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Human capital heterogeneity, collaborative relationships, and publication patterns in a multidisciplinary scientific alliance: a comparative case study of two scientific teams

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Abstract

In this paper, we compare the publication outcomes of two teams within a multi-university scientific alliance. Scientists in one team share similar scholarly backgrounds and work in a well established paradigm, while scientists in the second team have different backgrounds and work in an emergent discipline. While the alliance has increased the productivity of both teams, this increase was highest for the more heterogeneous team. In addition, while the variety of knowledge concepts employed in their research was initially higher for the heterogeneous team, this gap narrowed over time. We discuss the implications of our research for alliance design.

Keywords: Alliance; Knowledge; Human capital; Collaboration; Multidisciplinary

1. Introduction

Science has become increasingly collaborative during the past several decades, and many new organizational forms have emerged to manage collaboration among scientists in productive ways (e.g., Chompalov et al., 2001). In their review of the literature on scientific collaboration, Katz and Martin (1997) argued that collaboration has been spurred by changing patterns of research funding, the professionalization of scientific personnel, the need to pool resources to address increasingly complex and expensive research questions, progressively more specialized scientific disciplines, new communication technologies, and the desire of researchers to enhance their professional visibility and productivity. While empirical research does indeed suggest that scientific collaboration has many desirable outcomes (e.g., Katz and Martin, 1997), it is also

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clear that collaborative work is difficult, expensive in both time and money, and entails non-trivial problems of coordination and communication among sometimes diverse scientists that can undercut even the best of intentions (e.g., Williams and O'Reilly, 1998; Reagans and Zuckerman, 2001). In short, collaboration is very much a "double-edged sword," (Milliken and Martins, 1996), and this double-edge becomes increasingly sharp as firms, universities, and governments spend billions of dollars each year to fund large scale interdisciplinary projects to expand the frontiers of knowledge. It thus becomes desirable, from both a policy and theoretical standpoint, to understand the dynamics of collaborative forms of scientific work and the key tradeoffs that such work carries with it.

One form of cooperative endeavor that has become increasingly important in scientific research and development is the interorganizational alliance (e.g., Gulati et al., 2000; Powell, 1990). Alliances are voluntary arrangements between two or more organizations involving "exchange, sharing, or co-development of products, technologies, or services" (Gulati, 1998). Strategic alliances can be formed at many different organizational levels, and at many different positions along an organization's value chain. One common use of alliances, however, is to connect the research and/or development functions of two or more organizations in an attempt to capture the benefits of combining the scientific and technological assets of the alliance partners (e.g., Powell et al., 1996; Hagedoorn, 1993). The most important assets in this regard are the stocks of specialized knowledge possessed by each partner organization. The motivation behind most alliances is to create the conditions for organization-specific knowledge to be transferred across organizations and combined in ways that lead to varied insights that would not be possible if each organization were pursuing research and development activities on its own.

While research alliances and partnerships are perhaps most prevalent among private sector firms pursuing joint R&D activities (e.g., Hagedoorn et al., 2000; Powell, 1990), one important outcropping of the alliance movement over the past two decades has been the formation of scientific alliances among universities intent on sharing and recombining the knowledge of their faculty and research scientists to advance disciplinary and multidisciplinary scientific objectives. Different forms of inter-university collaboration exist in different countries (e.g., Ballesteros and Rico, 2001; Wen and Kobayashi, 2001; Okubo and Sjoberg, 2000), but in the US, university alliances have been spurred, in part, by the availability of government funds from the National Science Foundation (NSF) and other public agencies that have been earmarked for collaborative inter-university research. Good examples of these collaborative endeavors are NSF's Science and Technology Centers focusing on topics such as nanotechnology, adaptive optics, and behavioral neuroscience. Other forms of inter-university collaboration are evident in the NSF sponsored Engineering Research Centers on systems engineering, optoelectronics, and advanced electronic materials processing (e.g., Feller et al., 2002). Each of these endeavors represents a multimillion dollar program of collaboration, usually organized around one or two lead universities, and is focused on the transfer and combination of specialized domain knowledge across university boundaries. As in other types of alliances, the goal of inter-university collaboration is to spur new insights in the domains covered by a particular alliance by bringing together researchers at different universities who otherwise would not, or could not, collaborate in their research.

In this paper, we explore the dynamics of collaborative work in one large government funded scientific alliance incorporating researchers from 35 US universities and government laboratories. The stated purpose of the alliance is to create new scientific knowledge by deploying complex computational modeling and visualization techniques in a variety of disciplines through the use of high performance computing architectures and networks. While the activities of this alliance are quite varied and distributed, the focus of our study is two teams of scientists who were explicitly recruited to develop, explore, and promote high performance computing in their respective disciplines. These research teams vary in the density of their intellectual and social networks. Scientists in one team have longstanding relationships that existed prior to their alliance affiliation; they share similar scholarly backgrounds, and they work in a traditional area of research that is characterized by a well established disciplinary paradigm. Scientists in the second team have much more varied intellectual histories; they come from different scholarly backgrounds, and they work in a new and emerging discipline that is only now becoming established as a coherent body of knowledge. These differences in human capital make the two teams an ideal venue for exploring some of the dilemmas and tradeoffs of collaborative work in scientific alliances. In particular, the teams constitute naturally occurring comparative cases (e.g., Eisenhardt, 1989; Yin, 1994) that can be used to assess how the mix of human capital influences the trajectory of alliance-based knowledge production over time.

To this end, we will first develop the rationale for our study by reviewing arguments and evidence pointing to the inherent difficulty of knowledge production in interorganizational alliances. We will suggest that the complexity of joint knowledge production creates a set of countervailing social and cognitive forces that influence the amount and quality of the knowledge that is generated by alliance partners. These countervailing forces are intimately bound up with the characteristics of human capital in knowledge production teams. Following our development of this conjecture, we will explore the implications of our argument by empirically examining the publication histories of the two alliance teams that are the focus of our investigation. We will show how each team has a particular publication pattern, and we will suggest that these patterns are related to the intellectual backgrounds of team members. We will follow our analysis with a discussion of the implications of our research for alliance design and evaluation.

2. Scientific alliances, collaboration, and knowledge variety

Despite the growing popularity of interorganizational alliances in general, and scientific alliances in particular, the scholarly study of interorganizational cooperation is in its infancy, and much is still unknown about the forces that impact alliance formation, dynamics, and performance (Gulati et al., 2000). And yet, one conclusion that has already emerged from studies exploring knowledge transfer and combination across organizations is that knowledge sharing is quite difficult, and that many alliances fail to perform up to the expectations of their partnering organizations for this reason (Fischer et al., 2002). The difficulty seems to reside in the tension between the situational specificity of knowledge creation and the need for knowledge to be "mobile" in order to traverse organizational boundaries (Badarracco, 1991).

On the one hand, scholars studying knowledge production in firms and laboratories have suggested that the process of knowledge creation is bound up with the local idiosyncrasies of the people, routines, artifacts, and disciplines involved, and that a good deal of the resulting knowledge is tacit and contextually situated (e.g., Keller and Keller, 1996; Knorr-Cetina, 1999; Nonaka, 1994). Contextually situated knowledge is difficult to transfer, even in cases of scientific research where universalistic disciplinary norms and routines transcend local administrative arrangements and intellectual predilections. Moreover, even when common disciplinary discursive and research practices exist to facilitate joint knowledge production, knowledge transfer is sometimes inhibited by reputational and professional considerations that make it difficult for partners to trust one another enough to share insights and research findings (Dodgson, 1993).

On the other hand, the movement of knowledge across organizational boundaries is the explicit purpose of many interorganizational alliances, particularly scientific alliances, and the success of these collaborative endeavors rests on the ability of one organization to share its stock of knowledge with a partner, as well as the partner's ability to absorb and utilize such knowledge once it is received (Lane and Lubatkin, 1998). The integration of diverse sources of knowledge enhances the innovative potential of knowledge construction processes (e.g., Damanpour, 1991), and many research driven alliances have been formed on the assumption that the accumulation of knowledge across organizations can build the intellectual mass necessary for true technological and scientific breakthroughs to occur. To achieve this critical mass, however, requires that knowledge flows somewhat freely among alliance partners, and that independent research projects are melded together in a way that facilitates coordinated knowledge production.

Simonin (1999) suggested that the tension between the situational embeddedness of knowledge production within alliance partners and the requisite flow of knowledge across partners hinges greatly on the ambiguity of the knowledge production process involved. According to Simonin, knowledge ambiguity is a function of the tacitness, specificity, and complexity of the knowledge that is being transferred, as well as contextual factors such as partner experience in the alliance's knowledge domain and the partners' socio-cultural similarity. Simonin found empirical evidence for his contention that complex and tacit knowledge that is specific to partners who lack prior experience in the domain and who are quite different from each other will be difficult to transfer, and will, in turn, inhibit the process of joint learning and knowledge production. Conversely, more codified knowledge that was non-specific to partners who were deeply experienced in the domain and who were similar to one another was more easily transferred and facilitated knowledge production.

This conclusion complements research by other alliance scholars suggesting that the difficulty of knowledge transfer across an alliance is a function of the strength of prior ties among the alliance partners (e.g., Khanna et al., 1998). The logic underlying this argument follows from Granovetter's (1985) suggestion that strong relational ties between individuals and/or organizations "lubricate" social exchange, promote cooperation, and generally facilitate relational coordination and communication. Strong social ties among partners are a function of prior favorable interactions, interpersonal and professional similarity, and general affective states such as liking and friendship. All of these factors tend to encourage the extensive interactions that are required during knowledge sharing and joint problem-solving.

Taken as a whole, then, the above arguments imply that knowledge sharing and collaboration in alliances will be easier when the partners involved have prior experience collaborating with each other, deep experience in the relevant knowledge domains, are similar in their disciplinary backgrounds and professional qualifications, and are working in disciplinary programs with codified methodological and theoretical paradigms that cross-cut organizational boundaries. These conditions define a dense collaborative network among partners in which overlapping intellectual relationships provide the grounds for overcoming the situational specificity and "inertness" of knowledge. All things equal, then, one would expect that alliance partners who are embedded in dense intellectual relationships will have an easier time of coordinating and developing their joint knowledge production activities.

As Uzzi (1996) has pointed out, however, while dense networks of collaborative relationships facilitate knowledge sharing among informed and cooperative partners, the ease with which such partners interact tends to limit search activities outside of these relationships, thus narrowing the scope of information that partners encounter. In Uzzi's view, network density homogenizes informational environments given that such networks are based upon a history of prior interaction with others of similar intellectual and social dispositions. This suggests that dense collaborative networks may facilitate knowledge sharing, but also that the knowledge that is shared will be of narrower scope and variety. To the extent that knowledge is shared and expanded during the knowledge production process, one might expect that, all things equal, dense collaborative relationships among alliance partners will lead to greater knowledge sharing but incremental, rather than discontinuous, knowledge productions. If one is interested in generating such discontinuous knowledge, this line of argument suggests that alliances should consist of intellectually diverse partners among whom dense collaborative relationships do not yet exist. However, it is exactly this sort of alliance that is hard to manage because knowledge sharing is difficult among weakly connected partners, thus diminishing the efficacy of joint knowledge production.

This possible tradeoff between the extent of knowledge sharing and the degree to which shared knowledge is expanded in diverse ways is not equally severe or relevant for all forms of alliances. Alliances such as joint marketing or manufacturing agreements, for example, involve knowledge that is already highly codified and operationalized. The purpose of these alliances is not so much the creative combination of partner knowledge stocks as it is the joint application of complementary routines that are already well-understood. On the other hand, for research and development alliances, particularly inter-university scientific alliances, the knowledge sharing versus variety tradeoff seems more problematic. These collaborative endeavors are often justified by claiming that their costs will be repaid by the discoveries and insights that would not have occurred in the absence of joint knowledge production. This goal, however, creates a dilemma in the design of scientific partnerships. Scientists can be recruited who are embedded in overlapping intellectual networks, thus making their scientific collaboration easier, but this may limit the scope of alliance knowledge stocks, thus making diverse knowledge combinations less likely. Or, scientists can be recruited who are more diverse in their expertise and professional affiliations, thus maximizing the variety of alliance knowledge stocks, but such scientists will likely be embedded in weaker collaborative networks, thus making their knowledge sharing more tenuous.

Knowledge sharing versus variety tradeoffs in scientific alliances exemplify the "creative tensions" and countervailing social and cognitive forces that have been observed in scientific work at least since the research of Pelz and Andrews (1976). Alliances, however, bring with them particular design and organizational challenges, and very little research has been conducted in alliance contexts to explore the everyday details of how alliance partners manage these countervailing forces in the course of their scientific work. Thus, while research on alliances has been accumulating in recent years (e.g., Gulati et al., 2000), there exists a dearth of evidence regarding the micro-dynamics of collaboration within alliance boundaries, and even less about how these dynamics are shaped by human capital configurations. In light of this gap in the literature, we set out to explore the knowledge sharing versus variety tradeoff in the context of one US scientific alliance, which we will refer to as "the Alliance," that was created in 1997 to exploit the power of high performance computing in various computationally intensive scientific disciplines.

3. Research context and research questions

Very early in our investigation it became clear to us that the Alliance itself is a grand experiment in "seeding" research teams with different configurations of human capital. As explained to us by the Alliance's founding Director, the goal of the Alliance is to create distributed teams of scientists from many different universities that were handpicked for their ability and willingness to push the frontiers of computational science forward along many fronts by developing new computational models and visualization technologies that can be shared with others in their respective disciplines. Although the scientists in each team work in labs at their home universities, they are connected together via the Alliance computing network. Their participation in the Alliance means that they have agreed to allocate a portion of their work time to Alliance-related projects and to participate in Alliance activities and events. However, the Director made clear to us that the ability and willingness of partner scientists were not the only criteria for team selection. In particular, because the Alliance is an attempt to demonstrate to the world the potential of high performance networked computing to advance science, and even to influence how science itself is accomplished, the requisite teams had to be working in a range of highly visible academic disciplines that could capture the imagination of the scientific community and the general public.

Six teams of scientists were eventually recruited. The teams vary considerably in their composition and disciplinary expertise. Each team consists of six to twelve scientists distributed across multiple universities and academic disciplines. At least one member from each team resides at the Alliance's lead university and acts as a liaison between the other members of the research team and the Alliance's central administration and pool of common resources. Members of each team had varying degrees of intellectual ties to one another prior to joining the Alliance, but they all began working more intensively together around 1995, as the funding proposal for the Alliance was being prepared for submission to a government agency. This proposal was eventually accepted, and formal funding for an initial 5 year period officially began in 1997.

Although interorganizational collaborative arrangements can be administered in many different ways (e.g., Powell, 1990), the governance structure of the Alliance can best be described as a "joint equity" arrangement in which partner universities have pooled their human capital within a newly formed separate entity that is funded both by the US government and, through cost sharing agreements, the universities themselves. A central administration oversees and coordinates Alliance activities and funding disbursements. Various advisory boards with representatives from partner and non-partner universities, private business firms, and government agencies both monitor the activities of the central administration and provide ongoing direction and support. The Alliance is a broad ranging entity, and while the scientific teams that were the focus of our research are the core of the Alliance's intellectual mission, other inter-university teams have been recruited to develop new generic computing technologies that are then made available to the scientific teams. Still other personnel were recruited to be liaisons to private industrial firms, elementary and secondary schools, and local communities.

Our research team, itself multidisciplinary in nature, began meeting in 1998 under the auspices of the Alliance's Director, who sought participation by social scientists in the Alliance's activities. One member of our team was employed by the university research institute that eventually became the administrative center of the Alliance, and thus had many professional and personal ties to Alliance personnel. Other members of our team had been involved in prior social science research at the institute and were also quite familiar with the Alliance's scientific agenda. Still others were newly invited onto our team because of their specialized social science expertise. Our research objective was to study the knowledge production processes within the Alliance in an effort to understand how each research team resolves the inherent tension between the situational embeddedness of knowledge generation and the need to transfer knowledge across distributed team members in order for joint knowledge production to be successful.

We focused our research on two scientific teams, "Astro" and "Eco," that were of particular interest to us because they represent the two extremes of a design continuum that was explicitly mentioned by the Director when explaining the selection of team research topics. One design goal of the Alliance is to create different combinations of intellectual assets across the six original scientific teams such that the potential of high performance computing can be assessed under a range of disciplinary conditions, from teams that are working in older and more established disciplinary paradigms to teams that were brought together in a more eclectic fashion to focus on problems that are still developing a disciplinary coherence. Astro and Eco represent polar opposites along this continuum.

The six members of the Astro team were recruited to advance the state of the art in the computational modeling of astrophysical phenomena. One member of the team is a computer scientist, but the other five all have backgrounds in astrophysics and are faculty in either physics or astrophysical science departments at major universities around the US. These latter five individuals, all males, have overlapping intellectual histories because of time spent at one particular university as doctoral students, postdoctoral research associates, and/or faculty. Astro scientists are experienced academics. At the time of Alliance formation, they averaged 17.5 years since receiving their doctorate degrees. Several of these individuals have collaborated on previous grants, and their involvement in the Alliance was conceived as a carryover of their prior work on computational models of astrophysical phenomena. Astrophysics has long and deep roots and can clearly be characterized as a field with a strong scientific paradigm. Well known theoretical questions exist in the discipline, and the Astro team was recruited to address some of these fundamental questions and theories (e.g., the nature of dark matter) within the distributed high performance computing environment afforded them by the Alliance. The logic justifying Astro's inclusion in the Alliance was that a group of scientists within a single paradigmatic discipline who have overlapping intellectual and professional histories could make additional headway in testing the discipline's key theories and conjectures through the application of advanced computational resources.

In contrast to the single disciplinary focus of Astro, the twelve members of the Eco team were recruited from different disciplines to advance the state of the art in the computational modeling of ecosystems. Unlike astrophysics, modeling ecosystems is a relatively new science that is only now emerging as an integration of heretofore separate disciplines focused on air, water, and land resources. The logic justifying Eco's inclusion in the Alliance was that this new integration would be accelerated by bringing together a varied group of individuals with different intellectual backgrounds who would combine their expertise to build new computational models of the environment. While there had been some pairwise collaborations among Eco scientists prior to the Alliance, team members are quite varied in their disciplinary training, and the team does not share the densely overlapping intellectual histories that characterize Astro scientists. Eco team members, eleven males and one female, have doctorate degrees in physics, computer science, atmospheric science, environmental engineering, oceanography, fluid mechanics, geomorphology, and mechanical engineering. They too are seasoned academics, averaging 13 years of post-doctorate experience at the time the Alliance was created. They are currently employed as faculty in departments of computer science, oceanography, environmental science, mechanical engineering, landscape architecture, atmospheric sciences, ecological economics, and geoscience at leading US universities. Bringing these varied disciplines together within the Eco team was, in the words of the Alliance Director, a "bet" that common high performance computing resources would be the intellectual glue that would hold the team together and stimulate new and visible developments in environmental modeling.

The substantial differences between Astro and Eco in their human capital configurations provided a unique opportunity to explore the dynamics of collaboration in the Alliance and how these dynamics are influenced by the mix of human capital brought to bear on collaborative activity. Since the Alliance organized its scientific activities into distributed teams working through advanced computing technologies, one can inquire about the relevance of the large social psychological and management literatures exploring the relationship between human capital characteristics and team and organizational performance. Williams and O'Reilly (1998) pointed out in their recent review of this area that, despite the vast array of studies, definitive conclusions about the effects of particular types of human capital differences have been elusive because studies have produced conflicting results. Recent research has begun to suggest that the relationship between team diversity and team performance is very context specific, and that how human capital characteristics play out in team activities must be studied situationally, on a case by case basis, with emphasis given to the particular configurations of human capital that exist in a team and the organizational processes that are being used to manage team activities (e.g., Ely and Thomas, 2001).

In this regard, Eco and Astro are characterized by useful similarities and differences. Given the fact that the two teams are part of the same alliance, the performance effects of possible background factors unrelated to human capital differences are somewhat mitigated. Prior research on alliances, for example, suggests that one critical factor influencing the returns to collaborative research is how an alliance is administered (e.g., Oxley, 1997; Pisano, 1989). Different alliance governance structures (e.g., bilateral contracting, joint equity ventures, etc.) have varied effects on the willingness of partners to collaborate, their ability to coordinate their collaborative efforts, and the potential of each partner to monitor the performance of research teams. Since both Eco and Astro are embedded within the same Alliance structure, they are subject to similar knowledge sharing incentives, partner monitoring systems, and coordinative capabilities. Moreover, given that both teams were incorporated into the Alliance at the same time, and have been working concomitantly, they have had access to the same technological resources and have been equally subject to a multitude of period-based influences such as administrative turnover, technological developments, and evolving funding priorities.

This comparability of context helps to isolate the effects of human capital differences between Eco and Astro that may be important in shaping their Alliance-related activities. Astro is a small, disciplinarily homogenous, and socially embedded team working in an academic field characterized by a strong theoretical paradigm. Eco is a larger, more disciplinarily varied, and less socially embedded team working in a newly emerging field with a weak theoretical paradigm. While it may be impossible with our research design to isolate how specific human capital attributes, such as team size and disciplinary backgrounds, *separately* influence knowledge production, comparisons between Eco and Astro can be used to address questions about how differences in their *configurations* of human capital influence knowledge production. Yin (1994) suggested that the most important attribute of good case research is "analytical generalizability," or whether the unique properties of a case speak to theoretically interesting questions and generate useful insights that can spur additional research on the topic. In this regard, the contrasting human capital configurations of Eco and Astro represent opposing knowledge production architectures that are available to alliance designers interested in exploiting the potential of interorganizational scientific endeavors. As such, any similarities and differences in knowledge production between the two teams are relevant not only for theories of interorganizational collaboration, but also for the practical problem of alliance design. We thus, focused our efforts on addressing two general questions about the processes and outcomes of Eco's and Astro's collaborative work:

Research question 1	Do Eco and Astro differ in how collaborative work is actually coordinated and carried out in the two teams?
Research question 2	Do Eco and Astro differ in the outcomes of their collaborative activities?

4. Data and analysis

We started our investigations by discussing our project with the Alliance's Associate Director who promised us good cooperation and access to Alliance records. We then collected as much documentary information as we could find about the Alliance's mission and funding history. Since one member of our research team was a resident Research Associate at the Alliance's central offices, our team had excellent access to Alliance documents and records, including the original grant proposal upon which the Alliance was based, summaries of individual team projects, descriptions and demonstrations of actual Alliance technologies and the like. Once we had familiarized ourselves with the scope of Alliance activities, and the individual scientists who were participating in each team, we met with the Alliance Director for an extensive interview to review the Alliance's purpose and design. The Director was the prime mover behind the Alliance, and had personally devoted a large percentage of his time over the course of several years planning and executing the Alliance's master plan.

This background work was followed by a series of very unstructured interviews with some, but not all, members of Eco and Astro, with particular emphasis being given to discussions with the one member of each team who had been appointed the team's Alliance liaison. This liaison role places these individuals in a strategic position vis-à-vis other scientists on their team. As a result, there is an implicit expectation that the liaisons act as informal team leaders and facilitators, even though other members of each team might be more senior in academic status. It is the liaison's role to coordinate team activities and to keep the team moving along the scientific "roadmaps" that were constructed during the grant proposal process and updated throughout the period of their projects. Each liaison was interviewed simultaneously by two members of our research team. Although each interview was slightly different in character, the topics covered in both included the general scientific questions on which the teams were focused, the background of each team and how and why the members were recruited, and the general procedures used by the team members to coordinate their work activities. Subsequent to these initial interviews, one or more of us would occasionally contact the team liaison for additional information about team activities.

These interviews provided us with information about how each team conducted it's collaborative work, and in 1999–2000 we used our team contacts to acquire the academic curriculum vitae of team members as a description of their professional histories. We used these CVs to verify the configuration of intellectual capital on each team and to familiarize ourselves with the publication records of team members. Consistent with the literature on research collaboration (e.g., Katz and Martin, 1997), team member publication records constituted our major indicator of collaborative output. While using CVs as a source of publication data has certain advantages, such as providing information on working papers and publications in a range of outlets, individual CVs are non-standardized, and different scientists use different formats and levels of detail to describe their written output. Furthermore, each scientist is continually adding to his or her publication record. CVs collected at any single point in time thus quickly become out-of-date. Although the CVs provided us with a record of each scientist's publication history at a particular point-in-time (in 1999), they were less helpful in describing a scientist's more recent trajectory of published work.

We therefore, chose to collect publication data from the *Web of Science* database compiled by Thomson-ISI to standardize our publication histories. The *Web of Science* accesses multidisciplinary databases of bibliographic information gathered from thousands of scholarly journals. The database is indexed so that searches can be performed by author. We performed author searches for each team member during the first quarter of 2002 and recorded all journal publication listings for the 12 year period between 1990 and 2001. Since Eco and Astro team members began to collaborate specifically on Alliance related matters during 1996 in the course of contributing to the Alliance's funding proposal, we parsed the publication time series into two 6-year periods: pre-Alliance publications appearing between 1990 and 1995 and post-Alliance publications appearing between 1996 and 2001. We recorded each publication for each team member during these periods by noting the title of the article, the journal title, and the list of co-authors. Any problems in linking an author with a publication in the database were resolved by cross-checking publications listed on the author's CV or website, or by actually obtaining the publication and noting the author's university affiliation. Such problems occurred, at times, in the case of authors with common surnames. The *Web of Science* database only tracks journal publications, so any books, chapters in edited volumes, and other types of publications in outlets such as government reports, working papers, and the like were not included in our compilation of team publications. Since Alliance scientists made clear to us that their journal publications are a key output indicator used to evaluate their Alliance-based work, this restriction does not seem particularly problematic.

One ambiguity in using publication records as an indicator of Alliance-related output is the fact that it is difficult to ascertain whether a particular publication is a direct result of Alliance collaboration. This issue is made particularly difficult given that Eco and Astro team members each had non-Alliance funding for other scientific projects during the period of our study, and thus Alliance research represented only a portion of their active research portfolio at the time. Author attributions to grant funding in publication footnotes are unreliable, and even discussions with the scientists themselves revealed that overlapping research projects and the cross-fertilization of ideas between projects make the separation of Alliance from non-Alliance publications approximate at best. It is for this reason that we collected publication data for the 5 year period prior to 1996, when Alliance collaboration began. Publication data for the period 1990–1995 provide baseline output indicators against which output during the Alliance's funding period can be compared. Rather than attempt to isolate the Alliance contribution to each specific publication, we assumed that research activity not funded by the Alliance either remained at pre-Alliance levels during the Alliance funding period or varied in unpredictable ways from scientist to scientist. This makes a comparison with prior publication output a meaningful way of addressing the question, "Was Eco and Astro participation in the Alliance associated with any change in publication output for the scientists involved?" Within team comparisons with prior publications also control for the fact that scientific disciplines may differ in their baseline levels of publication activity, making cross-team comparisons difficult in isolation of broader publication trends in each field.

We constructed several bibliometric measures of publication patterns to shed light on this question. First, we counted the number of publications in scholarly journals by Eco and Astro team members for the two periods 1990–1995 and 1996–2001. These raw publication counts per team per period are an indicator of each team's mass volume of published work. Since Eco and Astro varied considerably in their membership size, we also adjusted the mass volume of publications for team size by computing the number of publications per team member for each of the two time periods. This size adjusted volume assesses average researcher productivity per team per period.

We also constructed a measure of collaboration within each team by counting the number of publications per team that were co-authored by at least two team members during the periods 1990–1995 and 1996–2001. Co-authorship is a standard measure of scientific collaboration (e.g., Katz and Martin, 1997). We computed both raw and size-adjusted measures of co-authorship for each team for each period.

Finally, we assessed the conceptual variety of the knowledge covered by Eco and Astro publications by analyzing the linguistic content of the publications and by determining the range of journals in which team members published. One prominent approach to knowledge representation in cognitive science is to conceive of knowledge as organized into "semantic networks" of concepts and linkages between concepts (e.g., Lamberts and Shanks, 1997). Within a network model of knowledge, conceptual variety is partly indexed by the number of concept nodes that are instantiated in a given problem situation. The more nodes that are activated, the greater the variety of knowledge that is being utilized by the actors involved. Concept nodes are typically taken to have linguistic markers in the sense that a relationship exists between conceptual concepts and word categories. Thus, linguistic variety is considered by many to be one key indicator of conceptual variety (e.g., Manning and Schutze, 2000).

While it would have been prohibitively costly for us to assess the linguistic variety inherent in entire publications, one estimate of the conceptual content of journal publications can be obtained by analyzing publication titles. Titles are written to communicate the content of journal articles succinctly and efficiently. An article title represents an author's chosen summary of the article's important concepts. We analyzed both the total number of word *tokens* and the total number of word *types* in publication titles for each of the two teams. We omitted from our analysis common prepositions, pronouns, and conjunctions such as about, and, a, the, or, etc. and focused only upon words that conveyed meaningful information about the content of each article. The number of word tokens was obtained by counting the total number of words across all of a team's publication titles in a given time period. In contrast, the number of types was simply the number of *unique* words. For example, if a particular word form occurred three times in the titles of a team's publications, it would contribute three to the token count, but only one to the type count. One commonly accepted indicator of linguistic variety in a text corpus is the "type/token ratio," or the number of word types relative to the number of total word tokens in the text (Manning and Schutze, 2000). A type/token ratio of one indicates that each word in the text occurs only once, such that each word is its own type. The ratio becomes progressively smaller as more and more word redundancies occur such that the number of types gets progressively smaller relative to the number of words. All type and token counts were obtained automatically using the VBPro software application (http://excellent.com.utk.edu/∼mmmiller/vbpro.html).

We used the number of different team journal outlets as another indicator of conceptual variety. Academic journals vary in their readership and content. Different journals target different intellectual communities or provide different content to the same community. Thus, one can infer that by publishing in a range of journals, scientists are either appealing to different audiences (e.g., different disciplines, academic versus non-academics, etc.) with the results of their work, or communicating different kinds of research outputs (e.g., quantitative models, empirical data, simulations, etc.) to the same audience. While journal range is not a perfect indicator of conceptual variety, since scientists publishing only in one journal over time might publish quite different research from article to article, it seems a reasonable assumption that publishing in a number of different journals indicates that scientists are seeking to broaden the implications of their work.

5. Results

5.1. Patterns of publication volume and collaboration

Our analysis of collaboration patterns among Eco and Astro scientists revealed interesting similarities and differences in how the two teams carried out Alliance-research. The most important similarity is that collaboration in both teams took the form of a loosely coupled confederation of distributed scientists each pursuing a designated research agenda, mainly in their own laboratory with their own research assistants, and coordinating their work with other team members via periodic meetings and reports. Table 1 presents the results of our publication and co-author counts during the period before the Alliance was formed (i.e., 1990–1995) and during the Alliance's active operation (1996–2001). The data in Table 1 reveal that Astro scientists published a total of 198 articles prior to the formation of the Alliance, and

Table 1
Journal publication and co-authorship counts of Astro and Eco teams during 1990–1995 and 1996–2002

	1990–1995	1996–2001
Publication totals		
Eco		
Team total	89.00	165.00
Per scientist (n = 12)	7.42	13.75
Astro		
Team total	198.00	242.00
Per scientist (n = 6)	33.00	40.33
Co-authored publications		
Eco		
Team total	3.00	5.00
Per scientist	0.25	0.42
Astro		
Team total	4.00	7.00
Per scientist	0.67	0 1.17

242 articles during 1996–2001, a 22% increase in raw journal output between the two periods. Astro scientists each averaged 33 publications (5.50 per year) in 1990–1995, and 40.33 publications (6.72 per year) in 1996–2001. Only four of the 198 publications prior to the Alliance, and seven of the 242 during the Alliance, were co-authored with other members of the Astro team, and the average number of Astro co-authors on these publications was only 2.25 and 2.43 for the two periods. The increase from four to seven co-authored papers between the two periods represented a 75% increase in co-authorship among the Astro scientists, but, overall, the percentage of papers co-authored with other team scientists was quite low (2% during 1990–1995 and 3% during 1996–2001). By and large, then, while publication and co-authorship rates did increase across the two 6 year time periods, Astro scientists were either publishing their work alone or with members of their own laboratories both prior to and during Alliance operation. On average, each Astro team member co-authored only 0.67 and 1.17 published articles with other Astro scientists during the 1990–1995 and 1996–2001 time periods.

Table 1 also shows the results for the Eco team. Eco scientists published a total of 89 articles prior to the formation of the Alliance, and 165 articles during 1996–2001. This represents an 85% increase in raw journal output between the two periods. Eco scientists each averaged 7.42 publications (1.24 per year) in 1990–1995, and 13.75 publications (2.29 per year) in 1996–2001. Only three of the 89 publications, and five of the 165, were co-authored with other scientists on the Eco team. These averaged two Eco co-authors for each period. Again, while the increase in co-authored papers between the two periods represented a 66% increase in co-authorship among Eco scientists, the percentage of co-authored papers was quite low (about 3% in each time period). On average, each Eco team member co-authored only 0.25 and 0.42 published articles with other Eco scientists during the 1990–1995 and 1996–2001 time periods.

This pattern of loose collaboration within a distributed work environment was confirmed in our discussions with team members, although there were significant differences in how the two teams coordinated their distributed efforts. Astro scientists had a history of collaborating on joint grants and had evolved a set of routines that combined ad hoc phone conversations, email exchanges, and periodic face-to-face meetings that rotated among the home universities of the Astro scientists. As one member described these meetings,

> The average is three times per year ... they are 2 days and we have sessions, we have business sessions, we have planning sessions, that is in the context of project plans and tracking and timelines. We always have a day devoted to research presentations by junior members of the consortium so that we can hear what they're doing and also remain focused on science. And then we also talk about resources, both money and computer time. Pretty standard agenda.

This pattern of coordination, according to team members, was a carryover of their pre-Alliance routines, and the Alliance was simply another funding opportunity to continue their distributed work. According to team members, this work primarily involved dividing up Alliance projects into separable aspects that could be completed independently by each scientist and his/her doctoral and postdoctoral research assistants. Periodically, however, subsets of the Astro scientists would publish papers together that reflected more intense collaboration on specific projects.

Like Astro, Eco scientists organized their efforts into modules allocated to each team member working more or less independently with his/her own research assistants. As one Eco member put it,

> ... we basically say, OK, this is how we're going to divide the labor. So everyone, each individual investigator prepares an annual plan based on what they're proposing to do in the subsequent year. So we have proposals from individuals that are negotiated to fit a common goal. Um, and specified within those are, essentially the deliverables.

Also like Astro, more intense collaboration among team members, perhaps leading to joint publications, was coordinated via emails, phone conversations, and sometimes by face-to-face meetings among the subset of scientists involved. However, unlike Astro, the Eco team had yet to evolve a routinized system for periodic team-wide face-to-face meetings where conversations could take place among all members of the team, and their assistants, simultaneously. In the words of one Eco scientist,

. . . you're building off of your personal relationships with people, in terms of day-to-day communication. What we haven't done that we need to do, is institutionalize more formalized opportunities, and I don't mean more formal, I mean more frequent opportunities for communication and collaboration. The ad hoc, you know, email, list serve things, they haven't become institutionalized in our own behaviors, I would say, to be very useful at this point. So I think you still need a quarterly face-to-face meeting, and other kinds of things for that... I think it's to, to take advantage of the joint knowledge and partly just for administrative purposes, checking up on progress, maintaining conversation. Um, you know ideally you don't want necessarily to say this is your product for the year, go off and do it and we'll see you in 9 months.

Despite having yet routinized joint team meetings, the publication productivity of Eco scientists increased by 85% between the 1990–1995 and 1996–2001 time periods. This compares to only a 22% increase for members of Astro. On the whole, however, Astro scientists published several times more papers on a per scientist basis than members of Eco, both prior to and during the Alliance funding period.

5.2. Patterns of publication variety

Table 2 summarizes our counts of the number of distinct journals used as outlets for Astro and Eco publications during the 1990–1995 and 1996–2001 periods. Astro scientists collectively published in substantially fewer journals than their Eco counterparts both prior to (29 versus 49 journals) and during (35 versus 72 journals) Alliance operation. On a per member basis, however, the typical Astro scientist published in 4.83 different journals during the first time period and 5.83 journals during the second period, while the typical Eco scientist published in 4.08 journals during the first period and six journals during 1996–2001. Thus, the typical Astro scientist published in nearly one more journal than his/her Eco counterpart in the pre-Alliance period, but this gap disappeared during Alliance operation. By the end of our observation period in 2001, the Eco team had produced publications in almost two new journals per team member since the Alliance was formed, or nearly twice the incremental increase in journal variety that was evident in the Astro team.

Table 2
Counts of different journals used as publication outlets by Eco and Astro teams during 1990–1995 and 1996–2001

	1990–1995	1996–2001
Eco		
Team total	49.00	72.00
Per scientist (n = 12)	4.08	6.00
Astro		
Team total	29.00	35.00
Per scientist (n = 6)	4.83	5.83

Table 3 provides the results of our linguistic analysis of journal titles. The titles for the 198 articles published by Astro during 1990–1995 consisted of a total of 1044 word tokens and 553 word types (type/token ratio = 0.53). Astro titles for the 242 articles published during 1996–2001 consisted of 1321 word tokens and 679 word types (type/token ratio = 0.51). Also, during the pre-Alliance period, each Astro publication title contained an average of 5.27 word tokens and 2.79 word types, while in the period from 1996 to 2001 Astro titles averaged 5.48 tokens and 2.81 types. Both the type/token ratios and the type and token counts suggest that although Astro scientists published more articles after the Alliance was formed, this increase was not accompanied by any increase or decrease in the overall linguistic variety of their article titles.

Table 3
Counts of word types and tokens in Eco and Astro journal publication titles during 1990–1995 and 1996–2001

	1990–1995	1996–2001
Eco		
Tokens	578	1180
Types	425	744
Type/token ratio	0.74	0.63
Tokens per title	6.49	7.15
Types per title	4.77	4.50
Astro		
Tokens	1044	1321
Types	553	679
Type/token ratio	0.53	0.51
Tokens per title	5.27	5.48
Types per title	2.79	2.81

Table 3 indicates that the linguistic variety of Eco publication titles was substantially higher than that for Astro publications. The titles for the 89 articles published by Eco during 1990–1995 consisted of a total of 578 word tokens and 425 word types (type/token ratio = 0.74). This type/token ratio is 40% higher than the comparable ratio for Astro during the same period. Eco titles for the 165 articles published during 1996–2001 consisted of 1180 word tokens and 744 word types (type/token ratio = 0.63), a 23.5% difference in type/token variety over Astro titles during the comparable period. During the pre-Alliance period, each Eco title contained an average of 6.49 word tokens and 4.77 word types, while in the period from 1996 to 2001 Eco titles averaged 7.15 tokens and 4.5 types. Thus, the reduction in type/token variety in Eco titles from the first to the second time period reflects a simultaneous increase in the number of tokens and a decrease in the number of word types. While the difference in linguistic variety between Astro and Eco remained throughout the two time periods, this difference grew smaller during the second time period as Eco titles became more conceptually redundant, thus approaching the levels of redundancy evident in the titles of Astro publications.

It is possible that this subtle narrowing of the difference between Eco and Astro linguistic variety reflects a more basic conceptual convergence motivated by the mission of the Alliance itself. The Alliance was formed to promote the use of high performance computing technologies to construct complex simulation models of varied natural phenomena. Astro scientists had already collaborated on a similar mission in their prior work, and thus their Alliance projects were continuations of their ongoing efforts to construct simulated models of celestial phenomena. On the other hand, Eco team members were largely independent scientists prior to the Alliance, each pursuing his/her own research in a specialized domain. Only some of the Eco team had prior experience with large scale modeling techniques, and it was made clear to us by Eco team members that joining the Alliance was professionally risky given that many of the team members were initiating research that was somewhat different from what they had been doing previously. This risk, as it was explained to us by one team member, was bound up in an inherent tension between their individual discipline-based paradigms and the joint demands of their Alliance-funded work in computational models:

> I'd say there is some tension there, because, we're all, everyone on these teams play dual roles, or triple roles, in that they are, uh, computer scientists, or engineers, or other kinds of faculty, in that sense, who are publishing in disciplinary issues, as well as the computational issues, and in some cases those two don't always comfortably mesh... So you've got that disciplinary tension versus the computational roles and responsibilities. And so there's an inherent tension, even within this level, between your disciplinary challenges and activities and your computational ones. And some disciplines are further along in managing those than others. The other one then becomes one of, of trying to respond at, you know, what's commonly called the leading edge, to developments that occur in these areas, many of which are speculative, many of which are, um, well, some are more real than others. And you're supposed, you kind of have to figure out what's real and what's not, and implement it, test it, same time that you're doing these other things.

It can be expected that these disciplinary tensions would take some time to work out, but also that the team's gradual assimilation of the Alliance mission would be reflected in the kinds of research that Eco scientists published. In particular, one would expect that the Eco team would collectively begin to produce a greater number of articles involving computational models during the 1996–2001 period. If so, some of the increased redundancy evident in the titles of Eco publications during this period might entail a conceptual convergence around words that reflect this common Alliance goal.

We tested this possibility using our counts of title words by determining whether any key words were substantially more frequent during the 1996–2001 period than they were during the 6 years prior to Alliance formation. Although title differences from period to period reflect the many idiosyncrasies of particular projects and nomenclatures, two key words were more frequent during the period of Alliance operation: "simulation" and "model." Of the 89 papers published by Eco team members prior to joining the Alliance, only four (or 4%) contained the word "simulation" (and close variants such as "simulated," "simulating," etc.). However, "simulation" appeared in the titles of 17 (or 10%) of the 165 papers published after 1995. Similarly, 10 (or 11%) of the 89 prior articles contained the word "model" (and close variants such as "models," "modeling," etc.), while this same word appeared in 35 (or 21%) of the 165 later papers. In other words, the frequency of "simulation" and "model" as summary descriptions of the work being reported in Eco publications more than doubled from the first to the second time period. Interestingly, the frequency of these words in Astro titles did not change appreciably over time, each appearing in 8–9% of the Astro publications during both periods.

6. Discussion and conclusions

Research alliances among universities, firms, and/or government laboratories have evolved as one interorganizational mechanism to combine human and technological capabilities in the service of scientific achievement. As such, alliances must come to grips with the countervailing forces that both encourage and discourage the movement of knowledge across organizational boundaries during joint knowledge production. Past research suggests that alliances are difficult to manage, and that the mobility of knowledge cannot be taken for granted (e.g., Gulati et al., 2000; Fischer et al., 2002). Joint knowledge production seems to be facilitated when knowledge is codified into transferable representations, when the partners are experts in the relevant knowledge domains, and when the partners have a history of repeated interactions and intellectual relationships (e.g., Simonin, 1999; Lane and Lubatkin, 1998; Khanna et al., 1998). Yet, these conditions seem to be the same conditions that homogenize the knowledge that is available to alliance partners in the course of their collaboration, perhaps limiting the scope of alliance accomplishments as well (e.g., Uzzi, 1996). If so, it appears that research alliances, as mechanisms for joint knowledge production, may be subject to a tradeoff between the amount and the variety of knowledge that is shared and combined by alliance partners. It was the possibility of this tradeoff, and the desire to understand how alliance partners manage the countervailing pressures involved, that motivated our explorations of Eco and Astro.

It is tempting to portray the tradeoff between the amount and variety of knowledge stocks in research partnerships quite starkly. However, in unpacking the similarities and differences between Eco and Astro collaborations, our study suggests that the intellectual composition of Alliance partnerships was intertwined with Alliance outputs in subtle and complex ways. Specifically, the Alliance seems to have been beneficial for both teams of scientists, but for different reasons that parallel their unique configurations of human capital.

For Astro scientists, the Alliance has been a funding mechanism to continue their collaboration in computational astrophysics. Ensconced in a single discipline with a strong theoretical paradigm, and already productive and routinized in their prior collaborations, Astro team members have increased their publication output by 22%, their journal variety by 21%, and the number of co-authored publications by 75% during the period of the Alliance's operation. However, the conceptual variety of their publications, as measured by the content of their publication titles, has remained constant across the 12 year period covered by our data. Although Astro scientists have evolved over time in their topical foci within computational astrophysics, their published output does not reveal significant changes in the degree to which computational modeling per se has been emphasized in their work. Across the 12 year period, the key words "simulation" and "model" have been present in 8–9% of Astro publication titles. Thus, Astro scientists are adding to their already considerable research productivity while working within the Alliance, but the marginal increase in output appears to be an increment to "business-as-usual" as opposed to a fundamentally new direction in their work.

For Eco scientists, on the other hand, the Alliance is a scholarly bet that combining their varied disciplinary expertise to produce large scale computational simulations of ecosystems will lead to new combinative insights and enhanced publication opportunities. Having only loosely collaborated on a pairwise basis prior to the Alliance, Eco scientists have faced the problem of developing new collaborative routines that allow them to work distributively on Alliance projects. Despite their self-assessments to the contrary, our data suggest that they have been successful in this respect. During the period of Alliance operation, Eco team members have increased their published output by 85%, their journal variety by 47%, and the number of co-authored publications by 66% when compared to pre-Alliance levels. Perhaps most significantly, however, concomitant with this substantial increase in research productivity and journal variety has come an increased focus of Eco publications around Alliance-related topical objectives. The frequency of both "simulation" and "model" in the titles of Eco publications has doubled across the 12 year period of our study. In short, Eco scientists seem to be using their increased productivity under the Alliance to embrace the new domain of computational modeling, and to disseminate the results of this new conceptual thrust via a broader variety of journal outlets.

Given their overlapping intellectual relationships, it is not surprising that Astro scientists have been able to maintain, and even enhance, the momentum of their work under the auspices of the Alliance. In the case of Eco, however, it might be expected that the diversity of the team would have been hard to manage, and that the projects funded by the Alliance would have floundered. While we encountered subjective indications that the Eco team has struggled to find an effective way to coordinate their collective activities, the fact that over time the team has been able to simultaneously increase their journal productivity, variety, *and* focus on Alliance-related topics suggests that Eco scientists have learned to manage their diversity and align their work with Alliance objectives. This finding lends important support to the increasing use of interorganizational alliances as a mechanism for promoting collaborative scientific research. It suggests that alliance collaboration can be productive even when the alliance partners are intellectually diverse and working in areas that have yet to form strong disciplinary paradigms. Indeed, the conceptual change toward Alliance objectives evidenced by Eco scientists during 1996–2001 provides *prima facie* evidence that discontinuous knowledge productions can be achieved under the auspices of university scientific partnerships.

Much more research is necessary to understand the conditions under which different configurations of human capital can be effectively managed within an alliance to enhance the amount and/or variety of knowledge productions. Both Astro and Eco can be considered alliance success stories, and it would be useful to investigate instances of alliance failures to enrich our understanding of how human capital diversity influences alliance performance over a range of outcomes. Moreover, even though we have argued that Astro and Eco represent two extremes along a continuum from disciplinary homogeneity to heterogeneity, more empirical research must be done to parameterize human capital in a way that makes judgments of homogeneity and heterogeneity less ad hoc. In a recent unpublished paper, for example, Sampson (2001) reported data taken from 464 R&D alliances in the telecommunications industry suggesting that alliance innovation, as measured by patent counts, was most facilitated by *moderate* levels of alliance knowledge diversity, as measured by overlap in the partners' previous patent domains. While patent data would not be particularly useful in the context of many university research alliances, Sampson's study does call attention to the need for standardized definitions and measurements of human capital diversity. It could certainly be the case that the human capital differences existing between Astro and Eco were quite minor when compared to the entire range of possible knowledge combinations that could have been included within the Alliance's boundaries. It could also be the case that different combinations of disciplinary paradigm development and prior collaboration could result in fundamentally different collaborative activity within alliances. We examined the two Alliance teams that appeared ex ante to have the most contrasting human capital configurations, but studying other combinations of human capital within alliances would be informative.

It would also be informative to measure not only the volume and conceptual variety of alliance outputs, but also the scientific *novelty* and *impact* of such outputs as well. Our measure of publication title content is only one of a number of different indicators of scientific knowledge production, and an imperfect one at that. Given that the Astro and Eco teams were formed only 5 years ago, it is perhaps premature to inquire whether their respective publications have had differential impacts on their respective disciplines due to the novelty and theoretical importance of data contained within them. Indeed, measuring the novelty and impact of collaborative work spanning multiple disciplines in varied stages of paradigmatic development is likely to prove difficult in any case. Nevertheless, future research is needed to address these complexities in greater detail.

Despite these methodological ambiguities, the outputs from Astro and Eco vary in systematic ways that parallel their demographic differences, and the distinctive successes of each team probably should not be dismissed as spurious artifacts. It is thus important to draw out some of the implications of our results for the organization and management of scientific alliances in general. When combined with previous research, our results suggest that three characteristics of scientific alliances might be particularly important in ensuring that an alliance's knowledge production objectives are met.

First, both Astro and Eco scientists have decomposed their Alliance projects into semi-independent modules that can be completed in distributed fashion by team members working in disparate locations. It has long been known that decomposition is one strategy for managing complex problems (e.g., Garud et al., 2002), and decomposition is encouraged in the Alliance given that scientists are dispersed among several different universities. Both teams apparently have recognized that complex collaborative work in distributed environments does not always bring with it the need for close interactions among research partners, and that, indeed, close interactions might actually inhibit the process of joint knowledge production by increasing the costs of coordination. Although team-wide coordinative practices (e.g., team meetings, etc.) seem to be more fully developed in Astro, in both teams such practices are only intermittent. Moreover, neither group of scientists exhibits high levels of collaboration on joint publications, since co-authored publications among team members have represented only a small fraction of their collective outputs. Paradoxically, then, the success of Astro and Eco suggests that collaborative work in distributed alliances might be more successful when loosely, rather than tightly, coupled work relationships exist among the parties involved. This loose coupling of research activity might be especially important for alliance teams having more diverse combinations of human capital.

Second, the success of Astro and Eco supports previous research suggesting that joint knowledge production is facilitated when alliances are organized and governed as separate joint equity entities (e.g., Oxley, 1997; Pisano, 1989). Collaboration on Alliance projects is not a result of direct bilateral or multilateral agreements among the scientists themselves. Astro and Eco are embedded in a centralized governance structure in which various administrative units and advisory committees exert top-down strategic and funding oversight. This independent administrative structure is very visible, includes representatives from partner universities, and is active in organizing websites, showcase events, planning meetings, and team presentations on a regular basis. The existence of a strong central administration has meant that teams are not encumbered with many of the overhead costs of funded research and are free to pursue their research activities within the boundaries of their Alliance goals. In some sense, then, Astro and Eco are situated in a tight Alliance system of centralized governance that has allowed each team to stay loosely organized internally. This tight-loose design could be an especially effective governance strategy in scientific alliances distributed across disparate universities.

Finally, a particularly salient characteristic of the Alliance is its stock of centralized high performance computing assets. On more than one occasion, Alliance personnel have described these assets as the "glue" that both justifies the Alliance's existence and helps to maintain the Alliance's coherence in its mission. But our results suggest that these assets are more than simply information processing devices. They constitute a representational system that acts as a "boundary object" (e.g., Fujimura, 1992; Star and Griesemer, 1989) linking disparate disciplines together by forcing team members to translate their ideas into common computer codes and standardized inputs for existing software applications. While such translations have been a matter of course for Astro scientists given their disciplinary focus and prior computational models, for Eco scientists the need to orient around a set of common computing resources has been a new work requirement, and has meant that team members cannot diverge too far from each other in their loosely coupled research efforts. The existence of a common representational task environment would seem to facilitate knowledge transfer and joint knowledge production within teams of disparate and distributed scientists.

The possible joint effect of these three contextual influences on how human capital configurations within Eco and Astro played out over time reinforces recent arguments in the management literature that team demography is only a partial explanation for team performance (e.g., Ely and Thomas, 2001; Martins et al., in press). Research suggests that it is important to understand how both team and organizational practices shape the effects of member demographics on team performance, and that few one-to-one relationships exist between particular team characteristics and subsequent team outcomes. Our data indicate that the Alliance has been a successful endeavor for both Eco and Astro, and that both groups of scientists have benefited in different ways from their participation in it. Joint equity governance, strong top down administrative expectations and support, modularized division of labor, and a pool of common computational resources seem to have allowed each team to channel their configuration of human capital toward productive, albeit different, ends. Our data thus support the growing practice of using interdisciplinary alliances to advance science and innovation, with the qualification that different results might have been obtained in other alliance contexts characterized by other administrative and task parameters. Future research must be conducted to explore more fully how alliance contexts interact with configurations of human capital to shape alliance performance.

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