Chapter 13

COLLECTIVE INVENTION AND INVENTOR NETWORKS

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Abstract

Collective invention occurs when competing organizations share knowledge about the design and development of new technologies. Such exchange and circulation of ideas and practices among communities of inventors was relatively common in the nineteenth century, most notably in geographically localized industrial districts. This collective system of innovation was eclipsed in the early and mid-twentieth century by the rise to prominence of the large corporate R&D lab. Recent decades, however, have seen the decline of stand-alone, internal corporate labs and the resurgence of collective efforts by networks of inventors, distributed across organizations and spanning distant locations. We draw on

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literatures in economics, innovation studies, management, and sociology to posit explanations for this recent rise. Suggestive additional evidence is provided from comparative analyses of patent data from the 1970s and the present decade.

Keywords

collective invention, governance, networks, technological change

1. Introduction

Historians, sociologists, and economists who study innovation often differ in their emphases on the features of settings in which technical change occurs. For many business historians and economists, the "organizational synthesis" is the central story, as the large firm developed through linking investments in technology and corporate strategy (Chandler, 1977; Galambos, 1983). The corporate research laboratory, established after 1900 at General Electric, DuPont, Kodak, AT&T, RCA, and others, was created to bring the innovation process inside the large corporation, and provide a continuing basis for both control over and renewal of technological change (Carlson, 1991; Hounshell and Smith, 1988; Mowery, 1984; Reich, 1985). As Graham (2008) points out, even critics of the corporation viewed the large firm as the central force in technological change, although arguing that it also monopolized invention, repressed craft knowledge, and stifled the creativity of engineers (Noble, 1984).

Instead of focusing on the centrality of the firm, historians and sociologists of technology who have studied the evolution of industries have emphasized a different current of innovation. Systems technologies—electricity, the telephone, and its successors—have developed not because of a particular corporate champion or active commercial pursuit, but due to a collective "momentum," or the accumulation of investment and interest in a system's progress from a variety of participants (Bijker, 1987; Hughes, 1983, 1987, 1989; MacKenzie, 1990). These systems technologies were the combined product of research carried out by individual inventors, government and university researchers, and corporate labs. Many technological systems reflect a confluence of uncoordinated research efforts driven by intense and widespread interests that intersect around the development of a novel technology. As a new technology evolves in a growing web of social, economic, and artifactual parts, the primary control that individual firms have is to configure their own activities in light of the needs of these systems.

Alongside these two powerful currents, alternate modes for organizing the innovation process have persisted. In the nineteenth and early twentieth century, such alternatives typically involved craft-based models, based in local communities. In research on the blast furnace, Allen (1983) identified how a group of firms could produce "collective invention" by sharing information about the design and effectiveness of new technologies. From his studies of the disclosure of improvements in manufacturing processes within the iron industry, Allen suggested that the distinctive feature of collective invention is the exchange and circulation of ideas and practices among distributed networks of individuals located in diverse settings, rather than the housing of such efforts within the confines of particular firms. Building upon Allen's (1983) work, Nuvolari (2004: p. 348), in his study of Cornish steam pumping engines, defines collective invention as a *setting* in which: "competing firms release information freely to one another on the design and the performance of the technologies they have just introduced."

In Allen and Nuvolari's analyses, there are four contributors to technical change: R&D labs of private firms, nonprofit institutions, individual inventors, and collective invention. Allen (1983) and Nuvolari (2004) suggest that three propositions typify the setting of collective invention. First, technical change must be driven by primarily incremental improvements. Second, firms and other organizations must disclose any improvements they make. And third, firms must use the disclosed improvements to improve the technology they have in common. We build on these insights, and connect them to recent work in the economics and sociology of technical change.

We begin by taking stock of the theoretical interests at stake in research on collective invention. In particular, collective invention has attracted much attention because it defies conventional wisdom about appropriability concerns; therefore, we suggest the link to intellectual property should be made explicit in defining collective invention. Next, it is important to highlight the tension implicit in the dual role of participants in collective invention as employees of competing organizations and as technologists who have personal or professional interests at stake in the overall advance of some technology. Thus, we distinguish between competing firms (or, more broadly, organizations including government and university labs), the loose network of inventors that cuts across these organizations, the growth of knowledge, and the actual improvement of technologies. We offer a substantively similar, but distinctly social definition of collective invention:

> *"Collective invention is technological advance driven by knowledge sharing among a community of inventors who are often employed by organizations with competing intellectual property interests."*

This definition broadens the scope of collective invention to instances of university–university and university–industry interactions, and encompasses voluntary and informal associations that are often critical to economic activity (Granovetter, 2009). In addition, the role of patent pools and other collective agreements that further technical change are more amenable to analysis within this framework.

We should note at the outset that collective invention is merely the tip of the iceberg of increased knowledge sharing over the past several decades. Such disclosure of valuable information to competitors is much more pervasive than "pure" collective invention. Yet, because it represents one end of a continuum of knowledge-sharing regimes, collective invention offers fertile ground for empirical research and novel theorizing about the determinants of technological change.

Having defined and situated collective invention, we turn to its origins. We argue that the increasingly specialized division of labor makes it difficult to predict where complementary knowledge will arise—leading to greater knowledge sharing in order for participants to remain abreast of developments in the field. Additionally, we suggest that high expectations for a technology (i.e., technological opportunity) can lead individuals across firms and nonprofit organizations to contribute their efforts to a community endeavor that drives collective invention despite the lack of apparent economic gain to any particular organization.

Historical examples bear out the importance of collective invention in improving a number of notable technologies (Lamoreaux and Sokoloff, 2000; McGaw, 1987; Meyer, 2003; Scranton, 1997). A general lesson from numerous historical studies is that collective invention was an attempt to overcome the limitations of information access that accompanied extant economic and organizational structures. For some organizations, the inability to appropriate many types of technical improvements resulted in a lack of motivation to pursue internal research programs. Why invest in expensive exploratory efforts when the odds of capturing the fruits of research were low? Participation in collective efforts offered one solution. Many instances of collective invention today represent joint efforts at solving problems whose value cannot be appropriated by a single party, but which represent a bottleneck for the interdependent economic activities of participants. On the other side of the fence, some companies that are actively engaged in R&D may want their researchers to be involved in a larger technological community.

Collective invention affords the chance for access to more diverse sources of knowledge, even if gaining control over these divergent ideas proves difficult.

With time, many knowledge-sharing practices associated with collective invention can become institutionalized as a set of norms or agreements (David, 2008; Merton, 1979; Sabel and Zeitlin, 1985). In the case of the diffusion of the Bessemer steel process, a patent license that nearly all manufacturers signed had a clause that required any subsequent operational improvements to be disclosed. This mandated sharing of knowledge led to the establishment of a small community of practice among engineers from different firms and launched a productivity race between participants from different firms (Allen, 1983: p. 11). A variety of practices—such as mutually respected prices, collective training programs, and technological standards, that spread risks and dampened competition were commonplace across industrial districts. Nuvolari's (2004) analysis of Cornish steam engines in the nineteenth century finds that the publication of advances in several trade outlets let to dramatic gains in the efficiency of the engines, due to the accumulation of myriad incremental improvements. Despite the variety of vibrant nineteenth century examples of collective invention, these efforts were largely displaced by the rise of the large corporate research and development (R&D) lab in the early twentieth century. For a time it seemed that these community efforts would be relegated to the annals of history.

Over the past 30 years, however, the large corporate R&D lab has fallen in prominence. Many of the most notable corporate labs have been shuttered and dismantled. A second wave of collective invention is now shaping the rate and direction of technological change in numerous technologically advanced industries (Freeman and Soete, 2009). These processes of distributed innovation characterize a wide array of contemporary industries, from the early origins of the computer to the development of software to the origins and continuing development of biotechnology. This transformation has been sparked by strategic, technical, and economic factors that influence the organization of innovative labor. Inventors with multiple contacts across organizations are more likely to be exposed to diverse ideas and benefit from them. Consequently, organizations attempt to position themselves in partnerships and alliances that foster connections across organizational boundaries, in hopes that novel ideas in one setting spark fresh approaches in another (Burt, 2004; Granovetter, 1973; Powell et al., 1996). Shared awareness of a technological frontier creates the circumstances for inventors to act in concert, regardless of the perceived tangible benefits for their organizations. The central technical drivers are shifts in technological opportunity, dictating the potential rate and direction of technological change (Malerba, 2007). The economic factors are demand (on economic *demand* vs. *need,* see Mowery and Rosenberg, 1979) and appropriability (Teece, 1986; Winter, 2006), which together represent necessary conditions for firms to invest in R&D.

Yet history and social structure also loom large, as many authors have noted (David, 2008; Scranton, 1993). The particularities of industry evolution and the historical organization of technical communities are deeply intertwined with economic and technical calculations. Whether nineteenth century glass making or blast furnaces, or the contemporary life sciences and open-source software, relationships within a community of inventors and researchers are influenced by a confluence of social, political, and economic forces. We summarize these disparate factors as follows:

1. The need to spread the costs of invention across multiple organizations.
    a. By implication, few participants possess a sufficient theoretical understanding to pursue new designs without incurring the high costs of unguided trial and error.

2. The inability to appropriate innovations creates a discrepancy between the private value and social value of invention.
    a. The private value of invention is too low for some firms to pursue a technology individually, but individuals within these firms are able to recognize its potential benefits.
    b. Despite a lack of knowledge about demand and strong intellectual property rights, collective invention allows for continued improvement of technical performance.
3. The emergence of norms and identification of governance structures that encourage knowledge sharing among legally distinct parties.
4. Uncertainty about the direction a technology will evolve and the kinds of applications that may unfold encourage greater discussion within and across communities and provide an impetus for organizing.

In this chapter, we examine these and other reasons for the recent rise in collective invention. We look at the changing nature of technological opportunity, as well as factors shaping the organization and governance of innovative labor. One understudied aspect of collective invention is the growing fragmentation of the knowledge required for many promising technological opportunities, leaving relevant know-how spread across diverse organizations.

The knowledge boundaries of firms develop due to many social and economic processes that are unassociated with changes in technological opportunity. As Schumpeter (1942) argued, it would be naïve to expect firms to immediately and optimally adjust to changes in technology (Rosenberg, 2000). Indeed, it would be difficult to maintain that new technological knowledge is ever brought about under ideal circumstances for its evaluation, elaboration, and diffusion. By its very nature, new knowledge is, to varying degrees, at odds with the social structures in which it is discovered (Mokyr, 2005). Put differently, the inability to reconcile newly perceived goals with the internal and external distribution of knowledge for invention may, under certain circumstances, render collective invention a more viable option than internally funded R&D.

Unpredictable technical change also makes it more difficult for firms to house all the innovative labor required to pursue many technological opportunities. Such shortfalls in capability and opportunity can prompt some to make use of collective invention. Thus, to the extent that data for decision making overwhelms the machinery of hierarchical organization (Knudsen and Levinthal, 2007; Powell, 1990), collective invention becomes more prevalent. At the same time, for those companies with strong internal research capabilities that operate in domains in which technological futures are uncertain, collective invention provides an option to become involved in a broader effort of exploration and learning.

We organize our chapter around four arguments that account for the persistence of, and greater reliance on, collective invention:

1. As the stock of knowledge grows, the need to access specialized expertise outside the boundaries of individual organizations increases.
2. When the sources of potentially complementary knowledge become more diverse, engagement with external communities increases.
3. The emergence of new forms of governance makes collective invention less costly and still compatible with the goals of private enterprise.

4. Persistent interindustry variations in technological opportunities and social institutions result in marked differences across fields in the reliance on, and form of, collective invention.

Potentially complementary innovative labor spreads across a wider array of organizations as the stock of knowledge grows, making it more difficult for a single organization to possess requisite depth and breadth of expertise (Section 2). Intuitively, then, we would expect collective invention to expand as a result of the increasing complexity of products and processes and the narrower specialization of innovative labor. Put simply, one reason we see a resurgence of collective invention now is that there are more pieces to each puzzle and each player has fewer pieces.

The difficulty of identifying and absorbing complementary knowledge makes investments in access to diverse sources of knowledge more desirable. Because it is challenging to predict the spreading of organizational, technical, and geographic locations of relevant expertise and ideas, firms engage in collective invention to keep pace with recent developments (Section 3).

Collective invention is also fueled by the creation of governance structures that enable individuals from different organizations to share knowledge at lower cost and with reduced risks of misappropriation or malfeasance. Additionally, new technological and physical forms of organizing for collective invention help mitigate many of the challenges associated with asynchronous or remote coordination and collaboration (Section 4).

Finally, there are unique and persistent interindustry differences in the qualitative nature and magnitude of collective invention. These differences arise in part due to the distinctive social structures that characterize different industries and their divergent stages of technological evolution. These two factors alter the potential benefits that firms might hope to accrue, altering the choice and mix of internal versus collective invention. Thus, interindustry differences in the use of collective invention stem from variation in technological opportunities, the uncertainty of technological trajectories, and the means of appropriating innovations that arise from collective knowledge. We discuss these differences, attending to the divergent norms found in various scientific and technical communities, which condition the creation and sharing of ideas (Section 5).

To add support for these arguments, we provide illustrative evidence from a number of technology-intensive industries. We also use patent data from key technology classes to add weight to our review of the literature, and gauge the extent of the changes over the course of recent decades.

2. The stock of knowledge has grown

Numerous arguments have been offered in recent decades that describe a transition from industrial society to a knowledge-based economy (Bell, 1973; Gibbons et al., 1994; Hicks and Katz, 1996; Powell and Snellman, 2004; Ziman, 1994 provide entry into these discussions). The relevance of these arguments for our purposes is their characterization of a marked change in the modern research enterprise. Collaboration—both domestic and international—has increased; and a more diverse set of organizations and nations are contributing to the stock of knowledge. In addition, the proportion of research that is interdisciplinary has grown, and key research funding agencies are now strongly behind efforts at translating basic research into application to solve pressing environmental and medical problems. The implications of these shifts toward greater collaboration and interdisciplinarity for collective invention are far-reaching.

Hicks and Katz (1996) were among the first scholars to use bibliometric evidence to examine the changing terrain of science. In an analysis of 376,226 publications between 1981 and 1991, they show notable growth in the average number of authors per paper, from 2.63 to 3.34, and a smaller uptick in the number of institutions and countries represented on each article. Their findings complemented earlier analyses of de Solla Price (1963), who chronicled the increasing importance of multiple authors in the chemical and physical sciences, areas he dubbed “Big Science.” More recently, Wuchty et al. (2007), in a comprehensive analysis of 19.9 million articles and 2.1 million patents covering the late 1950s–2000, found that the increasing prevalence of multiple authors, or “team science,” had extended from the physical sciences to chemistry, biology, engineering, the social sciences and even mathematics and the humanities.

The fields of medicine, biology, and physics have each shown at least a doubling in mean team size over the 45-year period from 1955 to 2000 (Wuchty et al., 2007: p. 1037). This growth in teamwork may well be triggered by an increase in knowledge specialization and the growing costs of doing research, but the number of authors on papers is also growing in fields where the overall number of researchers is growing less rapidly and costs are less a factor. Perhaps most consequential, Wuchty et al. (2007) find that, even after numerous relevant controls, papers by teams are cited more frequently and are much more likely to have high impact. In subsequent work, Jones et al. (2008) looked at a sample of 4.2 million papers published at US universities between 1975 and 2005, and observed that multiauthor teams increasingly involve authors from multiple universities.

We add more empirical support for the argument that the stock of knowledge has grown in recent decades through a comparison of the number of inventors on patents from five US patent classifications across two time periods—1975–1979 and 2001–2005. We chose the technologies as useful indicators of older industries with a history of innovation (aerospace, pharmaceuticals), as well as sectors that came into prominence in the last quarter of the century (optical communications, semiconductors, and biotechnology). We obtained patent data from Delphion, a commercial patent search service owned by Thomson Reuters. We searched for all patents containing at least one US patent classification corresponding to our technology domains of interest, which we use for illustrative purposes. Table 1 is based on all patents filed over these time periods for each patent class. The *inventors* column contains the mean number of inventors. For example, there were an average of 1.5 inventors across 1118 Aerospace patents in the late 1970s, and 2.2 inventors on average on 1619 patents in the early years of this decade. With the exception of the new domain of biotechnology, which had a high rate of collective invention at its outset and continues to be highly collaborative, the organization of innovative labor appears to have shifted, with considerably more inventors per patent. This transition to multiple authors suggests a greater need to integrate a wider stock of knowledge. Biotechnology had its origins in the 1970s in university labs and continues today to be a science-driven field. Inventor teams in biotech are, not surprisingly, the largest of any technical area shown, suggesting that the functional diversity of these teams is also greatest.

While the number of inventors increased across the board, there are key differences that merit attention. Apart from biotechnology, semiconductor manufacturing processes and pharmaceutical compounds represent the greatest contrast. Semiconductor inventions are highly modularized by steps in the manufacturing process, which often correspond to a particular disciplinary foundation or the juncture between two disciplines. For example, much of modern semiconductor manufacturing is enabled by chemical engineering, optics, materials science, mechanical engineering, and optimization

Table 1
Number of inventors per patent in selected patent classes[a]

	1975–1979		2001–2005	
Patent class	Inventors	# Patents	Inventors	# Patents
Aerospace	1.5	1118	2.2	1619
Biotechnology	6.4	6533	6.5	22,881
Optical Comm.	1.6	511	2.4	6217
Pharm. Chem.	2.5	2467	4.3	7212
Semi. Mfg.	2.0	5630	2.7	79,069

[a] The technology areas correspond to the following patent classification titles and numbers:
Aerospace—Aeronautics and Astronautics; 244
Biotechnology—Chemistry: Molecular biology and microbiology; 435
Optical Comm.—Optical Communications; 398
Pharm. Chem.—Drug, bioaffecting and body treating compositions; 424
Semi. Mfg.—Semiconductor Device Manufacturing: Process; 438

and planning software. Each step of the process, such as the manufacture of masks for laser etching onto wafers, the design of robotic machinery, and the chemical baths used to remove support structures, represents a fairly distinct body of knowledge (Orton, 2004). Collaboration across these areas of expertise occurs in order to coordinate steps in the manufacturing system. Given that the manufacturing process is fairly decomposable into parts, the size of teams can stay relatively small, reflecting the reduced need to simultaneously solve a complex problem.

In contrast, the field of pharmaceuticals often presents nondecomposable problems, which cannot be broken apart and addressed separately without significantly affecting the quality of the final result (Simon, 1962). Whereas the average number of inventors in semiconductor manufacturing processes increased from 2 to 2.7, pharmaceutical drug patents saw a larger jump in authors from 2.5 to 4.3. Economists often describe drugs as "discrete" technologies since they are not modular, whereas semiconductors and telecommunications equipment are called "complex" due to their many parts that need to be integrated (see Arora et al., 2001). Thus, the invention of pharmaceutical drugs cannot, for the most part, be cleanly divided across areas of expertise. Invention often requires intensive collaboration by organic chemists, microbiologists, and biochemists, as well as immunologists and pathologists in order to discover drug targets and potential drugs. Thus, the size of inventive teams depends on both the sheer amount of knowledge that needs to be integrated and the ways in which scientific and engineering training and expertise map onto technological problems.

Summary: We have presented a survey of some of the reasons that collaboration has increased in recent decades and relate these to an evolutionary logic of participation in collective invention. First, the knowledge required for involvement in any scientific and engineering domain has deepened, often leading to the involvement of a greater number of specialist researchers. Second, industries vary in their presentation of nondecomposable problems, but the tendency is for the interdependence of problem-solving activities to increase. Both of these trends help account for the shift in teams toward larger, more functionally diverse groups. The high costs of changing the knowledge boundaries of the organization to address the latest technological challenges make collective invention an attractive alternative. Thus, collective invention offers a medium for organizations to learn about and participate in technological advances that hold uncertain economic promise.

3. The sources of knowledge have become more diverse

Increasing specialization is the double-edged sword of technological change. On one hand, it reflects the deepening of knowledge that can lead to a greater rate of technological advance. On the other, increasing specialization also suggests that the directions of technological advance have become path dependent due to extensive learning and organizational investments (Antonelli, 2007; Arthur, 1989; David, 1975, 1985). Not only do firms become less likely to change course in their R&D investments over time (Patel and Pavitt, 1997), but also they are less likely to recognize important new knowledge due to the blinders imposed by their past work (Cohen and Levinthal, 1989).

The tendency toward local search has long been noted as a problem for any research and development organization (March, 1991; March and Simon, 1958). A common issue raised by economists and management scholars is the extent to which learning in R&D is path dependent (David, 1985; Zollo and Winter, 2002), sowing the seeds for technological lock-out (Cohen and Levinthal, 1989; Henderson and Clark, 1990; Schilling, 1998). Rather than merely serving as a guide in research, the increasing depth and breadth of potentially relevant knowledge has exacerbated the challenge and complexity of commercial R&D (Nelson, 1982).

This challenge stems in part from identifying which sources of technological opportunity are relevant and deserve ongoing cultivation via the involvement of technical personnel. A *source of technological opportunity* provides information used in making new products or processes (Cohen et al., 2002; Klevorick et al., 1995; Malerba and Orsenigo, 1997). Not only have the sources of technological opportunity increased in contemporary times, these sources of knowledge are qualitatively different in form and content as well:

- Firms draw upon knowledge from more distant geographic locations (e.g., Gittelman, 2007; Johnson, 2006).
- Firms make more use of interindustry knowledge flows (e.g., Fung and Chow, 2002; Mansfield, 1982).
- Firms draw upon a broader array of scientific and technical domains (e.g., Cohen et al., 2002; Giuri et al., 2007; Levin et al., 1987).
- Firms make greater use of knowledge from universities and government labs (e.g., Branstetter and Ogura, 2005; Powell et al., 1996; see Foray and Lissoni, this volume). Au1

As Antonelli (2001) suggests, collective knowledge is often the result of discovering latent complementarities among different sources. Given the widespread nature of technological opportunities, but the limited and costly means for appropriating returns from innovation, how do managers select where they will search? We posit that collective invention is a means for organizations to hedge their bets on technological futures. In addition to having the capacity to pursue a novel direction, collective invention enables contributing firms to be “in on the news” (Powell et al., 2005).

Collective invention may also serve as a form of knowledge "insurance" for organizations involved in overlapping technical domains. By sharing knowledge, organizations trade appropriability for access to unexpected technological opportunities. When previously intractable problems become decomposable through theoretical or technical advance, broader access to knowledge enables flexibility in factoring complementary advances into R&D (Brusoni et al., 2001; Rosenberg, 1982: pp. 104–119). In other words, collective invention is both a means for access to information and a coordinated way of developing relevant skills that aid in adapting to technical change (Cohen and Levinthal, 1994).

3.1. Costs of establishing knowledge access

The high costs of establishing access to a body of knowledge suggest that many organizations may prefer to merely pay the "maintenance costs" of ongoing sharing of knowledge in collective endeavors. As knowledge accumulates, the need for a specialized vocabulary, software and hardware tools, and unique theoretical models lead to the creation and branching of distinct epistemic communities (Cetina, 1999). Mokyr (2005) suggests that the larger the epistemic distance between technical communities, the greater the difficulties in communication and collaboration. Therefore, the tendency toward localized learning suggests that *potential*, more distant collaborators will find it both more time-consuming and difficult to simply establish a productive dialogue.

One of the principal challenges in forging new inventive collaborations is the acquisition of context- and technology-specific knowledge, rather than the general learning of new scientific facts or theories (Vincenti, 1990). Nelson and Winter (1982) argue that much of the knowledge of firms is embedded within routines. Because routines are the idiosyncratic result of many historical circumstances, articulating them systematically for transfer within and across organizations can be challenging (Arora et al., 2001; Von Hippel, 1994). Kogut and Zander (1993) provide evidence of this phenomenon in their analysis of 81 cases of technology transfer among firms in Sweden. They ask respondents to describe the technology being transferred across the dimensions of codifiability, teachability, and complexity, and to describe whether the technology was being transferred to outside firms or wholly owned subsidiaries. They found that transfers that occur to independent firms typically represented relatively codifiable and teachable knowledge, rather than tacit or novel ideas. Even in the case of joint-ventures in which companies may try to collaborate intensively to transfer knowledge, the costs were much greater than with intrafirm knowledge transfer.

Organizations attempt to articulate knowledge via standardized processes and documentation in order to make it more broadly useful internally, but this process itself can require learning and invention depending on the tacitness of the knowledge (Nonaka, 1994; Nonaka and von Krogh, 2009). Von Hippel (1994) refers to the context-dependent value of knowledge as *information stickiness*. He uses the term to describe the high costs that can be associated with extracting knowledge from organizational settings and routines in order to transfer it to a new context.

In a parallel vein, companies report that one reason for abandoning work on university-licensed technology is the challenge associated with knowledge transfer from the faculty inventors (Thursby and Thursby, 2003). Similarly, Jensen and Thursby (2001) find the most successful transfers of university technologies to a company were either more fully developed (e.g., in prototype stage vs. concept stage) or well-understood by the licensing firm, thus avoiding surprises in terms of incompatibilities between the firm's knowledge base and the university technology. Ongoing faculty participation was also found to be vital in the commercialization efforts. Thus, mature, formalized knowledge and a common "epistemic base" accelerate knowledge sharing. To the extent that organizations aim to transfer knowledge from particular sources, it would be reasonable to expect some level of participation by technical staff in associations that foster collective invention, such as standards bodies or communities of practice (Rosenkopf et al., 2001).

Given the many potential sources of technological opportunity and the relative invariance of appropriability mechanisms, merely knowing how and where to allocate research time is itself a dilemma. Thus, the new tightrope walk for managers is to simultaneously address appropriable short- and medium-term commercial opportunities while attending to the accumulation of internal expertise via participation in "open" activities such as collective invention.

3.2. Geographic dispersion of knowledge and collective invention

The need to access geographically localized knowledge suggests that firms will also engage in collective invention with distant parties to discover and gain access to complementary knowledge. Nevertheless, colocation is crucial to firm formation and innovation (Audretsch and Feldman, 1996; Whittington et al., 2009), hence the distance between individuals possessing complementary knowledge may delay the formation of projects aimed at creating near-term technology products. When research efforts are not aimed at commercializing a technology, individuals will disclose to the public domain, leading to a geographically dispersed accumulation of knowledge (see Breschi and Lissoni, 2009). To the extent that the stock of knowledge is diversifying, but complementarity is difficult to identify, we should see more geographically dispersed accumulation of technological opportunities (Lakhani, 2006).

Research on geographically distributed collaboration has found an increasing average distance of coinventors over the past three decades. This development suggests that both the need to access distant knowledge and the lower costs of access via communications technologies are at play. In a study of US inventors, Johnson et al. (2006) find that the average distance of collaborators rose from 117 miles in 1975 to roughly 200 miles in 1999. Johnson and his colleagues found that rapidly advancing areas such as computers and biotechnology tended to exhibit more clustering than older industries such as textiles and mechanical devices, but even these new industries have begun to geographically spread in recent years (Johnson, 2006; Johnson et al., 2006). In Table 2, we return to the five patent classes for which we have collected data and look at the average geographic distance among coinventors. We used the addresses of US-based coinventors from patents to identify their respective cities and states of residence. We matched the city and state information to the US Geological Survey and computed the average distance by considering the distance that inventor *a* would need to travel to get to inventor *b*, inventor *b* would need to travel to get to inventor *c*, and so on. Thus, there is slight underweighting that occurs due to inventors who live in the same city—who have an average distance of zero. Nevertheless, all of the technology classes show evidence of greater geographic range, even when including only US inventors.

Greater distance among inventors does pose new challenges, however. Herbsleb et al. (2000) report that in commercial software engineering projects, greater distance is associated with significant delays and coordination problems. In a study of multidisciplinary, multisite National Science Foundation

Table 2
Geographic dispersion of coinventors in selected US patent classes[a]

Patent class	Avg. coinventor distance (miles) 1975–1979	Avg. coinventor distance (miles) 2003–2005	Percent (%) change
Aerospace	134	236	76
Biotechnology	147	285	94
Optical Comm.	161	215	34
Pharm. Chem.	101	252	150
Semi. Mfg.	153	222	45

[a] Gittelman (2007) finds that the average distance of biotechnology collaborators on scientific papers that contain corporate authors is 1500 miles when both international and United States are included. Gittelman's findings differ from ours and those of Johnson et al. (2006) for three reasons: the use of scientific papers as opposed to patents, the international focus (which accounted for 30% of coauthors in her data), and the use of organization rather than individual addresses.

projects, Cummings and Kiesler (2005) found that increasing the number of disciplinary affiliations had no effect on coordination or research outcomes; instead, increases in the number of affiliated institutions posed larger collaboration obstacles. Thus, rather than epistemic distance posing the major difficulty for knowledge-based collaborations, much of the challenge of distance remains in the coordination difficulties that arise between organizations. Given that Asian countries, most notably China, Singapore, South Korea, and Taiwan, have increased their production of scientific papers (NSF S&EI, 2006), the challenges of distance may require new patterns of collaboration and competition among United States, European, and Asian scientists. Au2

At the international level, research has examined the causes of increasing distributed collaboration (see chapter by von Hippel for more discussion of this literature). We touch on that aspect that relates to the uptick in collective invention. Saxenian and Sabel (2008) posit that the establishment of institutions such as venture capital, which support inventive activity by returning immigrants creates business and technical ties to their host nation. Saxenian (2006) suggests that these ties are mediated by first-generation immigrants who have maintained relationships in their home country, understand its culture, and can navigate local institutions. Kerr (2008) makes use of changes in US immigration quotas and a classification scheme for names of different ethnicities to study flows of knowledge back to immigrants' home countries. Even after controlling for the composition of inventor populations within detailed patent classifications, he finds that there are strong community effects in citations, with foreign researchers being 30–50% more likely to cite US-based inventors of their own ethnicity. This pattern is most pronounced in case of Chinese immigration. Shrum et al. (2007) demonstrate that multi-organizational collaborations in the field of high-energy physics (in which papers routinely contain hundreds of authors) are often facilitated by the standardization of laboratory procedures and well-established conventions about experimentation that enable far-flung teamwork despite individuals not being closely acquainted with one another.

Even in the United States, however, the growth in collaborative and interdisciplinary research does not proceed equally. Jones et al.'s (2008) research on the rapid expansion of cross-university teams also revealed increasing stratification. While the incidence of between-university collaboration has grown rapidly, the highest impact research had an elite university as one of the participants. And while policy pronouncements, such as the National Academy of Sciences (2004: p. 25) contention that interdisciplinary collaboration is needed to “address the great questions of science”… and the “societal challenges of our time,” are increasingly common, it is the wealthiest universities that have been in the forefront of building interdisciplinary centers. Elite universities are most able to attract gifts for interdisciplinary centers from donors who are keen to build them. Consequently, while research activities spread, social distance still looms large. Even as research diffuses across organizational and disciplinary boundaries, elite universities in the United States are becoming “more intensely interdependent” (Jones et al., 2008: p. 1261). Consequently, the research efforts of top universities have become increasingly collaborative, and in many fields involve the joint participation of industry partners. Thus, universities often serve as a foundation upon which collective invention can arise.

Gittelman (2007) uncovered the interesting tendency for papers by geographically dispersed biotechnology collaborators to be cited less on patents by the firms affiliated with the papers, but cited more often on their other scientific papers. In contrast, more geographically concentrated authors did not receive as many citations for their academic work, but garnered more references to their patents. Her interpretation of these competing results is that the geographic dispersion of knowledge varies markedly for public science and private science. The findings of Gittelman and others on the costs and benefits of accessing distant knowledge may suggest that geographically dispersed teams are better suited to more scientifically oriented work in which results are more foundational and relevant to a broader array of work. Furthermore, research at the scientific level is often more easily codified through formal language whereas work at the engineering level is often tacit, requiring colocation in order to be transmitted from one individual to another. These findings have important implications for collective invention, as its range is a function of the tacit versus explicit nature of knowledge. In the case of high-energy physics, that range may be quite great, whereas in a craft-based setting, individuals may need to be colocated.

3.3. *Collective knowledge versus competing artifacts? The division of labor and segmentation of markets in technological regimes*

One understudied theme in the literature on collective invention is the shifting focus on innovation and appropriability toward the level of the technological regime rather than the firm. Rather than focusing their efforts on similar technological competitors, organizations may have a greater incentive to first ensure the entrenchment of their technological regime in order to benefit from increasing returns to learning. A focus on appropriability at the level of the technical domain leads to greater specialization and to an organizational partitioning of commercial technologies. In some regimes, organizations compete for overlapping intellectual property, but create products that complement one another in the marketplace.

In such settings, competition occurs for scientific prestige and intellectual property, but in many instances of collective invention firms do not plan to address the same markets. Because these organizations compete for scope of intellectual property rights rather than market share, the stakes of knowledge sharing are much lower. These firms are jointly interested in the advance of a technical domain while they pursue different outlets for further elaboration of collective knowledge. Particularly during the establishment of a technology’s commercial viability, survival of the technological regime itself may become a superordinate goal for the organizations invested in its research and commercialization.

To explore this idea, we collected data on the mobility of corporate researchers across industries. By mobility, we are not referring to job mobility, as is typical, but the movement of knowledge. We generated a sample of prolific inventors with over 10 patents in a "home" industry. We did this by matching the name of the patent assignee, or corporate owner, to an SIC code. We think of this as their industry of origin, and then we search the patent records to find patents by these inventors that were assigned to a firm in a different industry. We linked assignees to SIC codes using the NBER compustat—patent assignee matching file (Hall et al., 2001). When we limited our analysis to the 15 most heavily patenting industries, we were left with 572,000 patents. (Incidentally, these 15 industries accounted for 60% of the matched patents out of some 380+ industries.) We identified "unique" inventors based on a combination of matches from last, first, and middle names and their addresses. We found $\sim$371,400 unique inventors through this method. Of these, we looked for inventors who had patented more than 10 times within one industry and at a single organization, resulting in 26,025 unique inventors. Our goal in deciding on these parameters was to set a high enough bar to ensure that inventors were full-time in engineering or research and that there were no name ambiguities that caused overestimation of movement across industries. Next, we looked at what industries inventors moved to after establishing expertise in their industry of origin (Table 3).

The exercise clearly shows marked differences across industries, a theme we will discuss in Section 5. For current purposes, note how widely inventors may travel starting from electronics, communications equipment, semiconductors, photography, and computers. In these information technology and computing fields, research is advancing on a very broad frontier, with a high likelihood of spillovers across industries. Few firms can have a hand in all these activities, instead technological progress is made collectively by an array of firms and public research organizations, while individual firms carve out narrower niches for themselves to hone in on. Not surprisingly, there is both intellectual and occupational mobility from radio and TV equipment to semiconductors and from chemicals to pharmaceuticals. The exercise is one illustration of how inventors and their research move across fields.

In many domains, public research is taking on a more active rather than supporting role in collective invention. The fruits of government and university research do not typically have an immediate bearing on private R&D, with the notable exception of the life sciences (Branstetter and Ogura, 2005; Powell et al., 1996; Rhoten and Powell, 2007). In a survey of industry managers, Cohen et al. (2002) found that university and government lab outputs were generally not seen as directly contributing to new project ideas. Instead, many managers emphasize the importance of intangible flows of knowledge, particularly contacts at conferences, faculty consulting, and hiring students. Branstetter and Ogura (2005) observe a strong increase in industry citations to university patents, even after controlling for changes in the propensity to cite and the available stock of knowledge to cite, but observe that the growth in industry–academy interaction is dominated by research related to the life sciences.

Much focus in recent years has been given to university–industry licensing, in part because many universities strive to find alternative sources of funding as federal research dollars have not kept pace with costs and industry support of basic science is still modest (Mowery et al., 2004; Powell et al., 2007). To be sure, there have been a number of notable successes where university licenses have generated significant income. Yet, as Zucker and Darby (1996) find, the distribution of commercial activity by academics is highly skewed. They suggested that star scientists, accounting for less than 1% of the population in biomedicine, produced over 20% of the publications. Nonetheless, we think such commercial involvement *per se* by universities plays only a limited role in collective invention, as the

Table 3
Industry researcher[a] copatenting and movement across major industries

Industry of origin	SIC[a]	2800	2834	3571	3577	3663	3674	3711	3861	7370	7373
Chemicals & allied products	2800		59			1	2	1		2	
Pharmaceutical preparations	2834	15		2	1		1	1	7		2
Electronic computers	3571		4		5	5	36	8	15	18	4
Computer peripheral equipment	3577		1	2		4	14	1	20	29	1
Radio & TV broadcasting & communications equipment	3663		1	7			134	1	2	16	26
Semiconductors & related devices	3674	3		43	11	87		1	12	58	52
Motor vehicles & passenger car bodies	3711	2	1	12			3		15	1	
Photographic equipment & supplies	3861		10	60	27	10	9	31		21	1
Services-computer programming, data processing, etc.	7370		1	23	13	49	159	4	8		14
Services-computer integrated systems design	7373			3	2	28	88	2		6	

[a] Each inventor had to have more than 10 patents at one company in an industry of origin, which is displayed in the left column.

scale of such successes is rather modest. Moreover, successful licenses often represent an exclusive dyadic exchange between a university and a firm, rather than a collective or general-purpose license used by many.

Nonetheless, as Rosenberg (2000) points out, university research and training is broadly responsive to the needs of industry. And there are instances in which industry advances can trigger a series of complementary inventions by universities that absorb the new technology as a research tool or as an engineering system meriting its own study (Lenoir and Giannella, 2006; Rosenberg, 1982). The role of university science in private sector R&D is multifaceted. Thursby et al. (2009) consider the extent to which university faculty assign patents to nonuniversity entities. They find that roughly one-quarter of patents filed by university faculty are assigned to firms. They attribute this largely to faculty consulting. Murray (2002), in an analysis of the tissue-engineering field, reports that knowledge spills out of universities in myriad ways. In addition to consulting, scientific advisory board memberships, the exchange of research tools, and personnel movement in and out of laboratories are commonplace in this field. Fleming et al. (2007) analysis of inventor networks in Silicon Valley and Boston emphasized the critical bridging role of Stanford PhD graduates and a postdoctoral fellowship program at IBM's Almaden Labs in the larger Valley network, and the salience of MIT graduates in the Boston community. Whittington (2007), in a detailed study of inventor networks in the life sciences among Boston-area universities, research hospitals, and companies, found that a few key university laboratories and a small number of individual scientists who moved from universities to firms, or nonprofit institutes to firms, and vice versa, were the central nodes that tied a large ecosystem together and gave it vitality.

More direct participation in collective invention by universities has also increased. For example, the Biobricks project at MIT provides a repository for organizations to contribute knowledge about reusable genetic and proteomic structures. The license on the site enables firms to pursue private commercial interests using knowledge they obtain from the repository. In Gittelman's (2007) analysis of biotech firm coauthorships, she found that over 90% of the companies' research partners were universities or research institutions.

Many observers have noted the dramatic growth in university patenting, although there is debate over whether this represents an increase in valuable applied knowledge or herd-like behavior on the part of universities trying to signal their relevance to the private economy (Henderson et al., 1998; Owen-Smith and Powell, 2003; Ziedonis and Mowery, 2004). Sorting out the competing influences on universities is difficult, but there clearly is an upsurge in the quantity of university patents. We return to the five technology classes we have examined in previous tables and gauge the growth in the number of university and government patent assignees between 1975–1979 and 2001–2005. Table 4 shows how many patents were assigned to the government and universities during these two time periods, one three decades ago, one more recent. The two columns labeled # *patents* reflect the total number of patents filed by all individuals and organizations in each time period in each patent classification. We see an absolute increase in university involvement in every technical domain, but most notably in biotechnology, semiconductors, and to a lesser extent, pharmaceutical compounds. In contrast, absolute government patenting has only increased in biotechnology, in all other areas, government patenting decreased. Yet, the combined relative increase of government and university patenting tells a very different story. Compared with other patenting entities, universities and government labs only increased their activity in the fields of pharmaceuticals and biotechnology, whereas their activity declined as a fraction of overall activity in aerospace, optical communications, and semiconductors.

In addition to patents assigned to universities, we also looked at patenting by inventors who had been affiliated with a university on previous patents (Table 5). In particular, we looked at the industry of origin for patents in which an inventor had been matched to at least three university patents on the basis of first and last name, city, and state. This is a rather new line of inquiry, and we offer it as exploratory data. We capture one indicator of the cross-traffic between university scientists and private firms.

Table 4
University and government patenting in selected patent classes[a]

	1975–1979				2001–2005				
Patent class	Gov.	Univ.	Total	Gov & Univ. Share (%)	Gov.	Univ.	Total	Gov. & Univ. Share (%)	Ratio T2/T1
Aerospace	145	3	1118	13.24	72	24	1619	5.93	0.45
Biotechnology	150	328	6533	7.32	373	3267	22,881	15.91	2.17
Optical Comm.	70	5	511	14.68	25	251	6217	4.44	0.30
Pharm. Chem.	36	62	2467	3.97	83	524	7212	8.42	2.12
Semi. Mfg.	210	93	5630	5.38	173	1297	79,069	1.86	0.35

[a] University patents were identified using a text query that matched terms such as university, college, (technology and institute), "regents of," "board of trustees," and others to standard USPTO assignee names. Government patents were identified using a text query that matched terms such as government, "united states," "secretary of," administration, "department of energy," "national science foundation," "national institutes," "national lab."

We have long known there are all manner of informal linkages between university science and industry (Colyvas, 2007; Murray, 2002; Rosenberg and Nelson, 1994), but this exercise helps show how these contacts translate into intellectual property. Whether these patents are the consequences of consulting agreements, faculty startup companies, postdoctoral fellows who move to industry, or technology "going out the back door," we cannot say. But the volume is not trivial, most notably in several key technical fields. While the overall number of patents is relatively small compared to the total for the industries of origin, we find that they follow a similar pattern regarding the division of innovative labor.

Table 5
Patents by university inventors assigned to publicly traded companies, 1975–2001[a]

SIC	SIC description	1975–1977	1978–1980	1981–1983	1984–1986	1987–1989	1990–1992	1993–1995	1996–1998	1999–2001
2834	Pharmaceutical preparations	35	23	20	53	68	117	473	367	523
2836	Biological products	0	1	2	26	38	41	309	208	335
3674	Semiconductors & related	0	2	2	6	42	75	129	158	349
3841	Surgical & medical instruments	0	9	12	17	11	32	112	135	125
1311	Crude petroleum & natural gas	3	5	14	20	17	19	28	16	239
3845	Electromedical & electrotherapeutic	2	3	12	13	27	40	62	95	162
7370	Services-computer programming	10	19	15	7	13	48	90	94	79
7373	Computer peripheral equipment	6	0	5	18	25	59	71	68	90
3577	Services-computer integrated system	3	6	8	5	5	18	70	143	87
2835	*In vitro* & *in vivo* diagnostics	0	2	1	1	9	10	145	118	55
2911	Petroleum refining	7	6	23	48	34	52	95	36	15
2821	Cleaning supplies, perfumes, cosmetic	7	10	3	9	9	7	60	64	80
2840	Plastic materials, synthetic resins	0	8	10	11	16	25	51	75	64
3570	Computer & office equipment	6	5	1	9	25	34	36	45	44
3861	Photographic equipment	11	5	21	18	17	30	9	31	52
7372	Chemicals & Allied Products	3	5	7	9	5	25	33	34	35
2800	Services-prepackaged software	0	0	0	2	0	0	4	71	77

[a] Each inventor had at least three or more patents assigned to a single university.

Technical opportunities and challenges in pharmaceuticals, biotechnology, semiconductors, and medical devices generate the most frequent interaction between industry and university science.

Summary: In this section, we suggested that the increasing diversity of sources of knowledge has important implications for collective invention. First, the risk of technological lock-in is greater for organizations in fields where the streams of knowledge required for invention are all rapidly advancing. Given the high costs of transferring knowledge across organizational and epistemic contexts, firms may use collective invention to maintain a dialogue with a broad community to hone their ability to transfer knowledge from potential sources of technological opportunity. Second, because knowledge can quickly become geographically localized, firms invest in collaborations to expand their reach—nevertheless, appropriable knowledge often requires colocation for its tacit transfer; whereas scientific collaborations can span greater distances. Geographic distance may result in greater deepening of formal knowledge (as opposed to tacit), which can in some circumstances create a larger stock of basic science that can be built upon. Finally, we point out that in many instances of collective invention intellectual property is at stake rather than product or service revenues. Firms interested in approaching different markets may share IP, thus limiting the scope of their claims, but they may make few concessions in the target markets they protect. Participants in collective invention may often see such engagements as complementary rather than mutually exclusive.

4. New forms of governance facilitate collective invention

Collective invention efforts depend on a social and organizational infrastructure for coordination. The complexity of most modern technologies requires the participation of many individuals from a practical standpoint, but the shared ethos of building something that people will use also encourages collaboration. Wray (2002) suggests that the increasing dependence of technical personnel on common equipment socializes scientists and engineers into norms of collective work. More generally, the development of communications and information technologies have greatly facilitated contact across geographic boundaries, leading in turn to the greater refinement of practices and norms of knowledge sharing (Cummings and Kiesler, 2007; Olson and Olson, 2003; Olson et al., 2008). We review how the governance of collective invention is shaped by the usage of new collaboration tools, social norms within a technical community, and the organizational form of collective invention efforts. Au3

The basis for a technological community arises out of a set of common understandings. In his discussion on the stages of development of the electric grid in several countries, Hughes (1983) presents the idea that each stage is associated with a particular “culture of technology,” that is, a set of values and ideas that orient inventors toward a common goal. These cultures of technology provide life within and among organizations toward the elaboration of a technical endeavor, what he termed “technological momentum.” Mackenzie (1990) referred to technological momentum as an institutionalized form of technological change, created as participants mobilize to align political, social, economic, and technical structures around the survival of a technology. People not only build institutions to address technical uncertainties and obtain resources, but also invest their careers and credibility in the rapid alignment and pursuit of multifaceted goals.

Cultures of technology are important because they help explain the continuity of an underlying technical community despite temporal shifts in organizing for collective invention versus private R&D.

Allen's (1983) historical case of collective invention can be cast as a sustaining community at the intersection of private interests, or as a locus of accumulation for valuable knowledge. After knowledge accumulates for some time, internal or external participants can exploit the knowledge through network refunctionality. Research on the development of biotechnology in Boston, Massachusetts in the 1980s and 1990s showed that the initial anchors of the community were research universities, most notably MIT and later joined by Harvard, as well as such medical centers as Dana Farber Cancer Center and Massachusetts General Hospital (Owen-Smith and Powell, 2004). These public research organizations were connected to fledgling biotech companies through research partnerships and clinical trials. Over time, venture capital firms moved in, collaborations were forged with participants from around the globe, and an open community catalyzed private innovation. The imprint of public science remained, but the cluster of companies increasingly pursued more product-driven, dyadic alliances rather than exploratory research efforts. Leaky ties that previously served as the irrigation system for open collaboration were transformed into channels of private innovation.

Collective invention thus involves the combination of both open innovation and private interests. Participants move in and out of technical communities, and can use their connections for public or private gain. The important point, as Lakhani and Panetta (2007): pp. 104–105) observe in their work on open source, is that: "these systems are not "managed" in the traditional sense of the word, that is, "smart" managers are not recruiting staff, offering incentives for hard work, dividing tasks, integrating activities, and developing career paths. Rather, the locus of control and management lies with the individual participants who decide themselves the terms of interaction with each other." (See chapter by von Hippel for further discussion).

Hughes (1998) describes how the aerospace, computing, and communication industries acquired Au4 technological momentum with the injection of cash and the alignment of political and industrial interests behind the systems they produced. For example, in the case of communications, common goals were eventually institutionalized via the ITU's (International Telecommunications Union) implementation of standards that enabled regional telephone monopolies to interoperate. Systems engineers played the critical role in coordinating the development of various technological systems among dispersed organizations.

In general, participation in collective invention is typically voluntary and often the inventors themselves are highly substitutable. There are countless studies and surveys of why developers contribute to open-source software projects. As but one illustration, Lakhani and Wolf (2003) draw Au5 on an Internet survey of 684 developers across 287 different open-source projects to understand community participation, finding that enjoyment of the creative work is the most common and compelling motivation (this finding is even more striking given that 40% of their survey participants were paid to participate in open source). They find that addressing existing user needs, the intellectual challenges associated with programming, and learning are secondary drivers. With their intrinsic interest in the work itself and their common goals, open-source developers have been creative in developing effective governance structures.

At the group rather than individual level, another dynamic is at play that reinforces the drive to enlist and govern collective invention. Kling and Iacono (1988) argue that computerization (i.e., the deployment of information technology infrastructure) is not merely the result of a desire for efficiency. Instead, they suggest that an understudied aspect of computerization of the workplace is the mobilization of participants (early adopters) who advocate for the introduction of information systems. They do so by making appeals to ideologies that resonate within the organization, but which are often imported and translated in from the wider environment (Fligstein, 2001).

Different technologies call for different modes of governance. Collective invention can precede the rise of an industry that harnesses the accumulated technical knowledge of contributors or it can emerge as the by-product of existing inventive efforts. Effective governance mechanisms typically tackle several problems: compatibility with the knowledge-sharing norms of distinct technical communities, responsiveness to both interesting and mundane technical challenges, and some means of coordination.

Meyer (2003) notes that IP barriers to collaboration can be confronted up-front via the use of licenses. Similarly, Gambardella and Hall (2006) find that some level of legal coordination is often needed for collective invention to be effective. In the case of software, the establishment of the General Public License (GPL) provided guidance to future inventors on how to contribute. As the lead developers emphasized that their contributions were collective goods, other followed suit using the GPL to advance the efforts of the community. In hardware, the use of patent pools and cross-licensing often presents a workaround to challenges in a narrow technical space, but the same type of practice can raise antitrust concerns if the patents are used to deter new competitors.

O'Mahoney and Ferraro (2007) find that individuals engaged in collective invention seek to establish formal mechanisms for exercising authority, but "cap" its power with democratic tools that allow for technical and organizational experimentation. They suggest that when members settle on a shared conception of authority, the result is often much more comprehensive than their original design. The governance systems of open-source communities have coevolved with changing technical objectives and shared conceptions of authority.

Coordination can occur without a legal foundation, however. Ever since Marshall's (1920) evocative phrase, "the secrets of industry are in the air," researchers have focused on the productive relations that have typified some craft- and technology-based communities (Sabel and Zeitlin, 1997; Scranton, 1997). Foray and Perez (2006) emphasized the political factors that sustained an open technology in the eighteenth century silk industry in Lyon, France. Local elites were most concerned with the economic vitality of the region and the municipal government gave grants to inventors to support the sharing of new knowledge with the entire community of silk makers. They argue that although collective invention increased the risk of conflict, such disputes were dampened by common competitive pressures and the development of an ethos that encompassed contribution. Lamoreaux, Raff, and Temin observed that in the era before the vertically integrated firm, "business people. . .industrial communities interacted socially as well as economically, and the resulting multidimensional relationships facilitated cooperation for purposes besides production."

Similarly, studies of contemporary high-tech clusters uncover various modes of private governance that create collective benefits. Perhaps most notably, interfirm job mobility, high rates of firm formation, and an ample supply of skilled technical labor are common to most thriving clusters (Bresnahan and Gambardella, 2004; Saxenian, 1994). Focusing more on the emergence of clusters as opposed to their persistence, Powell et al. (2009) analyze the three regions in the United States where biotech took off, along with eight locales with considerable endowments and resources where companies were created but clusters have not developed. They argue that participants have to take steps to pursue new technological trajectories well in advance of full knowledge of their potential. Such exploration, in the biotech case, was assisted by anchor tenants—public research organizations in Boston; venture capitalists, first-generation companies that encouraged scientists to publish, and university tech transfer offices committed to relationship building rather than revenue maximization in the San Francisco Bay Area; and nonprofit research institutes and a young university in San Diego—that emphasized open science, transparency in relationships, and a willingness to transpose practices and recombine them across the public, private, and nonprofit sectors. In regions where biotech did not grow, the dominant local anchors reinforced existing practices, acting as 800 lb. gorillas rather than catalysts.

Summary: The governance of collective efforts commonly begins with a shared ethos or compatible goals among participants. Often, the establishment of effective governance is often aided by widespread use of information technology, and organizational innovations that enable geographically distributed collaboration and address the intellectual property interests of participants. Once knowledge accumulates to the stage that tangible outcomes are possible, private interests may take hold and commercialize particular streams of technology that emerge from collective invention. The growing involvement of universities and associations in recent episodes of collective invention may alter this trajectory, however, keeping technology collective for a longer period of time. Finally, studies of regional science and technology clusters provide insights into how collective efforts can harness the energies of a diverse community of participants. For instance, a key ingredient appears to be the use of governance systems and relational contracting early in the development of a technology that can provide an interactional template that serves to promote collective invention.

5. Interindustry heterogeneity

Despite the increase in collective invention in recent decades, there remain many reasons for persistent interindustry differences in its form and prevalence (Breschi et al., 2000; Klevorick et al., 1995; Levin et al., 1987). The longevity of collective invention in many industries also suggests that the need to both explore and exploit rapidly expanding technological opportunities has reshaped intellectual property choices. In some instances, collective invention has led to appropriability strategies that serve the technological regime as well as the individual firm. In other words, rather than being singularly focused on immediate sources of revenue, firms may strive for the success of their interdependent R&D activities, at least during times of technological ferment.

5.1. Nature and relevance of collective knowledge

Nelson (1982: p. 468) suggested that in “industries marked by rapid sustained technological progress a good deal of the *logy* has been created within the firms themselves, yet made public.” When knowledge is created by firms, as opposed to universities or individuals, it is at a point of “maturity” that makes it more likely to be relevant to other firms. In addition, the fact that firms in an industry openly share knowledge suggests that they are confident they have both organizational and legal means to pursue and protect these ideas. Nonetheless, industries differ markedly in the extent to which knowledge from one firm is complementary to the knowledge of another. Individuals require a common technical foundation in order for inventions to be easily learned and improved upon. Technical knowledge must be compatible across firms in order for collective invention to quickly take hold.

The variety of scientific sources underlying a technology can have a large impact on the speed of search (Klevorick et al., 1995). Collective invention provides a means for coping with this diversity of sources. For example, Cohen et al. (2002) report that the chemicals industry draws upon university research in chemistry and chemical engineering, whereas semiconductor firms draw upon a wider range of academic disciplines, including chemistry, physics, computer science, materials science, chemical engineering, electrical engineering, mechanical engineering, and math. The variety of scientific sources underlying a technology has a large effect on the number of useful directions that can be explored and the speed at which they can be pursued.

The development of biotechnology, with its extensive reliance on interorganizational collaboration in the R&D process, has been widely studied by scholars interested in innovation. Scientists from competing firms and public research organizations often share the "logy" (i.e., the theoretical understanding). Learning about a theoretical principle, or the basic idea of how a technique works, is often enough to stimulate search by a variety of firms. Diffusion of theory and appropriation of technique allows firms to search a richer opportunity landscape, while still profiting from their investments in research and development.

In order to provide an empirical basis for our discussion, we return to our analyses of five technological classes over two time periods. Table 6 offers insight into how concentrated the innovation process is across fields and over time. The first and third columns are counts of the number of organizations that account for 60% of the total patents in a specific technology classification. Columns two and four are the total number of patents filed in that classification during each time period. Only aerospace has seen a decline and become more concentrated. In the four other technology classes, the number of organizations has grown, burgeoning dramatically in biotech and pharmaceuticals.

5.2. The interorganizational decomposability of problems

The technical characteristics of problems faced by organizations also have important implications for organizational coordination and design. Technical problems sometimes "suggest" a search strategy (Hughes, 1983; Rosenberg, 1976; Vincenti, 1990). The nature of the knowledge underlying a technical problem may provide some clues about how to divide the process of search within or across organizations. The organization of innovative labor is partly driven by the complexity and decomposability of a problem.

Table 6
Number of organizations responsible for 60% of patents in selected patent classes

	1975–1979		2001–2005	
Patent class	Orgs. at 60th percentile	Total # of patents	Orgs. at 60th percentile	Total # of patents
Aerospace	81	1118	69	1619
Biotechnology	103	6533	261	22,881
Optical Comm.	24	511	40	6217
Pharm. Chem.	130	2467	655	7212
Semi. Mfg.	16	5630	24	79,069

Decomposability is defined as the ability to break apart a problem into subproblems that can be worked on independently (Simon, 1962). Most problems in organizations are not truly decomposable, but they are nearly so, suggesting that they can be divided up and coordinated without adversely affecting the final outcome. For example, the installation of a video card or a faster processor can cause overheating in a laptop. To prevent this, engineers must design in additional heat sinks and fans, making the laptop larger and heavier. Thus, the choice of one component constrains the selection of other components and the final design of the laptop, but this does not preclude the division of tasks in the organization. These diverse tasks can be performed by different organizations, with only modest need for common knowledge. Computer makers can buy standardized components from the same set of firms. Thus, the extent and complexity of technical interdependencies that need to be addressed throughout the search process determine the kinds of organizational arrangements suited to a technical problem (Nickerson and Zenger, 2004; Rivkin and Siggelkow, 2003).

Another aspect of search coordination that differs across technological regimes is the predictability of outcomes from search activities. Brusoni et al. (2001) study how and why system design problems are divided among groups based on the predictability and level of interaction among aircraft engine components. They find that predictable product interdependencies and an even rate of component change lead to independent entities that interact via market mechanisms. Predictable interdependencies and an uneven rate of change give rise to an interdependent sector of search and coordination via systems integration (e.g., the hard disk industry, in which manufacturers design the architecture and purchase components with standardized interfaces). When the product interdependencies are unpredictable but the rate of change is even, Brusoni et al. (2001) suggest that relatively independent organizations with coordination through systems integration will arise (e.g., the automotive industry, in which the architecture dictates some parts of the component design). When interdependencies are unpredictable and the rate of change is uneven, firms are more likely to vertically integrate (e.g., many mobile handset makers also manufacture infrastructure products such as base stations in order to exploit the highest end capabilities possible).

5.3. Feasibility of individual versus collective appropriability

Collective invention depends upon specific appropriability structures. The use of patents, trade secrets, complementary assets, and copyrights all have implications for both the degree of knowledge spillovers (improving technological opportunities for other firms) and the difficulty of circumventing barriers to using particular knowledge (Nelson, 2006). Because of their sequential influence on one another, opportunity and appropriability are inseparable in understanding the creation of fertile ground for collective invention.

The most pervasive influence of legal appropriability strategies on firm activities may lie in changing the costs and likelihood of pursuing particular technologies. Thus, many efforts at collective invention may in part seek to reduce the appropriability costs incurred by disjointed IP rights. Firms create paths of intellectual property reflecting their past and current research, which they can then either use to defend their products or as a tool to force competitors to cross-license. In some industries, there is no room for collective appropriability; hence firms may consciously avoid using the protected knowledge of their competitors in industries in which patents provide a key appropriability mechanism (Graham and

Sichelman, 2008; Lemley and Sampat, 2008). For instance, Lerner (1995) found that small biotechnology firms with high litigation costs actively avoid inventive activity in technology spaces that are associated with a large number of patents. Because these firms actively avoid the search paths of one another, it is unlikely they will engage in collective invention beyond peripheral or legally standardized aspects of their technologies.

In contrast, the paths of accumulated, legally claimed knowledge heavily overlap in the case of complex technology industries (Breschi et al., 2000; Hall and Zeidonis, 2007). Firms in industries with complex products cannot monopolize the intellectual property required for product development, nor can they realistically avoid infringing some of their competitors' patents (Cohen et al., 2000: pp. 13–14). Thus these firms are forced to cross-license due to "mutually assured destruction," which encourages negotiations and deters lawsuits (Allison et al., 2004). Because large patent holders in complex industries engage in and often encourage collective invention, it appears that patent pools and cross-licensing may clear the road for participation in collective invention. Au6

Summary: We have posited some of the factors that account for the variation in the intensity of collective invention across industries. First, the number and quality of sources of technology opportunity vary by industry, so we should expect that turnover of sources, motivation to engage new sources, and ease of accessing new knowledge have implications for the possibility of collective invention. Second, some problems cannot be broken apart because they must be solved simultaneously by functionally diverse teams. These challenges are the least amenable to collective invention. Third, and very much related to the previous section on innovations in governance and organization, the long-run feasibility of appropriating returns from invention must be clear to motivate commitments at the organizational level to collective efforts.

6. Conclusion

The importance of collective invention has varied markedly across eras, locales, and technologies. We have emphasized the sharing of information across a network of participants as the central feature of collective invention. One notable point of departure between late nineteenth and early twentieth century examples and current ones is that in the earlier cases the participants were geographically concentrated, whereas in the present era this requirement for information exchange has relaxed, due to advances in both information technology and modes of governance.

Uncertainty surrounding the technical feasibility and economic viability of a technology create pressures upon firms, leading them to choose to carry out R&D activities internally, in tandem with parties facing similar constraints, or by sustained engagement with a wider community of practice. When universities and research institutes have a large hand in development of a technology, firms attempt to join in collective efforts. When firms create spillovers and incentives for outside organizations—such as universities and technical or research institutes—to pursue, the existing division of innovative labor serves to mold the set of future technological opportunities. In these circumstances, firms use collective invention as a means for obtaining data about the evolution of technology, which they employ to structure their research during times of regime emergence and stabilization. While this might appear to lead toward conservative technological ambitions, the story is not so straightforward. General awareness of uncertain requirements or trajectories can create the necessary space for scientists and engineers to collectively build the foundations for more radical technologies. It is in these times of change in technological regimes that a community ethos and broadly distributed participation characterizes collective invention.

The general lesson from our review of the diverse literatures we have drawn on is that collective invention is sparked when a new opportunity opens—either by an invention, the expiration of a patent, or general optimism about a technology but is accompanied by a lack of clarity about its possible trajectory. In this period of ferment, various participants emerge and often develop collective institutions—publications, workshops, standards, associations—that foster integration into a community of practice (Rosenkopf and Schilling, 2007; Rosenkopf and Tushman, 1998). As a flow of new inventions emerge, new firms appear, sensing opportunities. These new entrants' efforts to connect to the community act primarily as an "admission ticket" to access information that others possess (Powell et al., 1996). Over time, as technological uncertainty recedes, firms develop private R&D and focus on their own specific applications. Reliance on collective invention accordingly wanes.

This evolutionary view suggests a specific phase of technological evolution that marks the scope condition for collective invention. We concur that technological ferment is an enabling condition, but we are hesitant to accept that such a determinist position is the full story. In recent decades, we have seen collective invention efforts in both emerging fields—computers, software, biotech, and in sectors such as electronics where arms-length contracting among specialists employing standard technical interfaces was considered routine. Sturgeon (2002) describes the development of "modular production networks" among vertically specialized firms in the electronics field, and speculates that much closer collaboration in product design among independent firms is growing as products become more complex and less specialized. These contemporary examples suggest a wide range of efforts at collective invention that have as much to do with technical factors as the institutional arrangements in which they are addressed.

Recent developments highlight the dual elements in collective invention—such practices are promoted by both technological uncertainty *and* "situational particularities." Rather than to see collective invention as dictated solely by technological requirements, we also stress that it can emerge or be selectively adapted in different locales or branches of the same industry and across sectors. To the extent that social and political conditions facilitate connections to groups of inventors beyond their own, there will often be advantages that accrue to those who have early access to ideas and interpretations.

Yet, we have had little to say about the genesis of collective invention: the question of motivation. We have only speculated that motivation to improve a technology often leads individuals to find ingenious organizational means for carrying forth their ideas and sharing them with others. While the literature has much to say about the varieties of collective invention, its emergence remains understudied. Such efforts, while requiring an historian's skills and an economist's or sociologist's toolkit, are challenging, but nonetheless would offer critical insights into the individual and collective dynamics that spawn novelty.

Our charge has been to illuminate how diverse types of organizations engage in common problem solving on a technological frontier; the next step is to identify how these networks are composed of individual inventors. Deeper understanding of how networks of inventors form and how these individuals decide what to disclose to one another would offer insight into the viability of collective invention in times of rapid technological progress.

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