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Research Policy 33 (2004) 643–659
research policy
www.elsevier.com/locate/econbase

The role of academic inventors in entrepreneurial firms: sharing the laboratory life

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Received 1 May 2003; accepted 1 January 2004
Available online 27 April 2004

Abstract

While science-based entrepreneurial firms are a key feature of the modern economy, our insights into their organization and productivity remain limited. In particular, our understanding of the mechanisms through which academic inventors shape entrepreneurial firms established to commercialize their scientific ideas is based upon a traditional perspective that highlights the importance of human capital. Based on a study of biotechnology firms and their academic inventors, this paper examines the extent and mechanisms through which academic scientists contribute not only human capital but also social capital to entrepreneurial firms. The paper makes two contributions to our understanding of the academic–firm interface: First, it establishes that the social capital of academic scientists is critical to firms because it can be transformed into scientific networks that embed the firm in the scientific community through a variety of mechanisms. Second, the paper argues that an academic inventor's career plays a critical role in shaping his social capital, thus scientific careers mediate the networks and potential for embeddedness that an academic inventor brings to a firm. Specifically, the foundations of an academic's social capital can be traced to two sources: The first element that the firm may leverage is the academic's local *laboratory network*—a network to current and former students and advisors established by the inventor through his laboratory life. The second form of social capital is a wider, *cosmopolitan network* of colleagues and co-authors established through the social patterns of collaboration, collegiality and competition that exemplify scientific careers. These findings suggest that scientific careers are central in shaping an academic's social capital which can be translated into critical scientific networks in which entrepreneurial firms become embedded.

Keywords: Entrepreneurship; Networks; Social capital; Cosmopolitans; Careers

1. Introduction

Science-based entrepreneurial firms are a key feature of the modern knowledge economy, contributing to the development of regional high tech clusters and the transformation of investments in basic science into economic growth, employment and competitive advantage. However, our insights into their organization, scientific productivity, and competitiveness remain limited. The prevailing view of the characteristics of these firms generally privileges firm-specific attributes or firm–scientist dyadic relationships based on human capital (Pisano, 1990; Calabrese et al., 2000; Zucher, Darby and Brewster, 1998; Stuart et al., 1999; Gittelman and Kogut, 2003; Shan et al., 1994).

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0048-7333/$ – see front matter
doi:10.1016/j.respol.2004.01.013

Furthermore, in spite of their origins within academic science, the contribution of academic scientists to science-based firms and the mechanisms through which their capital contribute to the shaping of the firm remains largely unexamined (with the exception of provocative work from Audretsch, 2001, and Catherine et al., 2004). In particular we have a limited understanding of the mechanisms through which academic inventors contribute social capital rather than human capital to entrepreneurial firms.

In this article I propose that in contrast to prevailing views that privilege human capital, an important and overlooked contribution of academic scientists to science-based firms is their social capital which may be translated by the firm into to the firm's own scientific network. I establish this proposition through a detailed field study of a small number of biotechnology firms founded on the basis of academic science.

With the work of Granovetter (1973), Powell et al. (1996) and others on social networks and networks of innovation as a theoretical foundation, I argue that for science-based firms building on a foundation of academic science, a simple dyadic view of the relationship between the firm and an academic scientist based solely on the exchange of human capital should be replaced with a view that encompasses the exchange of social capital. While the contribution of human capital is well characterized as arising through the exchange of tacit knowledge and individual reputation (Zucher, Darby and Brewster, 1998; Stephan, 1996), I show that the exchange of social capital leads the firm to become embedded within the scientific community. Specifically, the firm's embeddedness within a scientific network arises by translating the pre-existing social capital (specifically the social network) of the academic inventor into the firm's own series of network relationships.

Following the tradition of scholarship on boundary-spanning individuals and brokers (Allen, 1984; Burt, 1992; Tushman and Scanlan, 1981), I also examine the factors that shape an academic scientist's social capital, specifically that social capital which has the most significant impact on firm embeddedness. Following Bozeman et al. (2001), I argue that scientific careers play a critical role in shaping social capital as well as human capital. My empirical insights suggest that two elements of social capital can be translated by the firm into embeddedness: The first is the academic's local laboratory network, which arises from participating in and running a laboratory, while the second is the broader, cosmopolitan network of colleagues, collaborators and members of the invisible college again built up through the practices and social structure of science throughout an inventor's career.

This paper makes no comment about the performance implications of inventor involvement. Rather this paper aims to establish the multiplex nature of the contribution of the inventor–scientist to an entrepreneurial firm, and the origins of that contribution. The two central arguments of this paper are as follows: Firstly academic inventors contribute social capital, in addition to human capital, that can be translated by firms into embeddedness within scientific networks. Secondly, scientific careers play a critical role in establishing social capital and thus mediate a firm's embeddedness within the scientific community. Taken together, these arguments suggest that scientific careers are a key factor shaping science-based firms because they mediate the local and cosmopolitan social capital through which entrepreneurial firms become embedded in the scientific community.

2. Current debate and research questions

In examining the characteristics of science-based firms, scholars have moved from firm-specific characteristics such as the internal scientific capabilities and alliances (Henderson and Cockburn, 1994; Pisano, 1990; Stuart et al., 1999), to an understanding of the relationships that bridge the firm–university interface. This focus underscores the origins of many biotechnology firms within the academic community and the critical importance of basic scientific ideas for the founding and on-going development of the firm (Kenney, 1986; McMillan et al., 2000). Studies have identified a number of important relationships, in particular publishing across the boundaries and alliances with university laboratories (Zucher, Darby and Brewster, 1998; Powell et al., 1996; Gittelman, 2001; Liebeskind et al., 1996). Indeed, the notion of "entrepreneurial science" is now widespread, and describes the emergence and widespread adoption of a new set of norms within the academic establishment and among many (although not all) scientists (Etzkowitz, 1998; Owen-Smith and Powell, 2001b). Although entrepreneurial activities by scientists can be traced back at least to the 19th century, the complex university–firm networks we know today really took shape in the mid-1980s (Etzkowitz, 1983; Powell et al., 1996). The precise nature of this inter-connection has been noted to span the range from limited interaction, through extensive research collaboration at formal and informal levels, to scientists as fully-fledge entrepreneurial founders (Murray, 2002; Owen-Smith and Powell, 2001a; Roberts and Hauptman, 1987; Werth, 1997).

One important firm–university relationship that has received little attention is the relationship that may exist between the academic inventor and the entrepreneurial firm founded to translate the academic inventor's research into commercial returns. Current literature on the relationship of entrepreneurial firms to scientists emphasizes the importance of the exchange of human capital. In particular, an academic inventor's human capital is identified as making two plausible contributions: transfer of tacit knowledge and signaling. In the literature on tacit knowledge transfer, it is widely recognized that knowledge that is complex can be hard to exchange and move among different organizational settings (Winter, 1987). Traditional arguments regarding a scientist's contribution to an entrepreneurial firm are focused on appropriable human capital, specifically technical capital established through training and experience (Levin and Stephan, 1991; Stephan, 1996). According to Zucher, Darby and Brewster (1998), the performance of many early entrepreneurial biotechnology firms was dependent upon a close relationship with certain star scientists because they held the "key" to tacit knowledge that was otherwise hard to transfer to the firm. Likewise Agrawal (2002) finds a relationship between inventor involvement and the performance of licenses and attributes this to effective tacit knowledge exchange. According to alternative theories consistent with signaling mechanisms, the role of a well-respected scientist that is affiliated with a firm is rather to signal the quality of the underlying science. This signal helps to overcome the challenges that investors might have in trying to establish the veracity and quality of the complex and highly specialized scientific ideas that are presented as investment opportunities by scientists and entrepreneurs (Audretsch and Stephan, 1996).

While these studies have highlighted quite distinctive contributions of the scientist across a dyadic firm–scientist relationship, the human capital perspective ignores the importance of a scientist's social capital. Recent studies by Bozeman and others (Bozeman et al., 2001) highlight the importance of social capital as a critical resource established by academic scientists throughout their careers. This raises the possibility that the entire multiplex firm–scientist relationship may encompass the exchange or translation of a scientist's social capital (or social network) in addition to their human capital. The potential for complex networks of innovation to shape science-based firms is highlighted by McKelvey (1996) and Powell et al. (1996) who examine the firm's position in a network of relationships to other firms and institutions. In other commercial and individual settings the work of Granovetter (1973) and others highlights the importance of multiple webs of connectivity. Likewise, Uzzi (1997) describes firms in the garment district of New York as embedded in an extensive series of social exchange relationships rather than simple dyadic ties. This perspective raises the possibility that a firm's connection to an individual scientist may lead a scientist to contribute social capital and a means of establishing the embeddedness of the entrepreneurial firm within the scientific network. The perspective leads to the first research question addressed in this paper: *To what extent does an academic scientist contribute not only human but social capital to a firm and how does this social capital contribute to the embeddedness of the entrepreneurial firm?*

The possibility that a scientist may contribute not only human capital but also social capital raises the issue of what elements of social capital are most potentially useful to the firm and what are their origins. In arenas other than science, individuals who are able to form bridges either for themselves or their organization into other domains, social networks and functional areas are brokers (Burt, 1992, 2000) or boundary spanners (Allen, 1984; Tushman, 1977; Tushman and Scanlan, 1981). For such individuals the literature suggests that their ability to provide social capital and connections into distinctive networks is mediated by a range of factors of which careers seem to be of particular salience; notably their education, professional activities, and experience within an organization. In the scientific community, academic scientific careers have complex characteristics through which scientists may establish social capital in networks of collaboration in the one hand (Friedkin, 1978) but on the other remain somewhat bounded within distinctive epistemic cultures (Knorr Cetina, 1999). Recent scholarship in science policy suggests that at least in the purely scientific setting, the complex career trajectory facilitates the build up of capital that encompasses more than know-how and tacit knowledge. Rather, scientists accumulate experience in distinctive institutional settings, and in addition build social capital (Bozeman et al., 2001). I propose that this approach provides a useful lens through which to explore the way in which careers shape the critical elements of a scientist's social capital. This observation together with prior scholarship on the determinants of boundary-spanning individuals raises the second question addressed in this paper: *To what extent do scientific careers shape the social capital of a scientist and thus mediate the embeddedness of entrepreneurial firms in the scientist's own scientific network?*

3. Methods

3.1. Research setting

I explore these issues in a sub-set of a population of biotechnology firms drawn from a comprehensive population of firms in the regenerative medicine sector of biotechnology. The firms are all founded upon novel technology licensed from a University. For the purpose of this analysis, the newly founded firm is assumed to have no pre-existing capital. During the early life of the firm, such capital must be established. For simplicity and measurement purposes, I define this capital as a combination of the firm's scientific team, the scientific advisory board, and the broader scientific community outside the formal (hiring) boundaries of the firm who are engaged in collaborative research with the firm. I then confine the analysis to exploring the degree to which the inventor has contributed to this newly formed capital and the degree to which the firm's capital is strongly mediated by both the human and social capital of the academic inventor.

This article draws on in-depth interviews conducted over a 1-year period in 2001–2002. An initial study focused on scientists and inventors engaged in one sub-field of tissue engineering and traced out the scientific and commercial networks surrounding the idea (Murray, 2002). The current work is a follow-up study that takes an inventor–firm oriented perspective. The research reported here is primarily based on an analysis of interviews with the founders and inventors of these firms.

Regenerative medicine firms have typically been founded on the basis of a particular scientific idea with one or several potential therapeutic applications, ranging from spinal cord injury and other diseases of the central nervous system, to liver failure, diabetes and heart disease (Business Week, 1998). What they share is their scientific approach to the disease; specifically the use of therapies that rely on cells and on engineered scaffolds to support cells rather than on protein products or the more traditional small-molecule products that have long been the basis of the pharmaceutical industry. The basic science at the heart of these firms has arisen through the convergence of several distinctive intellectual contexts—molecular biology, chemical engineering, medical research, stem cell research, and even research into the physics of water. The field has been identified as one of the key medical research opportunities of the twenty-first century with the potential to harness the body's regenerative capabilities and to mimic the body's reparative mechanisms to repair or rebuild damaged tissues and organs (Niklason and Langer, 2001). Investment in firms in this industry sub-sector is estimated to be in excess of US$ 3.5 billion (Lysaght and Reyes, 2001).

3.2. Sampling

In building an understanding of the role of inventors in the knowledge-based activities of these firms, I have carried out over 100 hours of interviews with founders and inventors. To define the initial sample, I first had to develop the appropriate population boundary, which I did by triangulating three sources.[1] A small sub-population based in the North-East was chosen for research. In examining basic parameters of firm size, age, status (public or private), and ori-

[1] These included TechVest an annual industry conference on reparative and regenerative medicine; the Pittsburgh Tissue Engineering Initiative listing of firms; and http://www.marketresearch.com.

gins (university, corporate spin-out, other) these two samples were found to be equivalent. These firms represent a wide range of approaches to regenerative medicine, including scaffolds, tissue repair, cell therapies, xeno-transplantation and combination therapies.

Preliminary interviews were carried out with three firms. They started with the basic research question: How do biotechnology firms work with inventors to accumulate scientific knowledge while meeting commercial milestones? The initial interviews explored this question over a broad context, addressed multiple facets of the issue, and gave me the opportunity to build an understanding of the real problems and challenges encountered by such early-stage science-based firms. Following guidelines for inductive research, I was as descriptive as possible until major themes emerged from the data (Glaser and Strauss, 1967; Miles and Huberman, 1994). My interest in the detailed connection between the inventor and the firm was sparked when one CEO commented that he had a "real problem because the inventor cut off all involvement with the firm over an equity disagreement." In an interview a day later with another firm the CEO noted that the inventor "has been critical for us, at the moment he comes to our lab, gets involved in the scientific strategy, but we really have to make sure that we keep him interested and engaged."

3.3. Qualitative and quantitative data

The evidence guiding my description and analysis of the role of academic inventors is divided into three major categories:

(1) *Semi-structured interviews with inventors and founders*: I have conducted 25 semi-structured interviews; in all the interviews I was accompanied by a "scribe" who took extensive notes. At the end of the interviews these were written up and I added my notes and comments. Interviews with inventors focused on the role that they played within the firm; their balance between the firm and academia; their perceptions of what their role should be, what human and social capital they brought to the firm. In particular I explored their role in establishing the different scientific activities in the firm: internal research, external collaborations and the Scientific Advisory Board. The (non-inventor) founder interview was focused on the founder's challenges regarding the firm's early scientific development. I asked about the role the founder wanted the inventor to play and the reality of the interaction. For key members of the firm's scientific team (internal, external collaborations and Scientific Advisory Board) I explored how the connection was made.

(2) *Patent and publication analysis*: The quantitative data analysis presented here covers a sub-population sample of 12 of the East coast firms. Two distinctive sets of data were gathered: The first is centered on the inventor and collects all the publication and patent data in which the academic inventor appeared as an author/inventor. The second was a firm-centric data set that included all publications and patents that included the firm in the address/assignee field.[2] The patent data is based on granted patents from the USPTO patent database. Publication data was generated using the Web of Science publication database. The inventor data are used to build up a picture of the inventor's human capital and social network. The number of publications and patents is used as a "gross" quantitative measure of his or her human capital. These data are then used to build a picture of the academic inventor's social capital—the network of co-authors and co-inventors (on a range of patents) and institutions with which the academic inventor has engaged in scientific activities. The firm data is used to build up a picture of the individuals and institutions that the firm is able to access to develop its underlying knowledge through patenting and publication. This data was developed in order to explore the potential to develop bibliometric measures of the concepts developed in the qualitative work, rather than as the basis for statistical testing.

(3) *Archival data on firms and inventors*: In addition to interviews and bibliometric data I attempted to gather archival data on the firms that included

[2] Obviously this method may undercount a firm's patents because some may have been in-licensed to the firm from other institutions and the firm will therefore not be listed as the assignee but may have exclusive access to the ideas contained in the patent. For the purposes of exploring the role of the inventor (rather than the patenting productivity of the firm) I believe that this introduces minimum bias.

the list of their Scientific Advisory Board (SAB) members and the CVs of their key scientific personnel and CEO. For the inventors, I gathered their career history where possible, in order to have a listing of their laboratory affiliations—their Ph.D. laboratory and supervisor, any post-doctoral experience and the relevant supervisor, and their own laboratory, its affiliation and graduate students.

3.4. Merging and defining academic inventor and firm measures

In combination these three data sources were used to build up a picture of capital of the firm and the contribution of the academic inventor to that capital. I consider the firm's capital to be defined by the internal and external scientists with whom the firm undertakes the scientific activities of its business. While patents, publications (including co-publications) are measures of productivity and output, they also provide insight into the human capital used by the firm to generate these outputs. Likewise, the scientific advisory board provides another aspect of their human capital. Thus following Liebeskind et al. (1996) authors and inventors on the firm's patents and publications are viewed as individuals whom the firm has accessed to contribute to its initial and ongoing knowledge transfer and accumulation. The firm scientific activities and various elements of the firm's scientific network of connections are presented in Table 1.

Table 1
Descriptive statistics of firm scientific productivity and scientific network

$N = 12$	Percent firms with these activities	Mean (range)
Patents	92	8 (1–22)
Publications	83	28 (1–149)
Co-publications	83	18 (1–81)
SAB members	83	7 (3–12)
Co-authors	83	75 (2–390)
Co-patentors	92	11 (1–42)

As a means of measuring the inventor's contribution to the firm's capital, his contribution of human capital can be measured through direct co-publication, co-patenting, membership of the SAB and other activities within the firm. The academic inventor's contribution of social capital is established by the determination of the extent to which the network of people (internal and external) contributing to the firm's outputs (as defined above and including SAB members) over-

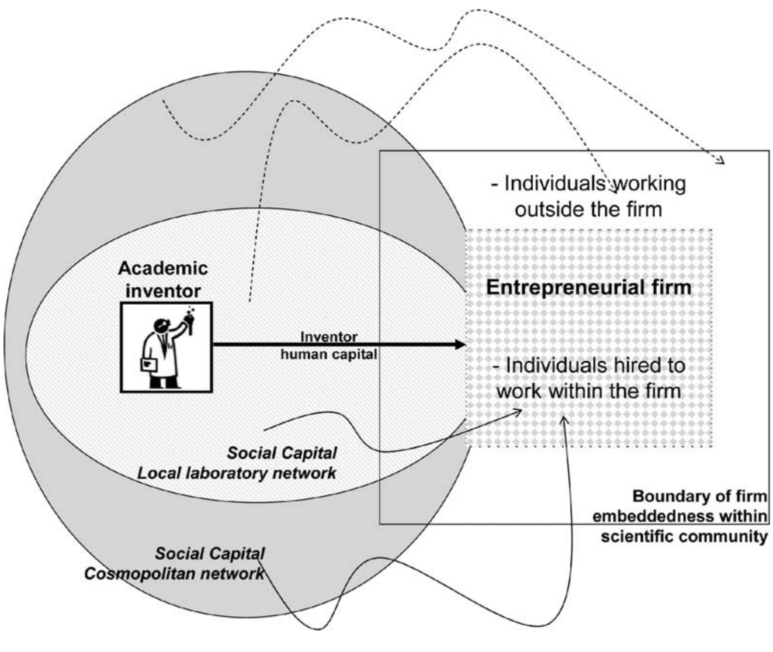

Fig. 1. Human and social capital across the academic–firm boundary.

lapped with and originated in the academic inventor's network, i.e. whether they had published or patented with the academic inventor prior to the founding of the firm. Those individuals appearing in both the firm's network of contributors and the academic inventor's network, were also coded for whether they had shared a laboratory relationship (as advisor, co-worker or student) with the academic inventor. Thus an inventor is defined as contributing to the firm in two ways (Fig. 1):

- Human capital through direct co-authorship, co-inventorship, SAB membership and other executive roles.
- Social capital through providing the firm with the ability to translate and access his network of key individuals into a network of individuals with whom the firm then establishes specific relationships and gains human capital.[3]

4. Three inventors' stories

The distinctive role played by inventors in firms that are founded to commercialize their ideas is exemplified by the stories of three different inventors from the East Coast tissue engineering community. All three inventors have advanced degrees (Ph.D.s) in either cell biology or biochemistry or biomedical engineering. They have each developed a novel scientific method that has the potential to transform disease through the development of a novel therapeutic agent. In each case, the idea has been published and patented and the patent licensed to the entrepreneurial firm by the respective academic institutions with which the three are affiliated. The new entrepreneurial biotechnology firms have raised some risk capital for commercialization. In the early stages each firm is attempting to meet the pre-clinical scientific milestones that are established by investors and that are necessary to translate the scientific idea into a novel therapeutic product. At this point, the three stories diverge: they illustrate the distinctive mechanisms through which the inventors lend their human and social capital to the transfer and commercialization of their scientific ideas.

In the first instance—Firm 1 (as identified in all subsequent graphs)—the inventor has a full time faculty position at a leading medical school. The inventor is a scientist rather than a clinician and has no previous involvement with commercialization. A venture capital firm "proactively sought out technologies from the National Institutes of Health and then other academic medical institutions" and came in to form a company around the novel cell technology concept developed by the inventor and brought in a local CEO from a nearby biotechnology firm. In the course of the licensing negotiations, there was some disagreement over the extent to which the inventor would receive equity in the company. At the time, the institutional rules were poorly understood and confusion arose over whether and how the inventor might receive equity but continue to undertake relevant research in this field and work on sponsored research with the firm. At some point in the negotiations, the inventor parted company with the firm and investors. The firm established an internal scientific team and for the first 1–2 years struggled to develop the core ideas in the absence of guidance by the inventor. They were able to render the cell-based system operational and make significant changes in its elements. They also built up a Scientific Advisory Board of several key individuals from the particular field of cell biology and clinical medicine. Several members were local, but were recruited by the CEO and venture investors with no input from the Inventor.

In sharp contrast is Firm 9. The Inventor was also a member of faculty at a large medical school also focused solely on research, having moved to this medical school from elsewhere on the East Coast to complete a second post-doctoral fellowship and had subsequently been offered a faculty position and established a small research laboratory. During this time, the Inventor (working with a graduate school colleague) developed a novel idea focused on particular scaffolds and their application to the transformation of cells. In spite of the potential to build an academic career, the potential for commercialization of this idea was intriguing, and his colleague had decided to found a company based on the idea. The inventor initially

[3] Given that the translation of an inventor's social network into human capital for the firm can be measured only when there is a traceable measure of the tie on the part of the inventor (through publication or patenting) and of the substantiation of the translation through publication, patenting or SAB membership, this method will under-count the academic inventor's social capital contribution to a firm's capital. Informal introductions, introductions to long-standing (but not co-authoring) colleagues, departmental members, etc. are not captured.

worked part time with the company, designing the early experiments, setting up the research facility and building up the internal scientific research team. He also focused on research partnerships; as the founder described it “he has been managing all the research collaborations in the last few years ... choosing a lab to work with is critical and [inventor] was critical to that process.” The inventor continued to run his own lab, training a small number of doctoral students and medical fellows (often in collaboration with a more senior colleague—his former post-doctoral supervisor), building up his own research reputation, and research connections throughout his academic institution. After 4 years, the firm was able to raise money through a range of sources, and the inventor decided to join the firm full-time but retain a limited faculty position in his academic institution. He also asked several leading scientists with whom he had published in the past to join the SAB of the firm. He had come to know these scientists through earlier collaborations established by his post-doctoral mentor. These individuals also started to engage in some collaborative research for the firm and the identification of key pre-clinical research sites.

The third inventor story (Firm 6) describes a possible middle-ground between the first two, and more closely conforms to what might be described as the emerging normative role of academic scientist–inventors in entrepreneurial firms. Once again the inventor is a Faculty member at a leading University. The scientific idea formed the basis of his post-doctoral work at the University and his subsequent research in the laboratory that he established after joining the faculty. The idea was published in several leading journals and the inventor had started to establish a significant reputation in the field of tissue engineering. The scientific idea focused on a novel scaffold for tissue engineered therapeutics, and followed one of a number of approaches that were being commercialized by different research groups. The University licensing office licensed the idea into an entrepreneurial firm in which the inventor had a significant role. In the early years after founding, the inventor sat on the SAB, but more concretely continued to work on the idea and make a series of inventions disclosed through publications and University patents, which were later licensed to the firm. The inventor continued to engage in sponsored research. After several years, a number of the firm’s new scientific team members started to co-supervise graduate students in the Inventor’s laboratory, and publish jointly with the Inventor. Several Ph.D.s from the laboratory moved to the firm and others were hired from within the academic network of the tissue engineering community. The head of R&D noted: “we try not to stay linked only to one group but it’s a small academic community.” Only after 3–4 years was collaboration broadened to incorporate a number of other institutions—mainly through the inventor’s broad network of connections. A significant industry collaboration was also brokered by the inventor and his previous post-doctoral advisor. The inventor maintained bi-monthly visits to the firm to discuss research ideas and comment on the firm’s scientific and technical progress, but also managed a range of distinctive academic research projects and collaborations with other firms, both established and more entrepreneurial.

5. Theme and variations—three dimensions of involvement

Inventors have the potential to influence and facilitate an entrepreneurial firm whose business focus is the commercialization of their scientific ideas and other related discoveries. This process entails more than the simple movement of a scientific idea from an academic laboratory to the firm laboratory; it can involve an exchange of tacit knowledge; on-going collaborative research to develop the idea more fully; the identification of key individuals who may provide access to unique complementary scientific resources such as animal models, measurement systems, or (often later in the process) access to unique patient populations.

These qualitative data underscore the two broad categories of capital that an inventor can bring to the entrepreneurial firm. The precise mechanisms of involvement through which this capital is exchanged and the way that they unfold as the firm develops are connected to both the inventor’s own capital and the willingness or ability of the inventor to translate that capital into direct activities, valuable connections, collaborations, and employee contacts for the firm. These interviews suggest that an inventor’s role in the build-up and transfer of scientific knowledge can be understood by considering both an inventor's human capital and social capital. In broad terms, as described by previous authors, the inventor can facilitate the firm in transferring and accumulating knowledge by bringing his or her own knowledge (human capital) to bear on the firm's activities. However, while current perspectives highlight co-authorship and other forms of tacit knowledge exchange (Zucher et al., 1998; Agrawal, 2002) this study found a range of modes of exchange of human capital. In addition, academic inventors could also shape the firm by translating their social capital into a network the firm can leverage for on-going scientific work and in doing so embedding the firm within a series of relevant relationships. Furthermore, the interviews suggest that an important distinction be made between two forms of social capital: One form of social capital is related to the current laboratory affiliation of the scientist which I have called the local laboratory network and one that is formed through the broader network of connections to the scientific community which I have called the cosmopolitan network. Each of these types of capital can be of potential value to the firm and can be accessed through a range of distinctive ties.

Therefore, across a range of inventor–firm interactions access to members of an inventor's social network (social capital translated into firm capital) is transferred and translated across university–firm boundaries, reflecting the interactions that are increasingly recognized as fundamental to entrepreneurial science-based firms (Etzkowitz, 1998; Zucher et al., 2001; Rosenberg, 1982).

This model of an inventor's scientific capital being composed of two forms of capital—human capital and social capital which includes both local network and cosmopolitan network capital—presents these elements as if they are independent. *Human capital* describes how the inventor is directly involved with the firm-providing advice on how to set up experimental systems, understanding the nuances of a novel scientific approach, or manipulate complex cell lines. *Local laboratory network capital* is the local social capital that an inventor can bring to the firm. It is associated with their own academic laboratory, graduate students, or laboratories in which they have worked as doctoral students or post-docs and can, for example, be accessed through collaborative research. *Cosmopolitan network capital* is the social capital that the inventor can leverage to facilitate the firm's development that is based upon a broader set of co-authorship relationships with individuals from a range of institutions, disciplines and settings, which constitute that inventor's invisible college (Crane, 1972). I use this approach because it provides an analytically useful way of summarizing the data. Nonetheless, as Bozeman has noted, "the production of scientific knowledge is by definition social, many of the skills are more social or political than cognitive" thus acknowledging that for any inventor, their human and social (local and cosmopolitan) capital are highly interdependent (Bozeman et al., 1999, p. 18; Rogers and Bozeman, 2001). Likewise if we reevaluate Merton's explanation for the Matthew effect in science, we find that human capital (the quality of particular ideas) is intimately connected to affiliations and positions early on in the career of scientists (Merton, 1973). While these elements of a scientist's capital are intertwined and evolve throughout a scientist's career (Bozeman et al., 2001), at the time when an inventor's work is licensed to a newly formed firm the academic inventor has accumulated a stock of experience, publications and overall capital which she may provide to the firm. Thus we can simplify the analysis by assuming that we are taking a "snap shot" of an inventor's capital. We can then explore the mechanisms through which this capital is translated by the entrepreneurial firm's scientific development and the origins of the capital.

5.1. *Academic inventor's human capital*

The academic inventors in this (albeit small) study bring a diverse range of human capital. Some are relatively junior scientists who have completed post-doctoral training and just migrated to a junior faculty position. Others are extremely accomplished and well-established tenured faculty of world-renowned institutions (as noted in Table 2).

Table 2
Descriptive statistics of academic inventor's scientific capital

Inventor ($N = 12$)	Mean (range)
Total number of publications	59 (5–182)
Total number of patents	10 (1–23)
Total number of co-authors	106 (11–321)
Total number of co-inventors	6 (0–23)

Table 3
Mechanisms of inventor relationship to the firm

Inventor's relationship to the firm	Description of role and contribution of human capital
Moves from academia to the firm	Scientist–inventor becomes a full time member of the firm's scientific team, often taking on role of CSO, chair of SAB, and occasionally CEO.
Moves from academia to the firm and retains an academic affiliation	Scientist–inventor becomes a full time member of the firm's scientific team, often taking on role of CSO, chair of SAB, but retains an academic affiliation typically within previous department.
Remains a full-time academic but retains involvement in firm	Remains a full-time academic but uses different modes to remain involved specifically consulting (often 1 day/week), may take on role as chair of SAB and occasionally acting CSO.
Remains in a full-time academic position with no involvement with firm	No involvement with the firm–arms length relationship with the technology transfer process.

This capital can be conceptualized as encompassing not only education (Becker, 1962), but also explicit knowledge captured in patents and publications, as well as tacit knowledge (Polanyi, 1967) and craft knowledge and know-how. Such human capital makes the inventor a potentially crucial player in the transfer and commercialization of his or her own scientific ideas. The precise role that an inventor plays appears to be determined by a range of factors including personal preferences; career stage; institutional barriers; professional norms and the incentives provided by the firm. In several firms the inventor was critical in the establishment of the firm's laboratory facilities making sure that a complex and difficult cell-line was reestablished and often did so through part-time consulting. Such roles relate to the specific challenges underlying a particular experimental system and are closely allied to the tacit knowledge exchange that has been highlighted as a critical mechanism through which star scientists shape firm performance. However, an inventor's human capital has other facets: In one firm the inventor (who was both CEO and CSO) laid out the entire experimental strategy through which key technical milestones could be met, in another the inventor developed the protocols with which proof of concept of the cell preservation technology was established. These are human skills generally based on the experiential dimensions of a scientific career and in some cases may encompass the experiences of a medical training in addition to a scientific one.[4] Such elements of human capital highlight the importance of substantive scientific and technical knowledge based on the inventor's own research experience and knowledge of the scientific literature. Throughout the interviews, the inventor's role in guiding experimental scientific work dominated the founder and the inventor's own assessment of their role. Upon further questioning inventors comment that this is part of their skill set—one more closely linked to being an "advisor" and designing scientific strategy even within the scientific setting rather than a holder of true "hands-on" craft or tacit knowledge. Nevertheless in many cases this results in publications and patenting with the firm.

Academic–inventors translated their human capital to capital for the firm in differing degrees and through distinctive mechanisms. One critical factor shaping these mechanisms is whether the inventor actually joins the firm, retains a full-time academic position or takes some intermediate path with a part-time academic affiliation. Table 3 describes four different possible modes of involvement.

In each of these relationships, except when the inventor remains at arms length, the inventor brings significant human capital to the firm. Scientists at different stages in their careers make the decision to move full-time to the firm or retain only limited academic affiliation. For relatively young scientists in the junior faculty stage, the decision to move to the firm seems to be related to "my past experience ... I saw my advisors work with a firm, it eventually failed but I decided I would rather get involved in commercializing

[4] This is increasingly true with the rise of the M.D./Ph.D. programs designed to train individuals in both the scientific and medical/clinical contexts and thus prepare them for research and practice that is focused on the translational activities of transforming basic science into clinical impacts.

a technology and have the ability to influence many individuals.” For a more senior scientist who joined a regenerative medicine firm after an academic career spanning many years, the decision was made because “I had had enough of the grant cycle, raising money from government agencies and working in a relatively poorly recognized area of biology” but this was only after working on a flexible basis for 3 years and maintaining an academic affiliation for that period. However, among the so-called star scientists, as might be expected given the benefits and distinctions of high status in the scientific community, none have moved to the particular firm in a full time position (except upon retirement). Rather they exert their influence and shape the firms through consulting activities, often as equity participants in the firm with significant incentives to shape its successful development. Among those who remain in academia, their role in the firm ranges from deep involvement as chair of the Scientific Advisory Board to more informal advice given to the internal scientific team.[5]

5.2. Academic inventor’s social capital

5.2.1. Laboratory network

The inventor’s interaction with the entrepreneurial firm draws on an inventor’s individual human capital. Nonetheless, such human capital is rarely built in isolation from a broader social context and is typically deeply embedded within the local laboratory setting within which the inventor trained and trains others. As a consequence, an inventor’s “laboratory life” often becomes intimately involved in the entrepreneurial life, the solution of the firm’s early scientific challenges and at times the on-going scientific development of the firm’s intellectual foundations. The nature of laboratory life is the subject of the detailed analysis by Latour and Woolgar (1979) who not only illustrated the cycle of idea production, transcription and credit, but also the different actors involved in the process. While those studying scientific careers have noted the importance of education and training (Allen and Katz, 1992) our understanding of the laboratory setting as the *locale* for much of this training is somewhat underdeveloped.

The laboratory is the context in which the inventors in this study developed their ideas, and is also a critical *local* social context. An inventor’s local laboratory network is structured and emerges through the traditional scientific career development of academic scientists particularly in the biological sciences (where multiple post-doctoral positions are common). The hierarchical structure of scientific education provides any scientist with a local social context that spans not only their own laboratory but also those laboratories in which they trained (moving from a doctoral position through a series of post-doctoral positions and finally into a faculty position). In this way the scientist has built up a local “laboratory network” which includes his former Ph.D. advisor, post-doctoral mentor, graduate student colleagues and his own graduate student, resident, and fellow advisees. Academic laboratories in tissue engineering and cell biology like those in other fields, display a strong sense of the laboratory context and the importance of a shared experience among the current and former members of the group.

The laboratory network can be translated for the firm’s advantage through a range of distinctive mechanisms. In most of the entrepreneurial firms in this study, the inventor’s local laboratory network was at least partially incorporated into the firm’s scientific activities. Like the role of the individual inventor himself, the ways in which a firm leveraged this laboratory network varied widely. In at least three firms, a technician moved to the firm from the inventor’s laboratory, two of these were associated with the Inventor moving into a full-time position in the firm. In instances of either a partial or full-time academic affiliation, the inventor engaged in multiplex utilization of his local laboratory context. While the precise nature of these interactions is difficult to pin down (and often confidential) they most typically include one of the following: on-going sponsored research at the inventor’s laboratory; on-going research pursued with external funding with licensing arrangements establishing a stream

[5] It should be noted that the institutional challenges of maintaining the variety of flexible relationships found in this relative small sample underscore the finding of Gittelman (2001) and others that institutional arrangements facilitating the involvement of the inventor as an individual actor in the early years of an entrepreneurial firm are valuable to the commercialization process. While they have become a widely accepted norm within the US East Coast biomedical complex studied here (see Etzkowitz and Leydesdorff, 2000, for a detailed analysis of this setting in a broader context) this is not the case in other parts of the US, Europe and beyond and varies widely from institution to institution.

of patents to the firm; informal collaborations based on material exchange; or collaboration on the use of specific animal models. Joint publication (and occasionally patenting) of research is a common output of such interactions.

At Firm 6 one member of the firm's internal scientific team was permanently positioned in the inventor's laboratory and worked with doctoral students on projects of mutual interest to the firm and the inventor, resulting in joint publications. Such intimate relationships have the potential to create significant blurring of the boundaries between academic science and commercialization.[6] With this in mind, at least two of the inventors interviewed who had maintain an academic laboratory in the early days of the firm (and had subsequently joined the firm full time) were keenly aware of these challenges and tried to keep research projects separate. In other instances, the participation of an inventor in an entrepreneurial firm rests on continued research in the laboratory sponsored by the firm and public sources. This arrangement and the relevance of the training provide alternative career opportunities for doctoral students who choose to leave the academy. Within this sample, it has not been possible to trace such movements: as one CSO noted "the students in that lab are real hot shots and most of them want to go into academia ... so although we would love to take advantage its not a route we have been able to follow."

Through their own training, academic–inventors have also come into contact with highly regarded senior scientists who may have acted as their advisors in the past. This is another element of their local social network that they may exploit on behalf of the firm notably when the firm establishes its Scientific Advisory Board. Leaving aside the specific activities of the board, inventors can use their connections to such individuals to facilitate the firm in building this aspect of its own scientific organization. As outlined above, the inventor may play a central role in SAB formation through the laboratory network.

5.2.2. *Cosmopolitan network*

Laboratory life is central to a scientist–inventor's social network. Nevertheless, scientists are simultaneously embedded within a broader social context of their peers within and around their disciplinary and problem focus. So-called "invisible colleges" were first described by Crane (1968, 1972) and have as their foundations interpersonal relationships built on shared interests, conference interactions, and exchange of students. This extensive social structure within the scientific community provides a scientist with a cosmopolitan network of colleagues and contacts, with whom as Merton (1973) described he may have more in common than more proximate individuals from outside his discipline.

In the case of a field such as regenerative medicine, these cosmopolitan networks span both the core discipline in which the inventor has trained—for example, the inventors who are chemical engineers have a cosmopolitan network of polymer specialists who span numerous centers in the US and beyond—but the network also bridges disciplines including cell biology, stem cell biology, and biomechanical engineering (Vacanti and Mikos, 1999). Furthermore, given the clinical relevance of much of the work the cosmopolitan network for many inventors encompasses a medical sub-specialty such as neurology, dermatology, or immunology. As with their human capital and local laboratory network social capital, scientists typically build their cosmopolitan network through the course of their career; gaining entry to the smaller invisible college through a mentor and through distinguished research activities (refer to Table 2 for data on inventors' cosmopolitan network a measured only using co-authors).

The precise mechanisms that lead to a scientist's embeddedness within the cosmopolitan network are not as well elucidated for science as they are for networks in the labor market (Granovetter, 1973), product development (Hargadon and Sutton, 1997; Hansen, 1999) and supplier relationships (Uzzi, 1997). However, limited empirical evidence (Liebeskind et al., 1996) supports the interview findings in this study:

[6] While the output of high quality scientific research can be of dual value and further the dual aims of an inventor (particularly one with equity), such arrangements have been of particular concern to Universities. At the broadest policy level, the concern voiced in the literature on this subject relates to the distorting of the scientific agenda towards more applied research (Blumenthal, 1986). However, at a more practical level, the concern is with the nature and direction of the training of undergraduates and particular doctoral students, with the contention being that laboratory life is shifting and students will not receive an appropriately broad and dispassionate training.

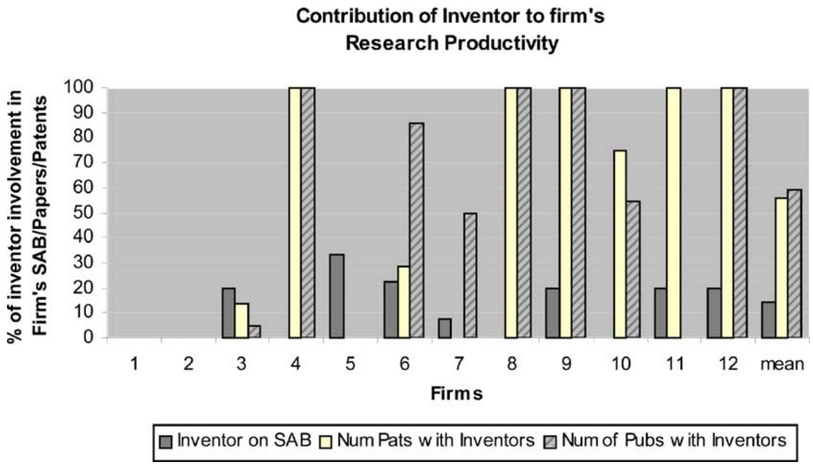

Fig. 2. Inventor involvement in the firm's productivity.

For academic–inventors, their cosmopolitan network facilitates research collaboration and leads to extensive co-publication among widely dispersed groups. The cosmopolitan network also allows for broader learning through the formation of new societies such as the Tissue Engineering Society, new journals, specialist conferences, and research funding opportunities through the National Institutes of Health, the Advanced Technology Program and the National Science Foundation.[7] Such relationships are also established through journal editorship, and shared experiences with grant review, government committees and the broader world of scientific policymaking in which star scientists often become engaged (Latour, 1987). Over time, senior scientists build a close group of colleagues to whom they can turn for advice or information about specific problems and challenges. This highlights one key attribute of senior or "star" scientists, namely their deeply embedded connectivity to the community. This is complementary to their deep stores of human capital but is potentially more valuable to a firm, particularly when the star scientist is actually somewhat removed from the lab bench.

From the firm's perspective, an academic inventor's cosmopolitan network has significant potential value. Through informal and more formal mechanisms, the inventor can translate his network to make the firm aware of the leading scientists in the field and of their particular scientific resources. Even when managers in the firm are *aware* of such scientists, their access to them may be limited. However, the inventor can introduce the firm and open up avenues to collaboration with key senior scientists who might otherwise be unavailable. As one CEO put it "we need to establish high-powered collaborations and SAB membership to prove that we are not thieves but to do this they need to know who we are." The data in this tissue engineering sample show that there is wide variation in the degree to which inventor's translate their cosmopolitan network into measurable ties that facilitate science and commercialization at the firm. Nonetheless, in cases where the inventor has a deep cosmopolitan network and is involved with the firm, his network does appear to translate into access to key scientific resources in two distinctive forms—research collaborations (which are measured here by co-publication) and also Scientific Advisory Board membership (see Fig. 2). To date it has not been possible to identify informal collaborations that have not resulted in publications. This suggests that the measure of inventor-originated co-publications and co-authors is likely to be under-counted.

[7] This is consistent with Coleman's view of social capital as the process through which the exchange of human capital—in this case scientific knowledge—is facilitated, but also encompasses a range of other activities including lobbying, funding mechanisms, etc. (Coleman, 1988).

6. Discussion

In this paper, I have combined social network and brokering/boundary spanning perspectives to shed light on empirical evidence of an academic inventor's role in commercialization. In doing so, this paper makes sense of the variety of contributions an inventor can make to facilitate the embedding of a science-based entrepreneurial firm in the scientific community. I also take a career perspective to understand the origins of these contributions. Overall, there is considerable variance, but inventors make contributions at two distinctive levels—human capital and social capital. Social capital (in its most reduced form) takes the form of the translation of an inventor's social co-publishing network into a network that is utilized by the firm for co-authorship, SAB membership and hiring.

My first finding is that the inventor brings his human capital—the range of scientific knowledge, knowledge of laboratory techniques and expertise in developing scientific strategy. The mechanisms through which he brings this knowledge vary widely but typically arise either through joining the firm as Chief Scientific Officer, or if he maintains a full-time academic position, through consulting. The specific observable outputs include co-publication, co-patenting and memberships of the SAB (see Fig. 2). This human capital is strongly shaped by the direct experience built up through a career in academic science.

The second finding is that the inventor simultaneously exploits his social capital (network) to build relationships between members of his social network and the firm. Of particular note is the finding that the inventor's social capital has two distinctive elements: The first is a *local laboratory network* that is shaped by the specific career experiences of the inventor training in different laboratories and building his own laboratory; the second is a cosmopolitan network of widely dispersed peers within his field who may constitute the invisible college of the discipline. The local laboratory network can be translated by the firm into a source of on-going scientific expertise around the core idea and can be accessed through sponsored research between the firm and the inventor, or through the mobility of the inventor's technicians and students to the firm. Members of this local network may also be invited by the inventor to form part of a firm's SAB. The firm can also translate an inventor's *cosmopolitan network* to shape a firm's embeddedness and allow the firm to tap into a broader scientific network for specific expertise that the firm may use in meeting technical milestones. These connections can be leveraged through the inventor acting to create collaborative research between the firm and the scientist, or once again through an invitation to the SAB (see Fig. 3). Through these two elements of an inventor's network, critical and complex technical information and advice seem to flow into the entrepreneurial firm.

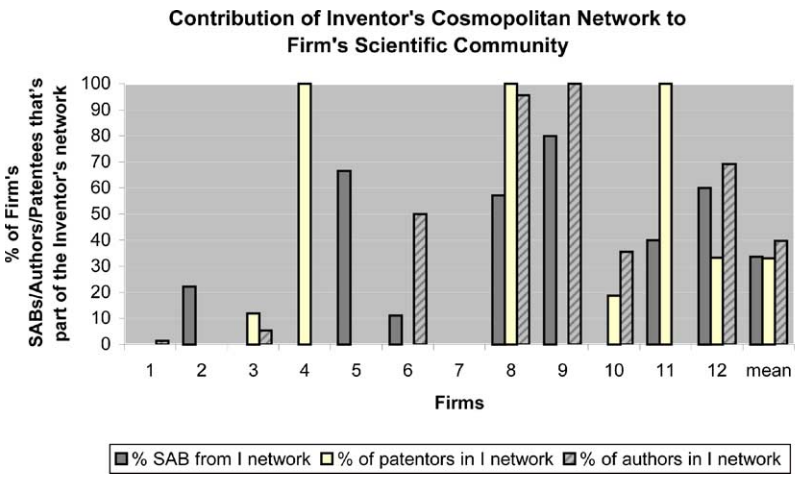

Fig. 3. Inventor cosmopolitan network contribution to firm's activities.

These elements of the inventor capital point to the importance of human and social capital well beyond tacit knowledge. It underscores the academic inventor's relationship to the firm as potentially multiplex in nature and encompassing considerably more than either tacit knowledge or reputation signals. Indeed the key signal provided by the academic inventor is a signal to members of his cosmopolitan network that the firm is a worthwhile endeavor and worthy of time and collaborative attention. The research highlights the critical importance of an inventor's social capital, the importance of the inventor's brokerage of his social capital to connect and embed the firm in his social network and the mechanisms that a firm then uses to exploit this connection—namely co-publication but also hiring, consulting and SAB membership. The origins of the inventor's most critical social capital are to be found in his career trajectory and can be thought of as containing two elements: social capital founded on his local laboratory network and that founded on his cosmopolitan network. The nature of brokerage and mechanisms of firm embeddedness to each of these elements of social capital remain to be more precisely understood.

This work has several limitations. Because the primary aim of this paper was to move beyond human capital oriented views of the firm–inventor interaction to encompass social capital perspectives and the critical career-based origins of such social capital, I have devoted little attention to explaining under what conditions an inventor is likely to translate his or her human and social capital for the commercialization of his idea. Incentives provided by university policy, other founding team members and investors are part of the explanation but are only one facet of the story. Another facet is probably connected to the career path and the opportunities it presents to an inventor—anecdotal evidence suggests that established faculty typically retain their academic position, while more junior scientists may see the commercialization of their ideas as an opportunity to move from academia into the private sector in a relatively senior position (typically Chief Scientific Officer) albeit a precarious one. The question of whether the social capital benefits to the entrepreneurial firm can be accrued regardless of whether the inventor moves his main affiliation to the firm or keeps it at the university cannot be fully addressed with the limited number of firms examined in this paper. However, it remains an important open question as to whether a close, full-time involvement is more or less preferable to a more distant relationship but one in which the inventor maintains and continues to build his social capital through scientific networks. It may indeed be the case that the transformation of the scientist's network into a firm network that embeds the firm in the scientific community is only possible to the extent that the scientist retains a strong academic affiliation and therefore academic legitimacy.

The paper is also narrowly focused on biotechnology and one emerging sub-field—tissue engineering. Thus it is difficult to generalize beyond the life sciences in determining whether these mechanisms form the basis of inventor–firm relationships in entrepreneurial firms in other disciplines on the forefront of science. Furthermore, this paper makes no statement regarding the relative performance outcomes associated with the distinctive role played by an inventor–scientist in the technology transfer process. Rather it sheds light on the complexity and variety of the underlying mechanisms through which ideas developed within an academic context are transferred and translated within the commercial world. Questions of which mechanisms an inventor chooses, how they vary by sector and their ultimate performance implications remain for future research.

From a policy perspective, this research raises a number of questions regarding the extent to which institutional policy can and does shape inventor participation in commercialization. The core dilemma facing institutions is the intersection of the inventor's role at two of the level's described—the inventor sharing his own scientific knowledge or human capital on the one hand and leveraging of the local laboratory network elements of his social capital on the other. Particularly in cases where inventors have high-powered incentives to positively influence the performance of firms commercializing their work, individual participation is a likely and probably desirable outcome for the firm. There are some concerns, however, that this involvement will provide a distorting incentive on the direction and secrecy of an inventor's continued research (Blumenthal, 1986; Krimsky, 1991). Although these are factors of some concern, the more problematic issues arise in cases when an inventor has a significant laboratory network whose current research is closely related to the ideas being transferred to the firm. In this case it is often beneficial for the firm to maintain on-going collaboration not only with the inventor but the laboratory network. Under such conditions, the inventor and the academic institutions face potential conflicts of interest regarding the research direction of students training in the laboratory. Although institutional rules vary widely, many institutions prohibit the combination of a firm providing inventor equity on the one hand and sponsored research to the inventor's laboratory on the other. Nonetheless, the firm can still translate the laboratory network through the mobility of students after their training or through more informal research activities. Exploring the precise boundaries of these issues is a question for further research and policy debate.

Acknowledgements

I gratefully acknowledge the support of the DuPont-MIT Alliance and the Cambridge-MIT Institute. Thanks also to all the individuals—executives and academics—who have participated in this study. My thanks go to Cyrus Beagley, Emanuele Picciola and Trent Yang for their valuable assistance throughout the research for this paper. I would like to thank Barry Bozeman, Jesper Sorenson, Paul Carlile and Rebecca Henderson for their advice on earlier drafts. An earlier version of this paper also benefited from comments by the participants in the European Group for Organization Studies, Lyon, 2001.

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