entrenched through a positive feedback loop related to scientists' careers: career-minded academics rely on disciplinary organization and well-understood boundaries to be marketable and promotable. Similarly, hiring institutions and tenure committees use disciplinary identifiers as shorthand when evaluating (potential) faculty members, and degree-granting universities must please graduate students working towards these credentials. This political economy of academia can dissuade scholars from engaging in interdisciplinary work or create career concerns for those that do (Derry & Schunn 2005; Hackett 2005). The inherent interdisciplinarity of research fails to reform the academy, according to Abbott, because it is focused on research problems and not on careers.

Interdisciplinary research is also cognitively challenging. That is, interdisciplinary research requires scholars trained in different knowledge bases to coordinate their work. Some have described this as a problem of speaking different languages where developing a "pidgin" or "creole" might serve as a coordinating mechanism (e.g., Galison 1999).But, practitioners and scholars have recognized that the notion of "language" is an impoverished characterization of the challenges of coordinating across knowledge bases and have highlighted other aspects, such as understanding methods, that might be equally problematic.[6] It is not just that their languages are different but that scholars from different disciplines do not share the same worldviews, use the same instruments, or follow the same experimental methods (Lenoir 1997; Mody 2011).

We ask, therefore, how do researchers coordinate their work on specific research problems that are by definition interdisciplinary in the context of a university political economy based on departments and of cognitive structures based in the disciplines? Because the majority of extant research on interdisciplinarity has treated it primarily as a "mode" or style of research, such studies have not been able to shed light on how coordination along cognitive and political dimensions of disciplinary boundaries works. Although studies of the disciplines (Abbott 2001; Turner 2000) identify several research roles – faculty members, hiring administrators, and graduate students – they do not incorporate those actors' specific activities into their analyses. It is a mile-high view of the academy, where larger forces obscure individual action.[7]

A related stream of research concerned with the gaps and tensions between theorists and experimenters calls our attention to the contrasts between the operation of the discipline at a macro level and the coordination of work at the micro level in specific research investigations (Bourdieu 1975; Galison 1999; Lenoir 1997). These scholars argue that disciplinary activity is not the same as actual research practice *in situ*. Yet, we are left with little understanding about how this local coordination works in specific scientific investigations (Lenoir 1997). What is missing is insight into the underlying practices of interdisciplinarity, about which much less research has been done (Jacobs & Frickel 2009),[8] and without which it is difficult to assess the degree of interdisciplinarity actually taking place. This is why policy makers and funders continue to call for more field work on this topic (National Academies (U.S.) 2005; Paletz, Smith-Doerr & Vardi 2011).

A few recent studies have already heeded this call. Some have focused on the political boundaries blocking interdisciplinarity. Rhoten's (2003) ethnographic study of six NSF-sponsored interdisciplinary research centers for environmental studies found that those in charge of interdisciplinarity's "systemic implementation" – the university administrators – were holding up the show. They failed to make the structural changes needed for interdisciplinarity to blossom. Even when intrinsic motivation was high (i.e., researchers were excited about research possibilities) and extrinsic attention was more than adequate (i.e., funders had both monies and enthusiastic rhetoric to dispense), the interdisciplinary enterprise lacked political will. Rhoten's solution: dedicated interdisciplinary facilities physically isolated from departmental pressures. Similarly, Sá's (2008) study of interdisciplinary administrative policies at U.S. research universities found that only rarely do universities implement systematic policies to change faculty hiring and evaluation to favor interdisciplinary activities, relying more regularly on separate "organized research units." These units are popular because they exist in a space apart from the rest of the university, thus posing no challenge to the existing departmental system (and avoiding challenge from that same system). Neither Rhoten nor Sá tackled the impact of these new organizational forms on the work of researchers in these units but indicated that more ethnographic studies were needed.

Other field research on interdisciplinarity has focused instead on its cognitive challenges, studying the means by which researchers solve the problem of coordinating across different knowledge bases. Jeffrey's (2003) participant observation in a collaboration among ten researchers of various social science and computer science backgrounds focused on the ways the group developed a common vocabulary and applied metaphors and story lines that promoted mutual understanding. Palmer (2001) also found that information and communication functions were central for coordinating across boundaries. Galison's (1999) related ideas about the use of "pidgin" or "creole" languages in trading zones to coordinate the actions of physicists speaking the different languages of theory and experiment suggests also that crossing the cognitive boundaries of disciplines is a primary challenge of interdisciplinary research.

Each of these studies offers a glimpse at the potential insight that can come from an exploration of the practices of interdisciplinarity. Yet, they have not considered the tensions that emerge as researchers simultaneously navigate both the cognitive and political boundaries that the disciplines create. To make progress on this question, we draw on organizational research on coordination in and across organizations that points us to two basic pathways for its study: by analyzing the use of objects (Bechky 2003; Carlile 2002; Hargadon & Sutton 1997) and the actions of boundary spanners (sometimes known as brokers) (Barley & Bechky 1994; Bechky 2006; Burt 2004; Levina & Vaast 2005; Lingo & O'Mahony 2010). We draw on these ideas to extend theories of coordination in the social studies of science by focusing on the ways in which instrumentation (as *objects* that operate at the nexus of disciplines) can enable interdisciplinarity – and also on graduate students as a class of *boundary spanners* that have previously been poorly explored in the literature.

Organizational research on coordination, has for the most part, focused far afield from scientific work, examining country music producers, new product development teams, information system implementation, and internet advertising projects. Methodologically, however, these studies are useful in suggesting several features of coordination to explore. First, they suggest that coordination efforts will be successful if located in temporary projects (Kellogg, Orlikowski & Yates 2006; Lingo & O'Mahony 2010; Obstfeld 2005). Second, the kinds of activities required for coordination will differ at different stages of work (e.g., in idea generation or later execution) (Lingo & O'Mahony 2010). Third, actors engage in collaboration not only to generate creative ideas that benefit the collective (sometimes called *tertius iungens*) but also to use the collaboration their own political benefits (*tertius gaudens*) (Lingo & O'Mahony 2010; Obstfeld 2005). And, finally, coordination is manifested in the interconnection between the use of objects and the work of boundary spanners (Barley & Bechky 1994; Black, Carlile & Repenning 2004; Levina & Vaast 2005). Barley and Bechky (1994), who are among the only organizational scholars to study coordination in research labs (though not explicitly interdisciplinary ones), focused their attention on the role of lab technicians. Their analysis emphasized the status ambiguity of these technicians: they are in a lower status occupation and have less formal training and theoretical knowledge than the scientists, but they have a certain kind of power accrued from their direct contextual knowledge of the experiments that comes from performing the work. Barley and Bechky do, however, call attention to these technicians as the coordinators between the material world (of experiments and instruments) and the symbolic world (of interpretation and inscription).

We use this work as a starting point to examine the work of researchers affiliated with the Nano/Bio Interface Center, focusing our attention on the objects (in this case the instruments used in experiments) and on the boundary spanners (most centrally, the graduate students and post-doctoral fellows who conduct the experiments) across the entire research process, from idea generation through to write up and publication. In doing so, we explore how interdisciplinary coordination operates in both the cognitive domain and the political economy of daily research and shed light on how practices put in place to facilitate interdisciplinary research actually work. Putting the organizational coordination lens on the study of interdisciplinarity helps us move beyond thinking of such research monolithically as a "mode" and toward a deeper understanding of interdisciplinarity in action.

The case of the University of Pennsylvania Nano/Bio Interface Center

The field of nanotechnology provides an appealing arena to explore interdisciplinarity as it is, by definition, one of those research domains that cuts across disciplinary boundaries. In the United States, Congressional passage of the National Nanotechnology Initiative (NNI) in 2000 routed an annual sum of $465 million in governmental support to nanotechnology research, and the budgeted amount steadily increased through the years to amounts exceeding $1 billion annually in 2009-2010.[9] The NNI's definition of nanotechnology notes its interdisciplinary character: "the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale."[10] The NNI's support for nanotechnology research has been predicated on researchers pursuing interdisciplinary questions.

Since nanotechnology is principally defined by the dimension of the object of analysis, it has served as an umbrella for research performed by chemists, physicists, material scientists, biologists, engineers (electrical, mechanical, biomedical, etc.), and physicians (Meyer 2007; Schummer 2004). The NNI, through its direct funders like the NSF, seeks to draw these disciplines into a common conversation about how to exploit nanomaterials and unlock their scientific and economic promise through medical, electronic, and energy applications.[11]

Whether interdisciplinarity has been achieved remains an open question. Bibliometric studies have provided a mixed message about the nature and degree such activity, depending on what metric the researchers used. One study performed in the early days of nanotechnology research (Meyer & Persson 1998) found that journal papers from 1991 to 1996 whose titles contained words with a “nano” prefix appeared in a significant number of “multidisciplinary” journals. Yet, studies of co-classifications of patents (Meyer 2007) or the departmental affiliations of authors (as shorthand for their disciplinary orientation) who published articles in nano-themed journals (Schummer 2004) concluded that the component disciplines of nanotechnology seemingly acted in isolation of one another and “classical disciplinary patterns have continued or reproduced themselves” (Schummer 2004, p. 451).

In a more comprehensive study, Rafols and Meyer (2007) used five different analyses to dig into the interdisciplinary character of Japanese research projects in bionanotechnology, examining what they call the social aspects of research collaborations (current disciplinary affiliations and background disciplines of the researchers) and the cognitive aspects associated with how ideas travel (journal article references, citations, and research methods). They found the degree of cross-disciplinarity in cognitive dimensions to be quite high but in social dimensions to be “lesser and more erratic” (p. 644). While these high-level bibliometric measures may not capture the underlying practices of interdisciplinarity, they do highlight the tensions between the cognitive and political domains of such research and the potential difficulties of coordinating across them.

Our project is meant to address this research gap by studying researchers in the Nano/Bio Interface Center (NBIC) at the University of Pennsylvania. Established in 2004, the NBIC is one of eight Nanoscale Science and Engineering Centers (NSEC’s) funded as part of the NNI. As its name indicates, the center promotes studies of the interfaces at the molecular level (i.e., the nanoscale) between physical and biological systems. The center’s 39 faculty members come from a variety of disciplinary backgrounds in engineering, natural sciences, and medicine. They typically align with one of two NBIC-sponsored research teams (RT): “molecular motions” and “biomolecular optoelectronic function” and may also associate with a cross cutting initiative (CCI) on single molecular probes (equipment that could facilitate research in either of the RT areas).[12] After the initial formation of the center with a core group of faculty, the NBIC has attracted additional (mainly junior) faculty members through the annual granting of Innovation Awards.[13]

Because of our concern with moving beyond the macro level analyses of interdisciplinarity that have predominated until now and our interest in uncovering the diversity of ways interdisciplinarity might manifest itself for different participants, we conducted a field study over nine months (September 2008-May 2009). We collected three sorts of data: in vivo observations of researchers at work, interviews with researchers, and documentary evidence covering meetings, collaborations and instrument use. We made regular observations of NBIC-related activities such as monthly NBIC meetings, RT meetings and lab meetings. We sat in the shared facilities and observed the use of NBIC research instruments such as the atomic force microscope (AFM). Because we are co-investigators in the NBIC under a grant to examine the social aspects of nanotechnology, we were participant observers in a wide range of activities, including the monthly meetings, NSF grant renewal efforts, and NSF review meetings. We also conducted semi-structured interviews with 22 NBIC participants across the spectrum of disciplines and career positions, including students, postdoctoral fellows, and untenured and tenured faculty (the interview guide appears in the Appendix).

Table 1 lists all of the NBIC faculty members as well as selected students and postdoctoral fellows who were informants in this study. Each person is indicated by a code that represents his or her rank and department. For all faculty members, we note how many NBIC-affiliated students each supervised, whether they had received funding through an Innovation Award, their affiliation with the Research Teams or the Cross Cutting Initiative on probes, and whether they had been interviewed or observed by us in NBIC and related activities.

-- Insert Table 1 about here --

Further, we also collected hundreds of pages of documentary evidence such as the annual reports to the NSF prepared by NBIC researchers; logs of daily instrument use showing who was using each instrument and when; attendance sheets, agendas and presentation materials from NBIC meetings, lists of publications prepared using NBIC support, lists of winners of NBIC innovation awards, and grant application and renewal documents. From these multiple data sources, we sought to identify the daily practices of interdisciplinary researchers in the NBIC setting.

We started with an analysis of two bibliometric measures on the 115 publications listed by the NBIC as output of NBIC-related projects in the first 5 years of the grant (2004-2009).[14] We found that 50.4% of publications would be classified as interdisciplinary in that at least two disciplines were represented in co-authors' current departmental affiliations and 69.9% were interdisciplinary when considering their background disciplinary affiliations (i.e., the disciplines in which their doctorates were awarded, as culled in a careful review of all CVs and personal websites). As a further assessment of NBIC researchers' interdisciplinarity, we found that 15 of 39 (38%) of faculty had cross appointments in other departments (see Table 1), indicating that many were cutting across disciplines in ways other than through the NBIC. The annual reports for the NSF also emphasize throughout the collaborative and multidisciplinary research being funded by the center.[15] These analyses show that the question of "how interdisciplinary?" depends greatly on the variable analyzed. Regardless of the metric used, we find that, even for research conducted with explicitly interdisciplinary intent, not all of it involves interdisciplinary coordination.

Attention to the daily practices of the NBIC researchers should get us closer to understanding how interdisciplinary coordination operates. To get down to the research *in situ*, in the next two sections, we locate the sites of coordination around the objects (the use of instruments in experimentation) and boundary spanners (the deployment of students and post docs to work on projects). We use this exploration to analyze the efforts of the NBIC to encourage interdisciplinary research and therefore change how science was practiced at the university. The final result is a richer portrait of interdisciplinarity, as a process enacted in specific projects, using certain instruments, staffed by particular students, and enabled by an interdisciplinary research center.

Instruments at the nexus of disciplines

We start with the instruments, as they have been central to the mission of the NBIC. According to their first annual report to the NSF:

> "The central theme of the NBIC, control of molecular function at the nano/bio interface, requires the synergy of concepts and experimental approaches from the physical sciences, biological sciences, and engineering. Nano property measurement requires the implementation of newly developed tools.

> The NSEC [Nanoscale Science and Engineering Center] is establishing a shared facility: the Molecular/Nanostructure Innovation Facility. The facility will be unique to Penn, where the newest advances in probing single molecule and nanostructure behavior… will be made available to the research community at large. In addition to scanned probe based microscopies, an opto electronic device probe station, advanced optical microscopies, and ellipsometry, will be available."[16]

Over time, the NBIC has invested nearly 30 percent of its annual budget in equipment and facilities, and this figure was tripled in the later years of the grant through matching funds and in-kind equipment donations from manufacturers. The Center hosts the Nano/Bio Probe Innovation Facility that contained a series of specialized instruments, including atomic force microscopes (AFMs) with different capabilities, a scanning tunneling microscope (STM), an interfacial force microscope (IFM), a probe station, and several other pieces of equipment for spectroscopy and microscopy that allowed researchers to visualize and manipulate matter at the molecular level. Several faculty members also made equipment in their own labs available to other NBIC-affiliated researchers. Over time, the NBIC general meetings and communications increasingly featured extensive discussions of which instruments were available and how they could be used.

The placement of many of these instruments in a central location and the regular advertisement of instrument capabilities was intended to enable interdisciplinary collaboration. This is much the case elsewhere in nanoscience and technology research, as elegantly documented by Mody (2011): probe methods have given impetus to nanoscale research, and these methods and instruments link people working in different disciplines. Heinrich Rohrer, a physicist at IBM who shared the Nobel Prize for his invention of the first probes (scanning tunneling microscopes or STM), argued that the field of nanotechnology was the product of electrical engineers and others working at ever smaller scale (in pursuit of Moore's law in electronics) and biologists and chemists moving from atomic to larger-scale molecules. As Mody summarizes, "this convergence in size scale created an opportunity for electrical engineers, biologists, chemists, and others to collaborate in new ways. For Rohrer, then, 'nanotechnology' *is* interdisciplinarity" (p. 180).[17] Probe microscopy thus facilitates the connections among communities.

Empirically and theoretically, we therefore expected that the instrumentation would serve as a locus of interaction across the disciplines at the University of Pennsylvania. Our findings suggest that this was both true and not true. Crucially, it was not true in the sense that the actual work on the instruments was conducted by individuals (mainly students), alone. After many hours of observations in the Nano/Bio Probe Facility and a review of the signup logs for the various pieces of equipment, it appears that most work on instruments was done by a single person at a time. If multiple people were in the nanoprobe facility, they rarely interacted, staying focused on their instruments. Only when a newcomer was being trained in the use of a particular instrument by someone else with experience, was there more than one person working at an instrument at the same time. Not that we would expect that interdisciplinary work would involve collaborators physically working together at all times across the entire research process. Of course, collaborative work will, over time, involve some work together and some work in solitude. However, this portrayal suggests that the role of instruments in interdisciplinary work is not about people interacting around boundary objects per se, as would be suggested by most images of boundary work previously evoked in the literature.

Instruments were, however, the locus of coordination at a more abstract level. The availability of instruments and techniques instigated investigations that would not have been possible otherwise. The strength of the coordinating activity was often characterized by the degree to which instrumental knowledge was shared. In discussing his collaboration with investigators from the medical faculty, one material sciences professor put it this way: "So we make patterns and templates that they normally wouldn't have, and they have the tools that engineers normally wouldn't have to probe biological molecules. So that's a very strong collaboration" [FullP-MSE-3]. A mechanical engineering faculty member with an expertise in diamond tips for AFM probes described this kind of interaction in more detail,

> "There are things that you could discover and will discover that you would not otherwise discover on your own because you just don't have, number one, the access to the techniques, the knowledge of the materials, the knowledge of the scientific problem, to approach it on your own. So [a radiology professor] makes these molecules that have a unique shape to them, and they're very useful to stick on the ends of an AFM tip to probe a surface, but they have limitations in how stable they are. Diamond is a more stable material so if you can take the molecule, attach it to diamond, you might have something that is very stable, robust, and you can go off and use it. So it really was her material and my material being combined and finding a way to bond them together. I have no expertise in molecular synthesis. I would not be able to guide a student to synthesize the molecules she makes. She does not have any background in diamond-based materials and through me she obtained these diamond probes...So neither of us could have done this on our own" [AssocP-MEAM-1].

The projects were not possible without the instruments. Said a mechanical engineer, "I think it was [a Professor of Medicine] who contacted me and said, 'Hey I know that you're doing AFM. I have something related to that that I do; let's meet.'" [AssocP-MEAM-1]. Similarly, a physiology professor expressed the importance of his collaborator's specialized know-how in the use of certain instruments for fabrication:

> "It's a project that I would never have done without [a mechanical engineering professor] and people in his lab. It has to do with suspending cytoskeletal filaments, predominantly actin, that we've done across microfabricated gold electrodes. So they know how to do that in the fabrication center over there, and they do all that part of it" [FullP-Physiol-1].

Cognitive interdisciplinarity in the use of instruments

Thus, the physical location of the instruments was not the "trading zone" in which interdisciplinary research ideas flowered.

> "The NBIC, for the most part, is sort of a virtual center. It's the participants that make the center. There is a central facility that people come and use for their research, but it really is a virtual entity. It's not like it's a specific lab, it's not like there's an NBIC beehive that's producing the honey. It's more like there's a bee from my hive communicates with a bee from [a medical professor's] hive or [a materials science professor's] hive and NBIC provides some flowers that they can pollinate some tools to use, okay?" [AssocP-MEAM-1].

Cross-pollination was not straightforward. Even the "low hanging fruit" (to continue the pollination metaphor) where "you can go and potentially have a unique skill set that allows you to work in areas where people have maybe worked for tens of years and come in and immediately be helpful to them and allow them to do things that they didn't know that they could do, or wanted to do but didn't have a way to do" [AssistP-Chem-2] are not easy to pick, because "we do have to be more creative to come up with techniques that are very specific to that type of material or matter" [AssistP-Chem-2].

This type of "borrowing" from one discipline to another has been characterized as not involving true interdisciplinary coordination (Klein 2000). Much of the literature on interdisciplinarity has devoted considerable attention to definitions, creating typologies and determining what is "true" interdisciplinary research (vs. cross disciplinary vs. multidisciplinary vs. borrowing, etc.) (Klein 2000). Our field study reveals that this debate may be moot when considering the daily practices of interdisciplinary research. Even in the simplest of cases of using a technique developed in one discipline to solve a problem in another discipline, cognitive coordination is required.

First, such borrowing requires a different way of thinking about the problem. Said one materials scientist about collaborating with researchers in medicine,

"On the material side we're much more careful, I think, on characterizing the materials that we're

> dealing with. So we tend to do a lot of electron microscopy and a lot of characterization of the materials platform. And, on the biological side, that's not as important, but what is important there is to make measurements of, in this case, how single molecules would behave. But, on the other hand, there's a growing interest on the biology side, recognizing that, hey, 'you guys could make all these fancy surfaces and do things, let's get together and do something unique.' So [this medical professor's] lab is unique in that sense. Most biophysicists would not think that way. They would think strictly along 'what are the biological assays that we have to interrogate our materials' and not think about, 'okay, there are some techniques out there on the engineering side that could be helpful as well.'" [FullP-MSE-3]

Similarly, a mechanical engineering professor described it as a basic difference in styles.

> "In physics it's, their instruments, they make very precise measurements. And not to say that other disciplines don't but they are extremely picky with their data. And they will simplify the problem to get the best answer possible, right? Well, engineering they're more applied so they might not look to simplify the problem. In fact they might look into more complex problems which makes physicists nervous, right? And the biological and biophysics well that is just a mess because the problem itself is so complex and complicated this scares the hell out of physicists and engineers! [Laughter] So there is different styles, definite different styles and how to handle a problem" [AssistP-MEAM-2].

Second, the use of these instruments requires collaboration to understand and interpret the results. As scholarship on scientific instrumentation (Galison 1999; Lenoir 1997; Pickering 1984) and on nanoprobes specifically (Mody 2011) and has already established, the results from experiments using these instruments are very hard to interpret. It is difficult to understand if the supposed result is simply an artifact of the sampling technique or the instrument's algorithm. Often coordination efforts across disciplines are simply about finding a means to calibrate the results. For example, in an NBIC general meeting where a professor from the School of Dentistry made a presentation on "Matrix Vesicle Mediated Mineralization of Collagen Fibrils," he noted that collagen strands have evenly spaced grooves of 67nm (nanometers). A materials science professor asked, "Can it be used as a measuring standard?" The presenter responded that "it is always 67 nm," to which the materials scientists replied, "Frankly, it is difficult to find" naturally occurring materials that can be used in calibration at the sub 100 nm level and that this could be used as a trick for calibrating x-rays. The presenter replied that it is "extremely regular" and offered "to share the samples or teach you how to make them."

Political economy of interdisciplinarity in the use of instruments

This coordination was not a purely cognitive phenomenon. We know that the use of instruments involves the political pursuit of interests, both in terms of gaining funding and in gaining legitimacy for new instruments and experimental techniques (Lenoir 1997; Mody 2011; Pickering 1984). What is obvious from our field study is that these political acts were also acts of interdisciplinary coordination. First, there is the practical consideration that STM's, AFM's and other probes are expensive. An AFM, for example, can cost anything from USD20,000 to over USD1,000,000. As a result, individual faculty members may have difficulty purchasing a specific instrument for their own labs, or may need to get funding from multiple sources. Thus, the NBIC's use of 30 percent of its budget for equipment was essential for making it attractive to researchers and for spawning collaborations. One mechanical engineering professor was drawn to the center for precisely this reason: "Since the Center has this emphasis on nanoscale probing, measuring things at the nanoscale, that's what I do, I use an atomic force microscope to measure small-scale friction. So it was very synergistic to get involved with the Center, to be able to have an increased focus on development of instrumentation for nanoscale probing" [AssocP-MEAM-1].

Yet, despite the potential attractiveness of these instruments as resources, the head of the NBIC was continually concerned that affiliated researchers were not aware of the capabilities of the various instruments and therefore were not availing themselves of NBIC resources. As a result, she devoted an increasing amount of time in the NBIC monthly meetings to presentations on instrument functionality – both those instruments housed in the nanoprobe facility and those located in the labs of individual faculty members – and these presentations often provoked post-meeting hallway conversations about potential new research projects.

Further, the NBIC participated actively in developing what Mody (2011) calls "instrumental communities." That is, in order to build the reputation of the research center, justify their work to the NSF and establish the legitimacy of different experimental techniques using probe technologies, the NBIC sponsored the Nanoprobe Network, which they describe on their website as,

> "a free, non-profit, web-based community for scanning probe microscopy scientists, researchers, educators, and students in industry, academia, and research labs around the world. Our goal is to provide an interactive web space for the exchange of information, ideas, techniques, protocols, images, software, and discussions…The Network is redefining how scientific communities collaborate and communicate – by bringing together an incredible pool of expertise from around the world to participate in discussions and forums, share best practices and news, build our wiki-based encyclopedia of scanning probe microscopy (ProbePedia) and much more."[18]

The Network had, as of 2009, 919 total members of which 181 were affiliated with the University of Pennsylvania. Thus, its reach has been much broader than the NBIC itself. The online forum offered specific technical feedback on posted questions about the details of operating the instruments, such as the "best wedge method calibration grating," "calibration of lateral sensitivity of AFM cantilever," "trouble scanning tungsten tips," and others.[19]

The Network dovetailed with the Cross Cutting Initiative on single molecule probes that worked on developing new instrumental capabilities such as "tools for three-dimensional optical imaging with nanometer resolution," "new microscopes combining several models of single molecule fluorescence microscopy with optical trap nanometry and AFM," and a "new variant [of probe] that combines high frequency scanning gate and scanning impedance microscopies."[20] In other words, they were moving well beyond any off-the-shelf capabilities of probes on the market and developing custom instruments with unique capabilities that would be resources for NBIC-affiliated researchers. This highlights another form of interdisciplinarity already well-examined in Mody's (2011) book on instrumental communities, that of the relationship between manufacturers and scientists to develop instrumentation. Though these collaborations did not feature prominently in our observations, their importance should not be discounted.

Within the NBIC community, the instruments enabled coordination across disciplines to take place throughout the research process. On the cognitive plane, learning about the capabilities of different instruments could spark a new project. Research design depended on identifying the right instruments for the experiments and the a knowledgeable research staff to be able to operate them. And, learning about new instruments or instrument capabilities helped solve problems that arose during experimentation. On the political plane, the NBIC worked to establish the legitimacy of their instruments and techniques in the research community. The availability of particular instruments for experimentation would shape the types of projects pursued and determine the selection of students to work on projects. The availability of specialized instrumentation paid for by the NBIC reduced the cost of research projects because these pieces of equipment were not available in individual labs. The *quid pro quo* for providing these resources was acknowledgement of the NBIC in any publications that resulted.

Students as boundary spanners

A central complication to the adoption of new experimental techniques using these instruments was that each probe was unique and required specialized knowledge to operate it successfully. We found that the students were the people who conducted the experiments, and therefore, collaborations between researchers involved matching a student who had funding, *and* the right skills, to a specific project. This is where the two central coordination mechanisms– the instruments and the boundary spanners – meet: the conduct of the experiment is impossible without students who know how to use instruments and are funded to do so.

The importance of the graduate student in the NBIC's interdisciplinary research process cannot be overstated. Faculty members labeled the students "the fuel that makes things happen" and the "glue" holding together the collaborating faculty researchers.[21] One advisor laughingly said, "They do all the work." Translating the brainchild of two faculty members into a workable student project was critical: "It really falls into the hands of the students. Students and postdocs, they're the ones that make it happen or not happen. It's up to them because we can't, professors, we barely go into the lab, we don't conduct our own experiments, it's very rare. And therefore the progress that's made depends entirely on the students, how productive they are" [AssocP-MEAM-1].

"The student" does not appear as a central feature, or a factor at all, in scholarly research on interdisciplinarity. Yet, at the NBIC (and surely at other interdisciplinary projects), they are at the center of the interdisciplinary coordination. Without students, experiments simply do not take place; without students, collaborations do not gel. The results of experiments depend crucially on a student's ability to use the instruments appropriately and control the materials adequately. Reciprocally, the investigations often become the centerpiece of students' dissertations, their ticket to a post doc, faculty position or industry job. Students in the interdisciplinary collaborations we studied were both the resources to be staffed on projects as well as the actors who coordinated across different knowledge domains in order to be able to conduct experiments.

Students occupy a special status not accounted for in organizational theories of coordination. In many situations, "boundary spanners" have fairly high or at least equal status within the collaborative group – e.g., Lingo and O'Mahony's (2010) country music producers or Levina and Vaast's (2005) IT professionals – or accrue status from bridging previously unconnected groups (Allen 1977; Burt 2004; Gould & Fernandez 1989). Barley and Bechky (1994) characterized a special case of boundary spanner, that of lab technicians whose status is ambiguous because of their low-ranking jobs but privileged access to contextual knowledge that made them indispensible to collaborations. In the NBIC, we find that students do not suffer from this same problem of status ambiguity. Students are, indeed, lower status than faculty members, but at the same time are seen as apprentices who will later achieve higher status if they are supported and advised properly. Unlike technicians, students can eventually join professorial ranks and are future status equals to the faculty researchers. Further, an advisor's status is tied to how well the student performs, as this will lead to both top quality publications as well as a reputation for training high quality people.

Students in the political economy of interdisciplinarity

Since faculty members laid out the project and "hired" the doctoral student help, they also had to handle funding concerns for their students, which involved both supply and demand. Faculty members commonly leveraged two sources of money to fund their interdisciplinary students. The first was the NBIC itself, which funded its senior members and Innovation Awards recipients enough to engage one student on a research project. Another common pool of money was a student-earned IGERT (Integrative Graduate Education and Research Traineeship) grant given by the NSF for students taking on interdisciplinary training and research. Thus, some students had funding for interdisciplinary work and were looking for qualifying projects; others were seeking out funded projects and might find an interdisciplinary project on which to work.

Picking the right student for an investigation required some deliberation. Key criteria were political savvy and persistence in a doing interdisciplinary research. Said one professor who was a principal investigator (PI) on multiple NBIC-related projects,

> "I mean, you have to have a certain personality to do interdisciplinary research, and it has nothing to do with science. You have to be very accommodating and very positive and very thankful to people when they take time to help you…Some have it, and some don't...No matter how good the project is, if they're not sort of outgoing and accommodating and persistent, [the project will not move ahead.] They have to be persistent because they think, 'well I've asked them once' and, you know, it's a month later and they haven't gotten back to us. 'It's a month later, you were supposed to do this in a week, right?' 'Well, they didn't get back to me.' 'Whose job is it to make it happen?' So there's a persistence too that you need to do these interdisciplinary projects that you don't need with, you know, the drill down deep, here's-my-research single PI-type work" [FullP-MSE-3].

This is the political economy of interdisciplinary research: faculty members getting down to business, worrying about student personality traits and arranging a meaningful project.

The students had to engage in the politics of research, in terms of how they managed their advisors and achieved their career objectives related to publication.

Students doing interdisciplinary research often have two advisors and would meet with each individually over the course of a project. The formality of the meeting varied by advisor, some preferring to restrict availability to a weekly scheduled meeting, while others having informal open-door policies. Advisory styles were idiosyncratic. “[My advisors are] very different, I guess, in the way they get work done. [One] is very hands-on, involved on a daily basis, weekly basis, and [the other] is much more laissez-faire….” [PhD/PostDoc-1]. Still, each advisor had to usher the experimental research along, acquainting the student with existing research, suggesting courses of action based on experimental results, and providing her or his own ideas on what would be a publishable result.

The one-to-one meetings were complemented by lab meetings. Typically held once a week, these were opportunities for all the members of a given laboratory in a department (the principal investigator, associated faculty members, postdocs, and students) to provide updates on their respective projects. They were also referred to as “data meetings,” suggesting that the focus was on specific results, not on administrative updates on a project’s progress. Again, the students within interdisciplinary collaborations attended the lab meetings of both their advisors. Despite the extra time in meetings, students perceived an advantage of having two advisors. According to one student, “We just came from our lab weekly meeting. [Another advisor] had one Monday morning, so I had two this week…[My advisors] have dramatically different advising styles so that’s a plus. You get exactly twice as much exposure to mentoring styles when you have two PIs.”

Writing up the results of these projects was made more difficult by potential conflicts in what journals should be targeted for publication. Particularly for the student and postdoc research staff (as well as untenured faculty), it was essential to get disciplinary-based publications that could be readily understood as contributing to positive decisions on promotion or recruitment. Interdisciplinary work might not fit in traditional disciplinary journals and interdisciplinary journals were not perceived to count as much in furthering one’s career. For tenured faculty members (i.e., those who are beyond the concerns of establishing themselves in a particular discipline), there appeared to be little issue with venturing into journals in different disciplinary areas. As a professor of medicine noted, “So [a mechanical engineering colleague] and I are doing the revisions, it’s in *PCCP: Physical Chemistry and Chemical Physics*. I never published in there before, but it’s a project that I would never have done without him and people in his lab.” A physics professor described how this split worked in his collaboration: “That’s always been pretty clear. The experimental papers, [a medical colleague] makes that call. They mostly go to biophysical journals, I think. The theory papers, I make that call, and we do have to make that decision very carefully based on who we think reads that journal and how that fits with what this article is going to be about” [FullP-Physics-2].

Students and non-tenured faculty collaborators, on the other hand, felt some pressures to ensure the publication would ultimately count towards their career development. One tenured faculty member described the issue for younger scholars:

> “So it matters for tenure. Obviously no one’s going to complain if you’re publishing in *Science* or *Nature* but beyond that it does matter. You do need to publish in your discipline. So that ends up being a challenge, if not a barrier, to interdisciplinary research: the physicist over here is teaming up with the chemist over there and the physicist really wants stuff to be published in *Physical Review* and the chemist wants things to be published in *Langmuir* or something else. Moreover the physicist might do research that, because it’s interdisciplinary, doesn’t appeal to the editors and reviewers of a physics journal [because] it’s not purely physics…Then, if you don’t have any publications in physics journals, your tenure case might be jeopardized. So there is a tension, there is a pull toward your discipline because of tenure criteria” [AssocP-MEAM-1].

For students specifically, since they were responsible for preparing a dissertation that would get them a post-graduate position, having a set of first-authored publications was critical because “when you get down to the publication, first author apparently weighs a lot more than second author” [PhD/PostDoc-5].

Students as cognitive coordinators in interdisciplinarity

The work in setting up and conducting an investigation was not all political. Important steps took place on the cognitive plane as well; here the students also turned out to be crucial to success. In a sense, the graduate student was not just a boundary spanner, but the cognitive conduit through which faculty members realized their interdisciplinary aims. Faculty advisors relied on students as channels of communication, proposing ideas and courses of action to each other through their students. Students and faculty reported that students were left more to their own devices than in more closely disciplinary work. One important reason: faculty members did not have the same kinds of in-depth knowledge of the full project that they would in research closer to home.

Success in interdisciplinary work, as scholars have noted, requires establishing a common language and understanding of concepts within the team. As one mechanical engineering professor noted, there are great benefits to having the “depth” that comes from talking with people steeped in other disciplines, but, “Sometimes it can be tough because people tend to speak different languages even if you’re describing the same thing. Traditionally there are different ways of approaching problems and topics, but it’s actually really nice and you get to learn a lot more by working with folks from other disciplines and someone who is grounded in a different discipline” [AssistP-MEAM-2].

More than learning different languages or developing a linguistic bridge that allowed communication across disciplines, participants had to develop in-depth knowledge in both disciplines. As one professor in physics indicated,

> “Right now I’m trying to learn some neuroscience because I think it’s important and cool. And, it’s very frustrating to not know anything and be surrounded by people gabbling away in – it’s not even the jargon, it’s the way they think that isn’t yet natural to me. And, you have to be willing to feel stupid for a couple of years if you want to do something new. So, that’s a downside. And, you might dig a dry hole. You know, nothing might come of that. Then you have a lot of anxiety: ‘Oh my god, nothing’s coming of it. Ahh!’” [FullP-Physics-2].

But, some faculty members had trouble, as another full professor in physics explained,

> “finding the time to get educated in new areas. That’s an enormous challenge. I haven’t done it as well as I would like. Instead of having the time to really go to some book or textbook or set of articles and really get immersed in ideas from biochemistry and chemistry and other areas. I’ve tended to, through the course of talking to people or going to talks, I hit upon some idea… Then I try to figure out how to use that. But, I don’t have the time to get a broad understanding of these new areas but rather just like little nuggets” [FullP-Physics-1].

Because faculty members often had little time to get immersed in other disciplines, the cross-training fell to the students. Students engaged in journal clubs and colloquia to get exposed to ideas outside their disciplines: “[My advisor] was good, he used colloquiums where he would explain some of the fundamental topics and we actually have homework and stuff.” [PhD/PostDoc-3]. Just as importantly, students were expected to do substantial formal coursework in the new discipline. This was essential for coordinating across disciplines but led to some frustration amongst students who felt their time pulled in too many directions. The departments had not adapted their curriculum for the interdisciplinary work in which students were participating. Said one student,

> “We could do with a special curriculum. If you’re identifying an interdisciplinary topic and you’re hiring a graduate student to do this project, sit down, and come up with a different curriculum for that student. I really think that would be appropriate. Because we all take several electives here for the department itself. The course requirements, the departmental requirements perhaps can be altered or simply augmented to include more courses” [PhD/PostDoc-3].

Another set of mechanisms was informal, with student training occurred within the project team. One advisor offered an example: “So [a Professor of Medicine] has a student, I have a student, [a Materials Science Professor] has a student, we all got together and made a plan, and said let’s try this. And we fleshed out the ideas, read some papers, had some discussions. From there it really falls into the hands of the students” [AssocP-MEAM-1].

Faculty distance from the lab might be particularly acute in interdisciplinary research. One advisor explained that professors committing to interdisciplinary research projects could feel inadequate in making recommendations on lab techniques since their disciplinary training might not have exposed them to the instrumentation their interdisciplinary students needed to use,

> “As an engineer you’re trained, I mean, I have had hands-on experience with microscopes and all the instruments my polymer physics students do. Now my students are using techniques that I’ve never touched. Like single molecule spectroscopy. So I am in some ways less useful to them. I’m naïve, and if you haven’t actually used the equipment, you could make recommendations to students that are just ridiculous, right, just not going to ever work, because you don’t have a practical working knowledge of the equipment” [FullP-MSE-3].

The implication is that the students may be even more central to coordination in interdisciplinary projects than they would be in disciplinary projects where faculty members are more familiar with the approaches taken.

In rare instances, advisors spent some of their one-on-one time in the laboratory to tinker around with the experimental setup. It was much more common, however, for faculty to stay away. One student’s explanation: “I think most PIs are kind of removed from that where they wouldn’t necessarily know the nuts and bolts” [PhD/PostDoc-1]. Indeed, efforts to debug experiments often involved interactions between students.

> “It can be from informal discussions all the way to doing a part of the work, you know. … So if people wanted to do AFM measurements on some polymer structures they had, and I did a few days of AFM and that was it, then, it was just kind of a helping role for them. I mean I don’t necessarily understand the details of their project or anything like that. They give me a material and I give them an image and that’s the extent of the interaction in some cases. In other cases, you start discussing some idea and then you go pursue it later and it’s a much more intellectual exchange instead of just a data exchange” [PhD/PostDoc-2].

One student recounted how stabilizing his project involved finding another student to get the proper know-how: “When I joined our group, [a Materials Science Professor] showed me a project but this was a really new project. And [this professor] never worked with [a certain Professor of Medicine] before so, yeah, I was the first person who started this collaboration. I think that [the two professors] had a very general idea when they started but they didn't have any specific detail, and I had to set up this work. And I found [another doctoral student with the required knowledge], but it took awhile, like I think a year. After a year, the collaboration got stabilized" [PhD/PostDoc-4]. In interdisciplinary projects, then, students operate at the nexus of the disciplines, doing the work of interdisciplinarity. But this work is encumbered by a multitude of complications, as it requires targeted funding to make the students available, extra time for broader training, and extra time in meetings, and, even more, a particular personality that can handle the potential conflicts and draw the connections among faculty.

An interdisciplinary research center – facilitating change in university research practices

So, if instruments and students are the central mechanisms of interdisciplinary coordination, then, what does or can the Nano/Bio Interface Center do?[22] The essence, we will argue, is in reducing the costs and increasing the benefits of coordination. Existing studies of interdisciplinarity have focused on the benefits of cross-fertilization of ideas and the costs of censure from the disciplinary system, and therefore have recommended research centers that are physically isolated and where the researchers are collocated (Rhoten 2003; Sa 2008). The NBIC does not look anything like this model, possessing only one room for shared instrumentation and involving faculty members dispersed in their home departments across the Penn campus.

The NBIC does engage in activities that could be seen as a substitute for collocation, such as its monthly meetings, the RT and Cross Cutting Initiative meetings and seminar series. These bring together researchers both to lower the cost of sharing information across the disciplines as well as to enhance the opportunities for chance encounters. Some informants painted a comparative picture of what collaborations outside of the NBIC context looked like. Rather than the joint identification of interesting problems that predominated in the NBIC, researchers suggested that they first identified a gap in their own expertise and then set out to find the right collaborator, someone who was not necessarily at the university. One physics professor described this search as shopping: "The way I've thought about it in the past is one person has an idea. It's got a piece that I can handle and a piece that I can't handle, and then I go shopping out there in the universe for anybody I might know who might help me out,…another professor who's got a research group that's got a capability that I don't have" [FullP-Physics-2]. He continued with a specific example,

> "So I got a paper in *Nature Nanotechnology*. And the right guy was in Delft. And he had a postdoc and a PhD student who were all tooled up to do this sort of thing but had never done the thing that I thought was theoretically interesting. And we recruited them onto this project and they liked it. So that started at the top with an idea and turned into one person calling the other...So that's how it would work if we didn't have any NBIC. What's cool about the NBIC is that you are very likely to find people you can help right here at your own institution where you can walk into their labs" [FullP-Physics-2].

Thus, without a center like the NBIC, finding a collaborator tended to be scattershot: doing research on faculty websites, attending department seminar series, and querying scholars who come in during faculty recruitment. The NBIC decreased search costs for finding collaborators and in turning those collaborations into projects. Research centers such as the NBIC therefore do not only provide a bureaucratic function in the political economy of research but create cognitive opportunities through lowered search costs that shape how researchers devise their questions and choose tools to answer them.

But these chance encounters do not necessarily lead to collaborative research projects. As one assistant professor noted,

> "Two weeks ago within the NBIC we were talking about people in Bioengineering to one theoretician, one experimentalist, one theoretician from Solid Mechanics, and me talking about how we can make a contribution within protein and DNA folding and unfolding. And so you learn about what they can do and what they've been doing and you say 'wow, this is pretty cool, you know? Why you haven't talked to me?' And then they go away, and you don't talk to them again. So, it's sort of hot and cold, and you have to be very proactive to make things happen" [AssistP-MEAM-1].

While less directly connected to specific projects or labs, NBIC-sponsored meetings also were fruitful in pushing experiments forward. At the Research Team (RT) meetings, researchers apprised colleagues of their research efforts and could play with research ideas in a comfortable setting. One student praised these meetings' usefulness to his own research progress, "So it did foster discussion in people who aren't keenly aware of what you're doing. That input and those types of people can sometimes be extremely valuable" [PhD/PostDoc-3]. These meetings took time. One student explained that Mondays were usually out of consideration for experimental research because it was the day of all major NBIC meetings and most lab meetings. An advisor acknowledged, "The students feel like they're dragged to an awful lot of meetings; they go to both labs' lab meetings so that's an extra hour or two hours a week. And then the NBIC is particularly heavy on weekly, monthly formal meetings…I think they get something out of it but then, on the other hand, there's always a trade-off between that and what they could be doing on their own, working, getting their own stuff further along." [FullP-Physiol-1]. Most informants therefore recognized that the benefits of the additional NBIC meetings (opportunities to share information, learn about new solutions, find collaborators and generate new research ideas) came with some burdens (time lost that could have been spent in the lab, for students in particular).

Yet, the work of the NBIC has been considered a success by both the researchers themselves and by the NSF who renewed the grant for another five-year term in 2010. Our focus on instruments and students as the coordinating mechanisms offers some insight into why this might be the case. New instruments have the potential to lead to exciting new breakthroughs, but they are costly to purchase and difficult to learn to use, not just in a technical sense of operating the machine, but also in a theoretical sense of understanding what the instrument can do and how the results of experiments using it can be interpreted. Students may be attracted to interdisciplinary research because of the richness of the unexplored terrain, but they can only work where they are funded to work, only certain types of personalities are a good fit for interdisciplinarity, and their involvement in interdisciplinary projects requires a commitment to substantial additional training. The NBIC has focused primarily on shifting the equation on these two sets of costs and benefits, providing funding for the purchase and development of new instruments (and the training to use them) and for supporting students in interdisciplinary research projects.

The funding is not only about money, of course. In the political economy of research, the affiliation with NSF funding as a PI or as a recipient of an Innovation Award brings prestige and legitimacy to the researcher pursuing interdisciplinary projects at the nano/bio interface. On the cognitive plane, the availability of these resources is fuel for the initiation of new investigations and the development of innovative research designs to explore phenomena in ways not previously imagined. Further, buying or developing an instrument does not guarantee its use. Over the course of the development of the NBIC, they discovered the need for more training on the use of each instrument and more communication about the kinds of research questions for which each could be deployed. This led to the creation of new organizational forms such as the Nanoprobe Network and live online forums for developing skills.

Similarly, providing funding for a student was not enough to place a student on a project. To make the right match, the students had to become trained in multiple disciplines. Some of this involved the use of existing university resources, as students would simply take additional coursework outside of their home disciplines. In other cases, the researchers developed new organizational structures and processes for developing interdisciplinary knowledge, such as custom colloquia, interdisciplinary journal clubs, the Research Team meetings, and the like.

It is through these improvisations of researchers engaged in their own work that new paths of coordination were created. This theme of change being enacted in the daily activities of organizational participants has been developed in a branch of the organizational change literature focused on practice (Kellogg 2009; Orlikowski 1996; Tsoukas & Chia 2002). In our setting, we find that engaging in the practices of interdisciplinarity enacted changes in the organization of university research.

The interdisciplinary term “nanotechnology” and the NBIC,

> “…brings people together because there is grant money for these large collaborative research centers and so it forces people to work together because that’s the only way that they’re going to get money to do research…A lot of people are going to flock to that because that’s where the money is…It forces people to work together and actually it’s probably a good thing because sometimes things can be done very well in isolation but sometimes you really need to have folks coming together” [AssistP-MEAM-2].

The success of the NBIC’s interdisciplinary research program has required the coordination of individual researchers who acted based on their own interests to pursue projects. Our analysis points out that these interests can be understood on both the political and cognitive planes. Politically, interests involve getting funding, locating doctoral students and postdocs to run experiments, gaining access to the required instruments, adding to one’s list of publications. Cognitively, interests are in pursuing “really cool ideas” [Phd/PostDoc-5] solving “more interesting puzzles” [FullP-Physics-2], and pushing the research frontier ahead. The interplay between these two planes is an essential aspect of how interdisciplinarity is coordinated.

Interdisciplinary nanotechnology as a means to reorganize science?

Nanotechnology is seen as one of those emerging research fields that is inherently interdisciplinary. As the National Academies (2005, p. 17) argues, “A glance across the research landscape reveals how many of today’s ‘hot topics’ are interdisciplinary: nanotechnology, genomics and proteomics, bioinformatics, neuroscience, conflict, and terrorism.” Our informants mainly agreed, some even going to the extreme of arguing that “interdisciplinarity is losing its meaning because it’s just the science. I mean, you cannot do good biology if you don’t know physics, mathematics, and chemistry. Neither can you do physics if you don’t know your biology…” [AssocP-ESE-2]. Though, some informants felt that “interdisciplinarity” is a modern “buzz word” because researchers have always been doing work across the disciplines. Thus, we encounter the same old arguments about interdisciplinarity that have existed in scholarly research on the subject: researchers must deal with the “contradiction” that the “administration promotes the territorial part [of disciplinary excellence] while the mind, the intellect, promotes the interdisciplinary work” [AssistP-MEAM-2].

Is interdisciplinary nanotechnology, then, a model of how academic science might be reorganized? Certainly policy proponents of the field would hope this this would be the case.[23] Perhaps the label is just a creative means for attracting research funding: the NBIC proposal to the NSF was, according to one researcher, “crucial for convincing them that biophysics on molecular motors could be covered under nanotechnology, considered within the nanotechnology program” [FullP-Physiol-1]. Thus, the debate about the durability of disciplines vs. the increase of interdisciplinary research rages on, both among scientists practicing interdisciplinarity and those social scientists who study it. Some (e.g., Abbott 2001) find that, despite the pull towards research that cuts across traditional disciplinary boundaries, disciplinary departments remain resilient. Others (e.g., Palmer 2001) argue that scientific work is characterized by work *on* problems, not *in* disciplines or departments.

By unpacking the research process itself in one interdisciplinary research setting, we find ourselves agreeing simultaneously with both perspectives. Attention to the process shows that research must simultaneously work on the cognitive and political planes. Ideas ignore boundaries; interesting questions are not solely disciplinary. But, research in universities (or elsewhere) is not just about ideas. It is also about the need for funding and for staff resources, in other words, the political economy of research. In this paper, we argue that to understand interdisciplinarity, it is useful and even necessary to study the day-to-day workings of such research processes to understand how coordination across disciplines on both the political ad cognitive planes takes place. From a practical standpoint, our analysis of the interdisciplinary process provides a framework for evaluating the potential effect of different practices put in place to facilitate interdisciplinary work.

Where departments are the only as the source of funding, instruments, students and intellectual connections, interdisciplinary questions will be harder to pursue. Where other mechanisms, such as research centers like the NBIC, are in place, interdisciplinary research may be facilitated. Departments, labs, specialized knowledge, publication norms and promotion criteria draw researchers towards the discipline, while unsolved problems, opportunities for collaboration, and tantalizing funding and resources can draw them toward interdisciplinary activity. To the extent that academic administrators (and funders of research) take into consideration the cognitive and political planes of operation, their efforts to increase interdisciplinarity will likely be more effective.

Yet, research centers with explicitly interdisciplinary aims only create conditions but do not guarantee outcomes. Interdisciplinarity occurs as researchers appropriate the funding, instruments and collaborative structures put in place by the research center, enacting new research processes as they improvise new practices. Such a portrayal of situated organizational change in how university research is accomplished suggests that interdisciplinary research should not be understood as a "mode" (Gibbons, Limoges, Nowotny, Schwartzman, Scott & Trow 1994) but rather as a set of processes and practices. To the extent that disciplinary research is being challenged by interdisciplinarity, it is through the day-to-day practices of actors attempting resolve the tensions between professional demands and opportunities for new ways of working.

Rhoten (2003) and Sá (2008) in their studies of interdisciplinarity note the difficulties of trying to do interdisciplinary work in a university context that is organized by discipline-based departments. To promote interdisciplinarity, they argue that universities should create separate units, physically apart from departmental activities, with their own incentive structures and researchers who come and go as their expertise is needed. These recommendations are strikingly similar to the recommendations in the management literature regarding the promotion of radical or disruptive innovations in organizations. For example, Christensen (1997) advocates for separate, spin out organizations when innovative efforts would be made to compete with existing streams of work for resources or when the innovative work would be incompatible with the existing organizations values and norms. Yet, creating separate organizations tends to be a solution to the political blockages created by innovative work, and, such solutions may ignore or even amplify challenges on the cognitive plane. Our analysis suggests that the fluid movement within and across labs, chance hallway encounters, regular interactions in meetings and long time frames over which ideas can develop are essential for innovative, interdisciplinary progress. Thus, any policy or managerial advice must take into account both the political and cognitive planes of work.

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Table 1: Faculty and selected student members of the Nano Bio Interface Center at the University of Pennsylvania

Research code	Title	School	Department	Secondary Appointment(s)	# NBIC students	# years in NBIC	Group[a]	Innov. Award[b]	Inter-viewed	Ob-served
AssistP-Chem-1	Assist. Professor	Arts & Sciences	Chemistry	Chemical & Biomolecular Engineering	0	1				√
AssistP-Chem-2	Assist. Professor	Arts & Sciences	Chemistry		7	5		√	√	√
AssistP-Chem-3	Assist. Professor	Arts & Sciences	Chemistry		7	5		√	√	√
AssocP-Chem-1	Assoc. Professor	Arts & Sciences	Chemistry		7	6	RT1	√	√	√
FullP-Chem-1	Professor	Arts & Sciences	Chemistry		4	6	RT1	√	√	√
FullP-Chem-2	Professor	Arts & Sciences	Chemistry	Materials Science & Engineering	10	4	RT1	√		√
FullP-Chem-3	Professor	Arts & Sciences	Chemistry		0	4				√
AssistP-Physics-1	Assist. Professor	Arts & Sciences	Physics & Astronomy		8	6		√		√
FullP-Physics-1	Professor	Arts & Sciences	Physics & Astronomy	Materials Sci. & Eng., Electrical & Syst. Eng.	11	6	RT1/CCI	√	√	√
FullP-Physics-2	Professor	Arts & Sciences	Physics & Astronomy		2	6	RT2	√	√	√
PhD/PostDoc-1	Doctoral Student	Arts & Sciences	Physics & Astronomy		n/a	5	RT2		√	√
AssocP-Bioeng-1	Assoc. Professor	Eng. & Applied Science	Bioengineering		0	5				√
FullP-Bioeng-1	Professor	Eng. & Applied Science	Bioengineering	Electrical & Systems Engineering	3	6	CCI	√		√
AssistP-CBE-1	Assist. Professor	Eng. & Applied Science	Chemical & Biomolecular Eng.	Bioengineering	0	2				√
AssocP-CBE-1	Assoc. Professor	Eng. & Applied Science	Chemical & Biomolecular Eng.		0	4				
FullP-CBE-1	Professor	Eng. & Applied Science	Chemical & Biomolecular Eng.	Bioengineering	0	1				√
FullP-CBE-2	Professor	Eng. & Applied Science	Chemical & Biomolecular Eng.	Mechanical Eng. & Applied Mech., Bioeng.	10	6	RT2	√	√	√
FullP-CBE-3	Professor	Eng. & Applied Science	Chemical & Biomolecular Eng.		0	1				√
PhD/PostDoc-2	Doctoral Student	Eng. & Applied Science	Chemical & Biomolecular Eng.		n/a	5	RT2		√	√
AssistP-ESE-1	Assist. Professor	Eng. & Applied Science	Electrical & Systems Engineering	Mechanical Eng. & Applied Mech.	1	5		√		
AssocP-ESE-1	Assoc. Professor	Eng. & Applied Science	Electrical & Systems Engineering	Materials Science & Engineering	8	2		√		√
AssocP-ESE-2	Assoc. Professor	Eng. & Applied Science	Electrical & Systems Engineering		2	6	RT1	√	√	√
FullP-ESE-1	Professor	Eng. & Applied Science	Electrical & Systems Engineering	Bioengineering	1	6		√	√	√
AssistP-MSE-1	Assist. Professor	Eng. & Applied Science	Materials Science & Engineering		6	5		√		√
AssistP-MSE-2	Assist. Professor	Eng. & Applied Science	Materials Science & Engineering	Chemical & Biomedical Engineering	0	2				
FullP-MSE-1	Professor	Eng. & Applied Science	Materials Science & Engineering		10	6	RT1/CCI	√	√	√
FullP-MSE-2	Professor	Eng. & Applied Science	Materials Science & Engineering		15	1		√		√
FullP-MSE-3	Professor	Eng. & Applied Science	Materials Science & Engineering	Bioengineering, Chemical & Biomedical Eng.	12	6	RT2/CCI	√	√	√
FullP-MSE-4	Professor	Eng. & Applied Science	Materials Science & Engineering	Chemical & Biomedical Engineering	4	3		√		√
PhD/PostDoc-4	Doctoral Student	Eng. & Applied Science	Materials Science & Engineering		n/a	4	RT2		√	√
AssistP-MEAM-1	Assist. Professor	Eng. & Applied Science	Mechanical Eng. & Applied Mech.		5	2	RT2	√	√	√
AssistP-MEAM-2	Assist. Professor	Eng. & Applied Science	Mechanical Eng. & Applied Mech.		1	6		√	√	√
AssistP-MEAM-3	Assist. Professor	Eng. & Applied Science	Mechanical Eng. & Applied Mech.		2	2	RT2	√	√	√
AssocP-MEAM-1	Assoc. Professor	Eng. & Applied Science	Mechanical Eng. & Applied Mech.	Materials Science & Engineering	6	4	CCI	√	√	√
FullP-MEAM-1	Professor	Eng. & Applied Science	Mechanical Eng. & Applied Mech.		8	6	RT2	√	√	√
FullP-MEAM-2	Professor	Eng. & Applied Science	Mechanical Eng. & Applied Mech.		1	6	RT2	√	√	√
PhD/PostDoc-3	Doctoral Student	Eng. & Applied Science	Mechanical Eng. & Applied Mech.		n/a	6	RT2		√	√
FullP-Biochem-1	Professor	Medicine	Biochemistry & Biophysics		26	6	RT1	√		√
RAssistP-Biochem-1	Research Assist. Prof.	Medicine	Biochemistry & Biophysics		0	4	RT1			√
AssocP-Pathol-1	Assoc. Professor	Medicine	Pathology & Laboratory Medicine		0	1				√
FullP-Physiol-1	Professor	Medicine	Physiology		10	6	RT2/CCI	√		√
PhD/PostDoc-5	Postdoctoral Fellow	Medicine	Physiology		n/a	4	RT2		√	√
RAssocP-Physiol-1	Research Assoc. Prof.	Medicine	Physiology		0	2				√
AssistP-Radiol-1	Assist. Professor	Medicine	Radiology	Chemistry	1	2		√		
Total	**39 faculty[c]** **5 students/postdocs**	**3 different schools within the university**	**11 different departments**	**15 of 39 faculty w/ secondary appointments** **n/a for students and postdocs**	**188[d]**	**4.3 avg.**	**23**	**28**	**22**	**39[e]**

a: Faculty and students participated in different subgroups. RT1= Research Team on Biomolecular Optoelectronic Function, RT2=Molecular Motions, and CCI=cross cutting initiative on Single Molecular Probes

b: Innovation Awards are one-year competitive grants that support, according to NBIC documentation, "exciting new ideas, new partnerships with NBIC, and the evolution of research themes of the center"

c: Of which: 18 Full Professors, 7 Associate Professors, 12 Assistant Professors, 2 Research Professors

d: Total number of NBIC PHD students and Postdoctoral Fellows as of October 2009 was 192. Only 188 listed because 2 students were unassigned, 5 were working with faculty outside of the core group of NBIC faculty members, and 3 students were working with two advisors.

e: We observed many other faculty, graduate and undergraduate students at NBIC-sponsored meetings and research seminars. These were occasional participants who are not directly affiliated with the NBIC.

Appendix: Interview Guide

1. Tell me about your educational and professional history.
2. Who do you work with? (For faculty, do you lead a research team? What are your co-researchers' roles and disciplines?)
3. How do you divide your research time between the NBIC and other pursuits?
4. Are you involved with the administrative and outreach activities of the NBIC?
5. What is your involvement in the relationship between the NBIC and NSF (types of contact, quantity, quality, funding)?
6. What are your sources of research support other than the NBIC? What proportion of your total research efforts are associated with NBIC activities?
7. How long have you been interested in subjects related to nano-bio? How does your research fit into the NBIC mission?
8. What were the reasons that you got involved with the NBIC? (Access to funding? Access to instruments? Access to new ideas? Possibilities for career advancement? Other? For students, to work with a particular advisor?)
9. Describe the experience of working with researchers of other disciplines in your work associated with the NBIC?
    a. What are the benefits? What does it bring to your scholarship?
    b. What are the challenges? Has the way you do your work changed?
10. What are the differences in research styles in your lab and at the NBIC (in terms of methods and instrumentation, in terms of language/communication)?
11. Can you talk about the day-to-day challenges you face in your own lab (for students, in the lab of your advisor)?

Endnotes

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[1] Concerning the definition of interdisciplinarity, the NSF's description suffices for most funders and researchers doing interdisciplinary work, but there remains terminological disagreement among those who research the researchers (i.e., historians and sociologists of science). Klein reminds us that the term "interdisciplinary" has long been an imprecise word, earning itself inclusion in the *Dictionary of Diseased English* (Klein, Julie Thompson (1996) *Crossing boundaries : knowledge, disciplinarities, and interdisciplinarities* (Charlottesville, Va.: University Press of Virginia). The purpose of our study is not to enter into the effort to clarify definitions that has preoccupied many scholars who have attempted to impose stricter criteria in the definitions of existing terms. Some prefer to reserve "interdisciplinary" for collaborations in which disciplinary contributions are integrated equally and transcendence of the input disciplines is achieved through cooperation. They argue that most projects do not hit the interdisciplinarity bar because there is not a symmetric integration across the disciplines (Rhoten 2004, Barry, Born and Weszkalnys 2008). For our purposes, we are interested in any type of research that involves coordination across departments and disciplines, and we find the fine-grained distinctions less helpful.

[2] Bibliometric studies (most recently, Porter and Rafols 2009) have attempted to track interdisciplinary dynamics by analyzing citation practices in scholarly articles. Results suggest that interdisciplinarity in the sciences is growing but at a fairly slow pace, drawing mainly from closely related fields and more rarely connecting to more distant disciplines.

[3] National Nanotechnology Initiative, "What is Nanotechnology?" http://www.nano.gov/html/facts/whatIsNano.html Accessed January 2010.

[4] Concerns about how and when interdisciplinarity takes place is not only of interest in university scientific research contexts but also in organizations more broadly. Studies of medical care show that the ability of cross-disciplinary teams to work together improves patient outcomes (Edmondson 2003). Research on product development and innovation show that the ways in which different disciplinary and functional groups work together across boundaries effects organizational outcomes (e.g., Black et al, Dougherty 1992, Howard-Grenville and Carlile 2006). And, in our own field of management and social sciences, scholars have examined the challenges of doing work across disciplinary boundaries to generate richer understandings of phenomena while avoiding paradigm wars (Baum and Dobbin 2000, Moody 2004, O'Connor et al 2003).

[5] This point should not be overstated, of course. Disciplines create useful structures for problem solving and may even trigger new problems because they are organized around paradigms, as Kuhn's analysis exemplifies (Kuhn, Thomas S. (1962) *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press)). And, further, as we find in Kohler's story of the *drosophila* fly, disciplines and problems can be co-constructed (Kohler, Robert E. (1994) *Lords of the fly: Drosophila genetics and the experimental life* (Chicago: University of Chicago Press)).

[6] For example, Ruzena Bajcsy, director of the Center for Information Technology Research in the Interest of Society, University of California, Berkeley, stated in the NAS (2005, p. 27) report on interdisciplinarity, "Interdisciplinary research by definition requires the researchers to learn the other discipline. I like to stress vocabulary, but also methodology; I feel very strongly about it."

[7] Even an edited book called *Practising Interdisciplinarity* contained only one study delving into the actual processes and practices of interdisciplinary research, and that study was confined to descriptions of the work of four scientists (a chapter by Eric Scerri entitled "Interdisciplinary Research at the Caltech Beckman Institute," pp. 194-214) Weingart, Peter & Nico Stehr (2000) *Practising interdisciplinarity* (Toronto ; Buffalo: University of Toronto Press).

[8] Most recently, a Workshop on Interdisciplinary Collaboration in Innovative Science & Engineering Fields convened November 4-5, 2010 by the NSF concluded in its report that more qualitative, even ethnographic, data is needed (Paletz, Smith-Doerr & Vardi 2011)

[9] McCray, Patrick W. (2005) 'Will Small Be Beautiful? Making Policies for Our Nanotech Future', *History & Technology* 21(2):177-203. and National Nanotechnology Initiative website, http://www.nano.gov/about-nni/what/funding, accessed August 30, 3011

[10] http://www.nano.gov/, accessed August 30, 2011

[11] Nanoscale Science, Engineering, and Technology Subcommittee, and National Science and Technology Council (2007). *The National Nanotechnology Initiative Strategic Plan*, December 2007. http://www.nano.gov/NNI_Strategic_Plan_2007.pdf. Accessed January 2010.

[12] According to the NBIC website, the molecular motions RT "develops novel techniques to manipulate and characterize motion of motor proteins, DNA, and protein folding; study the mechanical and electrical properties of single molecules and the interface between the molecule, the solvent and nearby surfaces; exploit microfluidics and surface engineering to control local environments; and design, construct and test a unique molecular motor-driven device that demonstrates separation, concentration, purification and detection of proteins or nucleic acids" while the biomolecular optoelectronic function RT "unites novel approaches in the design of molecular structure to create and control electro- and electro-optic functionality in synthetic biomolecules, specifically de novo designed proteins..."

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http://www.nanotech.upenn.edu/researchMM.html and http://www.nanotech.upenn.edu/researchBOF.html, accessed October 11, 2011.

[13] The NBIC also has an education and outreach mission. It created an undergraduate concentration in nanotechnology, a Masters Degree in Nanotechnology as well as a graduate certificate. It also sponsors an annual NanoDay on campus to reach out to the broader community and also pairs up with high school teachers so that they can go back to their schools and introduce nanotechnology concepts in their classrooms. Some faculty in the center focus primarily on the educational mission and not on specific research initiatives. Because the focus of the analysis reported in this paper is on the interdisciplinary research process, these other functions of the NBIC are omitted.

[14] As listed on the NBIC website, http://www.nanotech.upenn.edu/pubs.html, accessed July 2009.

[15] As an example, in the 2005-2006 report, they summarized the work of the two research teams (RT) with examples of accomplishments of each. "RT-1: Biomolecular Optoelectronic Function M. J. Therein, Chemistry SAS & A. T. Johnson, Physics, SAS (Leaders); W. DeGrado, Biophysics, SOM, D. Bonnell, Materials Science, SEAS, J. Saven, Chemistry, SAS, Kent Blasie, Chemistry, SAS [4 graduate students, 2 post doc] Example accomplishment: "Computational design (Saven, DeGrado) of four-helix bundles that bind and orient non- biological metalloporphyirn cofactors has been extended towards larger chromophores which exhibit potent electrooptic properties (Therien), such as RuPZn, which features a (porphinato)zinc(II) unit covalently linked to a ruthenium terpyridyl moiety via a single ethyne spacer." Example accomplishment: "We plan to continue the development of single chain four-helix bundle motifs that bind functional electrooptic cofactors in asymmetric environments (Therien, DeGrado, Saven). Protein expression (DeGrado, Therien) will be exploited to produce these proteins. Computational methods (Saven, DeGrado) will be used to direct protein mutations that tailor electrooptic response and organize these structures on the nanoscale (Blasie, Therien)."

[16] Nano/Bio Interface Center NSF Annual Report, 2004-2005, as provided to us from the NBIC archives.

[17] Mody reproduces the graphic and other materials from Rohrer's 2002 article, Rohrer, H. 1992. STM: 10 Years after. Ultramicroscopy 42: 1–6., showing the movement of solid state technology from macro (millimeters) to micro (microns) to nano (nanometers) and of chemistry in the opposite direction to the point where they converge in macro molecules and biology as areas of inquiry. (Mody 2011, p. 181).

[18] http://nanoprobenetwork.org/about, accessed August 30, 2011.

[19] http://nanoprobenetwork.org/forum/, accessed August 30, 2011.

[20] Nano/Bio Interface Center NSF Annual Report, 2004-2005 and 2005-2006, from the NBIC archives.

[21] The NBIC researchers are not the only practitioners to refer to students as the "glue" of projects. For example, Harvey Cohen, professor of pediatrics, Stanford School of Medicine and chair, Interdisciplinary Initiatives Program, said nearly the same thing in the National Academies Convocation on Facilitating Interdisciplinary Research (January 29-30, 2004): "The most interesting observation is that the students are the integrating glue. Graduate students, undergraduates, and postdocs are the ones that go between the laboratories that make things happen." (quoted on p. 62 of the 2005 NAS report). Thus, it seems well recognized amongst the practitioners of interdisciplinary research that students are a central factor in such work but this is less recognized in the scholarly research about interdisciplinarity.

[22] The answer to this question is one response to ongoing calls from nanoscientists for the reform of university research practice to accommodate the demands of nanotechnology inquiry. As Heinrich Rohrer put it in a plenary speech for a conference in Japan on nanoscale science in 1992,"The nanometer age, or the "age of interdisciplinarity" poses formidable challenges beyond issues of purely scientific and technical nature. . . . [S]cientific bodies have to rethink their objectives and practices seriously and to find ways and means for an effective promotion of interdisciplinary science." Rohrer, H. 1993. Limits and Possibilities of Miniaturization. *Japanese Journal of Applied Physics, Part 1* 32.3B: 1335–1341, as quoted in Mody (2011, p. 181).

[23] As Mody (2001) notes, U.S. policy makers such as James Murday and Mihail Roco support nanotechnology as a means for the disciplines to revive themselves after the decline of research funding with the end of the Cold War.