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Unmasking the interplay between technology evolution and R&D collaboration: Evidence from the global semiconductor manufacturing industry, 1990–2010

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ABSTRACT

Technological progress in an industry is enabled by the collective R&D efforts of suppliers, users and research organizations. In this study, we explore how the pattern of R&D collaboration within the industry community evolves over the technology life cycle. We propose that as the technology evolves from an initial emergence stage to subsequent stages of growth and maturity, there is a corresponding change in the opportunities and challenges confronting industry participants. This results in a shift not only in the relative propensities for internal and collaborative R&D, but also in the distribution of the different types of collaborative interactions involving research organizations, suppliers and users. The context for the study is the global semiconductor manufacturing industry from 1990 to 2010. During this period, the industry experienced exponential technological progress that was fueled by the deep ultraviolet (DUV) manufacturing technology. We draw upon a comprehensive archival dataset of more than 12,000 articles presented in industry technical conferences to analyze the pattern of collaborative R&D during the emergence, growth and maturity stages of the DUV technology. The observed trends in the semiconductor manufacturing industry point to intriguing shifts in the efforts and interactions among suppliers, users and research organizations as they collectively push the technology envelope forward.

1. Introduction

Technological progress is an important driver of economic growth. The trajectory of progress has often been conceptualized using a life cycle model in which a technology evolves from an initial period of infancy and experimentation, through a stage of rapid and cumulative growth, and into a period of relative maturity where performance approaches technical limits. This model has been effectively used to characterize evolutionary processes that underlie technological progress and derive implications for firm strategies and industry evolution (Sahal, 1981; Dosi, 1982; Foster, 1986; Anderson and Tushman, 1990; Nelson, 1994; Utterback, 1994). Within this literature stream, focal firms are typically portrayed as the locus of innovation such that it is their autonomous R&D efforts that drive progress over the technology life cycle (e.g., Dosi, 1982; Foster, 1986; Christensen, 1992; Schilling, 2008).

In parallel, the literature stream on networks of innovators has considered the industry's locus of innovation as being significantly broader, and comprised of a collaborative network of suppliers, users and research organizations, who offer distinct but complementary resources to push the technology forward (Freeman, 1991; Rosenberg and Nelson, 1994; Hagedoorn, 1995). While scholars have generated valuable insights regarding the motivations and implications of such collaborations (see Powell and Grodal (2005) for an extensive review of this literature), they have devoted less attention to the evolutionary processes over the course of the technology's life cycle that shape the context for R&D collaboration (Ahuja et al., 2011). Hence, these related literature streams on their own have focused on different aspects of the phenomenon of technological innovation and typically treated the focal innovators and the innovation context in general terms. As a result, they have been unable to offer any specific guidance concerning how the industry's locus of innovation, comprised of a multiplicity of actors and their collaborative interactions, evolves over the technology life cycle.

One possible reason for this gap is the nature of empirical evidence that has been used to study R&D collaboration. As noted by Hagedoorn (2002), a large proportion of empirical research has relied upon survey-based cross-sectional data, and this has severely limited our ability to generate longitudinal insights. Moreover, while efforts to develop longitudinal databases, such as the widely cited MERIT-CATI database, have resulted in a detailed account of

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intertemporal trends on industry-level differences, internationalization, and the different forms of contracting, these databases are limited to the formal inter-firm arrangements that are reported in the popular or industry press. Hence, they do not capture informal arrangements among firms or between firms and universities, which represent a large proportion of R&D collaboration within an industry (Link and Bauer, 1989; Freeman, 1991; Hall et al., 2003).[2]

The primary contribution of this study is to draw upon a newly assembled dataset based on articles presented in industry technical conferences to identify how the pattern of collaborative R&D among suppliers, users and research organizations evolves over the technology's life cycle. Following the extant literature, we consider three distinct types of collaborative interactions within the industry's R&D network: science-based collaborations involving research organizations (i.e., universities and dedicated research institutes), technology integration-based collaborations between suppliers and users, and co-opetitive collaborations among rivals (Miotti and Sachwald, 2003; Belderbos et al., 2004; Powell and Grodal, 2005). We propose that as the technology evolves from an initial emergence stage to subsequent stages of growth and maturity, there is a corresponding change in the opportunities and challenges confronting industry participants. This results in a shift not only in the relative propensities for internal and collaborative R&D, but also in the distribution of the different types of collaborative interactions.

The context for the study is the global semiconductor manufacturing industry from 1990 to 2010. During this period, the industry witnessed rapid economic growth and achieved remarkable exponential progress along the trajectory referred to as Moore's Law. This progress was fueled by the emergence of deep ultraviolet (DUV) manufacturing technology in the late 1980s and its evolution over the subsequent two decades (Iansiti, 1998; Martin and Salomon, 2003; Kapoor and Adner, 2007). We draw upon a comprehensive archival dataset of more than 12,000 articles presented in industry technical conferences. The dataset not only characterizes the R&D efforts expended toward the DUV technology over its life cycle, but also captures the collaborative interactions among semiconductor manufacturers (i.e., users), their suppliers and research organizations.

The findings point to intriguing shifts in the efforts and interactions among the different types of actors as they try to keep pace with Moore's Law. During the emergence stage of the DUV technology, R&D efforts within the industry community had a somewhat stronger internal orientation and the collaborative R&D efforts were directed mainly toward science-based collaboration with research organizations. As the technology evolved through the growth and maturity stages, the R&D efforts became increasingly collaborative and, while science-based collaborations continued to be prevalent, the distribution of collaborative interactions evolved from predominantly science-based to increasingly technology integration-based. Moreover, the industry's technology integration-based collaborative efforts shifted from principally vertical collaboration between upstream suppliers of technological inputs and downstream semiconductor manufacturers to increasingly horizontal collaboration between upstream suppliers of complementary technological inputs (e.g., between suppliers of manufacturing materials and equipment). While the relative intensity of co-opetitive collaboration among rivals remained somewhat stable, an exploration of the structure of the collaboration network suggested a gradual evolution in co-opetitive collaboration from a learning orientation (i.e., using collaboration to learn and accumulate knowledge) to an increasingly resource pooling orientation (i.e., sharing R&D resources to generate economic efficiencies).

Although we are cautious in generalizing our findings in light of examining a specific industry, the study illustrates how technological progress is sculpted by a multiplicity of innovation actors, and how the pattern of R&D collaboration among these actors evolves over the technology's life cycle. In doing so, it provides an example of how the literature streams of technology evolution and networks of innovators inform one another, and makes a case that their joint consideration presents a valuable line of inquiry for innovation scholars. Our analyses offer important guidance for managers concerning the need to reconfigure their collaborative R&D efforts, both over the course of the technology's life cycle and when the industry transitions from an old to a new technology. The results also reinforce the significance of universities and suppliers in facilitating technological progress in addition to the focal innovators (e.g., semiconductor manufacturers), and suggest an ongoing need to adjust policies so as to ensure that progress within an industry or a region is not stifled by misaligned incentives that may hinder different types of R&D collaboration.

2. Technology evolution and the pattern of R&D collaboration

Technological progress is often characterized by an S-curve trajectory, through which improvement in a technology's performance is depicted as being a function of cumulative R&D effort expended (Foster, 1986; Christensen, 1992). Early in the life cycle, technological uncertainty is at its apex; the ensuing experimentation and exploration leads to performance progress that is slow and unpredictable (Tushman and Rosenkopf, 1992). As the technology is better understood and more widely diffused, the life cycle subsequently shifts to a period of rapid growth that is kindled by cumulative and incremental innovation (Dosi, 1982; Sahal, 1981). Life cycle maturity, while still a vital phase in a technology's progress (Harley, 1971; Henderson, 1995; Utterback, 1994), is often marked by diminishing performance returns to the R&D efforts expended.[3]

Progress within a technology trajectory is shaped by a multiplicity of innovation actors. These actors, who include suppliers, users, and research organizations, provide varied and complementary responses to move the technology forward (e.g., Dosi, 1988; Rosenberg and Nelson, 1994; Henderson, 1995). Correspondingly, this underscores the importance of collaboration among these actors (e.g., Freeman, 1991; Hagedoorn, 2002; Powell and Grodal, 2005). While the overarching principle guiding the R&D collaboration is to achieve technical advances, the diversity of actors within the industry community points to important differences in the motivation underlying a given R&D collaboration (Belderbos et al., 2004; Hagedoorn et al., 2000; Miotti and Sachwald, 2003).[4]

Collaborations involving universities and dedicated research institutes are often aimed at solving problems of a more fundamental nature and involve basic research (Rosenberg and Nelson,

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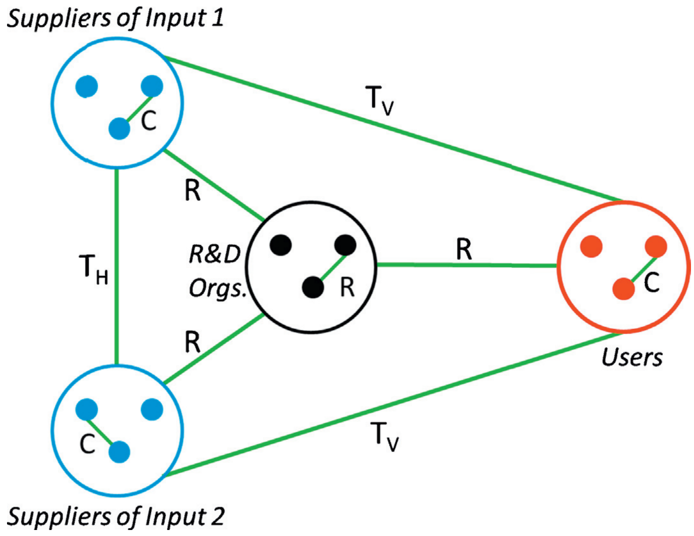
[2] For example, Link and Bauer (1989) found that among their sample of U.S. manufacturing firms that were active in R&D collaboration, over 90% of the collaborative partnerships were based on informal arrangements.

[3] Our focus is squarely on the technology life cycle, rather than on the product life cycle or the industry life cycle which operate at different levels of analysis (product life cycles are nested within technology life cycles, which in turn are part of industry life cycles).

[4] We define R&D collaboration as any voluntarily initiated collaborative exchange between organizations that involves finding solution to a known problem within a given technological context (e.g., Gulati, 1999; Hagedoorn, 2002). Our measure of R&D collaboration is based on the affiliation of authors of articles presented in industry technical conferences. As we elaborate in the methods section, this approach offers several advantages over traditional data sources to explore how the pattern of collaborative R&D efforts within an industry evolves over the technology's life cycle.



Type	Description
R	Science-based collaboration with R&D organizations
T_V	Vertical technology integration-based collaboration between users and suppliers
T_H	Horizontal technology integration-based collaboration between suppliers of complementary technological inputs (e.g., between suppliers of complementary inputs 1 and 2)
C	Co-opetitive collaboration between firms competing in the same product market (suppliers or users)

Fig. 1. Stylized representation of the types of R&D collaborations among suppliers, users and R&D organizations.

1994; Pisano, 1988). Such science-based collaborations provide firms with complementary research capabilities and opportunities to radically advance the technological frontier (Cohen et al., 1998; Meyer-Krahmer and Schmoch, 1998). Not only do universities offer access to basic scientific knowledge, but strategically structured agreements may also provide the university's partners with a first option on the rights to new discoveries made in the course of their joint R&D effort (Arora and Gambardella, 1990; Ham and Mowery, 1998).

Collaborations between users and suppliers are aimed at improving the technology's performance through coordinating changes to the suppliers' components and resolving technical bottlenecks for the users to realize the performance improvement. For brevity, we refer to these collaborations as technology-integration based collaborations as they entail the collaborative development and integration of components within the broader technological system (Hughes, 1983). Such collaborations could take the form of "vertical" collaboration between upstream suppliers and downstream users who work together to develop and integrate the components for the specific user (Clark and Fujimoto, 1991; Chesbrough, 1999; Appleyard, 2002). They could also take the form of "horizontal" collaboration between upstream suppliers of complementary components who coordinate their component R&D efforts so as to ensure that the technological components can be seamlessly integrated by the users (Mitchell and Singh, 1996; Kapoor, 2013a).[5]

Besides collaborating with research organizations and actors in the value chain, competing firms also collaborate with each other (Hamel et al., 1989). Co-opetitive collaboration is facilitated when competitors share an exceptionally strong interest in a research arena that is far upstream from commercialization (Miotti and Sachwald, 2003). Underlying such co-opetitive R&D collaborations are typically two distinct types of motivations (Sakakibara, 1997; Hagedoorn et al., 2000). First, firms may cooperate in order to learn and accumulate knowledge (e.g., Powell et al., 1996; Mowery et al., 1996). Second, firms may also partner in order to generate economic efficiencies (i.e., economies of scale, sharing costs, avoiding duplicate investments etc.) by pooling R&D related resources. Fig. 1 uses a simplified schema to illustrate these different types of collaborative relationships within an industry's R&D network.[6]

During the early emergence stage of the technology, the environment is characterized by high technological uncertainty, and R&D efforts are aimed at building absorptive capacity, accumulating knowledge and pursuing technical or scientific breakthroughs (e.g., Sahal, 1981; Dosi, 1982; Pisano, 1988; Cohen and Levinthal, 1990; Jiang et al., 2011). As experience is gained and the technology trajectory is solidified, R&D efforts during the growth stage evolve toward achieving cumulative advances in technical performance through improvements within the technological system (Rosenberg, 1982; Hughes, 1983; Christensen, 1992; Murmann and Frenken, 2006). Finally, as the limits to the technology's performance approach during the maturity stage, R&D efforts take the form of extending the performance of the technology in a highly resource constrained environment with compelling substitutes (Utterback, 1994; Henderson, 1995).

How might such an evolutionary process of technological change shape the pattern of collaborative R&D within the industry? Given the sustained intensity of interest surrounding collaborative R&D, it is easy to overlook the importance of in-house R&D efforts autonomously undertaken by organizations (e.g., Gambardella, 1992). Hence, we first consider the relative prevalence of internal and collaborative R&D, and we then elaborate on the changes in the different types of R&D collaborations over the technology's life cycle.[7]

The emergence stage of the technology represents a period of high technological uncertainty. Internal R&D efforts during this stage are likely to be critical in helping organizations develop

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[5] We note that firms may face important tradeoffs regarding efforts to maximize system performance and their own performance. These tradeoffs may affect both the intensity of efforts and the choice of the collaborating partner.

[6] Our categorization for the different types of collaborations is primarily based on the roles of the collaborating entities as shown in Fig. 1 in the paper. This is a typical approach in the R&D collaboration literature (e.g., Miotti and Sachwald, 2003; Belderbos et al., 2004; Powell and Grodal, 2005). The reference to collaborations involving research organizations (universities and dedicated research institutes) as science-based, and those between users and suppliers and between suppliers of complementary technological inputs as technology integration-based, have an intended functional characterization that is again guided by the literature (Hughes, 1983; Rosenberg and Nelson, 1994) – but is not the source of categorization.

[7] Note that in this study, due to data unavailability, we do not explicitly consider the firm's make-or-buy choice with respect to R&D (Pisano, 1990; Cassiman and Veugelers, 2006). Rather, our focus is on understanding how the pattern of collaborative R&D among the different types of actors evolves over the technology's life cycle.

absorptive capacity and generate knowledge about the new technology (Cohen and Levinthal, 1990). For example, Gambardella (1992) provides convincing evidence regarding how Eli Lilly, a long-established pharmaceutical firm, became a successful pioneer in biotechnology by undertaking significant in-house R&D. The existence of high technological uncertainty during the emergence stage also exacerbates the appropriability concerns and contractual challenges that are strong deterrents to collaborative R&D efforts (e.g., Pisano, 1990).

As the technology life cycle progresses, absorptive capacity is developed and uncertainty is resolved, increasing the benefits that accrue from collaborative R&D (e.g., Mowery et al., 1996; Lim, 2009). The resolution of uncertainty is both a result of R&D efforts by industry participants as well as exogenous events such as scientific discoveries that occur outside the specific technology and industry domain (Nelson and Winter, 1982). Furthermore, organizations have gained pragmatic experience in organizing for innovation cooperatively; overcoming hesitations from initial inexperience may be facilitated by confidence gained through their own direct involvement in cooperative R&D efforts (Hagedoorn, 1995), repeated positive interactions (Gulati, 1995) and by observing the successes of their peers (DiMaggio and Powell, 1983).

Thus, while there are clear benefits to be gained from both internal and collaborative R&D efforts throughout the technology's life cycle, the relative appeal of collaborative R&D markedly increases as experience is gained, absorptive capacity developed, and appropriability concerns subside. Therefore, we propose:

Hypothesis 1. R&D efforts within an industry will become increasingly collaborative over the technology life cycle.

While we expect a somewhat greater emphasis on internal R&D during the emergence stage of the technology, collaborative R&D still represents an important avenue for firms to access new and distant domains of knowledge, and generate breakthrough innovations (Pisano, 1988; Jiang et al., 2010). Science-based collaborations present an ideal opportunity for firms to accumulate knowledge while mitigating appropriability hazards. This is because universities and research institutes are more likely to possess knowledge that is distinct from suppliers, buyers and competitors, and their primary research-based role makes such collaborations less susceptible to opportunism, a concern that often characterizes collaborations with competitors, suppliers and buyers (Fey and Birkinshaw, 2005; Bercovitz and Feldman, 2007). Pisano (1988) described how firms in the pharmaceutical industry actively pursued science-based collaborations with universities and research institutes during the emergence of biotechnology. Similarly, Jiang et al. (2010) provided evidence regarding the benefits of collaborating with universities during the recent emergence of nanotechnology in the semiconductor industry.

As the technology life cycle progresses beyond the emergence stage, R&D efforts increasingly evolve toward pursuing cumulative advances within the now established technological constraints and interdependencies (Sahal, 1981; Dosi, 1982). Rosenberg (1963) identifies how technical progress in the face of such interdependencies results in "technical imbalances" requiring coordination and adjustments by users and suppliers before the progress can be realized. Hughes (1983) describes such a phenomenon shaped by uneven rates of improvement in technological components using the notion of "reverse salients."[8] Correcting such technical imbalances or reverse salients through technology integration-based collaborations among suppliers and users, while not easy, offers substantive benefits (e.g., Clark and Fujimoto, 1991; Mitchell and Singh, 1996; Chesbrough, 1999). For example, Hughes' rich description of the evolution of the electric power technology illustrated how the post-emergence period of the technology was characterized by extensive efforts by the industry community to correct reverse salients and ensure that the technology's performance continue to improve over its life cycle.

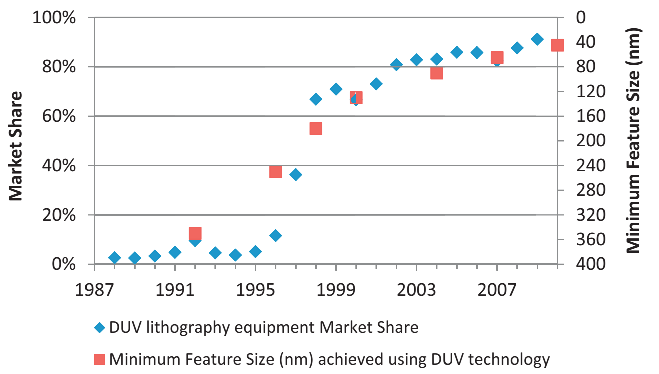

Fig. 2. Trends in the DUV lithography equipment market share and minimum feature size depicting the industry's trajectory of technological progress.

Data source: International Technology Roadmap for Semiconductors (ITRS) and VLSI Research Inc.

Therefore, we expect that during the emergence stage of the technology, R&D collaboration within an industry will be predominantly science-based. As technology evolves from emergence to growth and to maturity, the preponderance of science-based collaboration will give way to increasingly technology integration-based collaboration among users and suppliers as their conscious coordination becomes a necessity to pursue cumulative advances. Accordingly, we propose:

Hypothesis 2. Collaborative R&D within an industry will evolve from predominantly science-based collaboration during the emergence stage of the technology life cycle to increasingly technology integration-based collaboration during the growth and maturity stages of the technology life cycle.

Technology integration-based R&D collaborations may be oriented either vertically between users and suppliers or horizontally between suppliers of complementary components. In both cases, firms are working together to address Rosenberg's (1963) "technical imbalances" and Hughes's (1983) "reverse salients" arising from interdependencies in the technological system. In vertical collaboration, the user firm typically orchestrates the participation of the different suppliers; in horizontal collaboration, the different suppliers of complementary components proactively work together to resolve the imbalance on behalf of the users.

Vertical technology integration-based collaboration between users and suppliers ensure that the suppliers' components are efficiently and seamlessly integrated by the users (e.g., Clark and Fujimoto, 1991). These interactions allow for precise coordination of R&D efforts as required for a specific use, and are the primary driver of technology integration-based collaboration in many industries. As suppliers gain more experience over the technology life cycle, they develop the necessary architectural knowledge of how the different complementary components interact with each other (Henderson and Clark, 1990). For example, Prencipe

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[8] Borrowed from the military, a reverse salient refers to a section of an advancing front that has fallen behind; out-of-sync and lagging, the reverse salient slows the front, impairing its performance. This concept is aptly applied to technological progress, wherein Hughes explains that reverse salients within the technological system – uneven rates of improvement in technological components – act as the "brakes" of technological advancement.

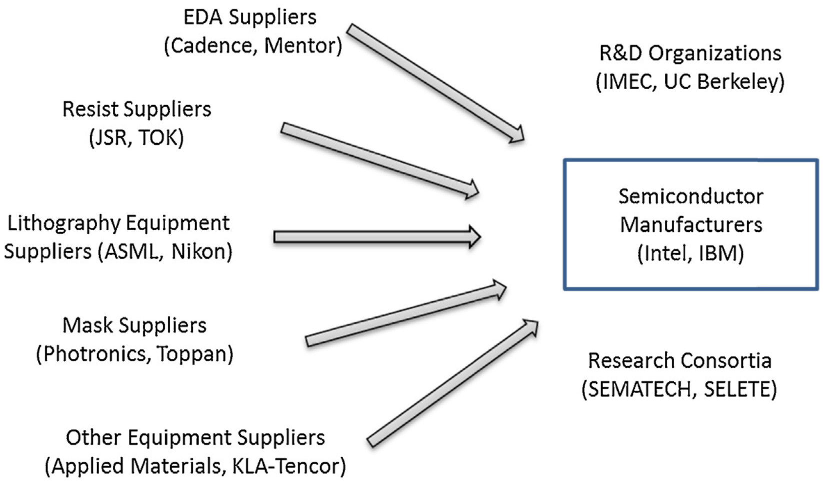

Fig. 3. Different sources of innovation in the semiconductor manufacturing industry. Organization names listed in parentheses are only representative of organizations in the industry.

(2000), Takeishi (2002) and Lee and Veloso (2008) provide evidence regarding component suppliers acquiring architectural knowledge about new technologies in the aerospace and the automotive sectors. These authors argue that architectural knowledge allows suppliers to assume some of the responsibilities underlying technology integration from users (e.g., car manufacturers), and to create greater value from their efforts.

The rewards for collaborating with other suppliers of complementary components toward technology integration are palpable (Mitchell and Singh, 1996; Kapoor, 2013a). The more seamless the components are within the focal technology, the fewer the challenges for the user in adopting it – which in turn enhances the competitiveness of the participating firms. Furthermore, once the technology moves beyond the emergence stage, the prevalence of a dominant design and industry standards makes it easier for suppliers of complementary components to collaborate with each other. Therefore, while collaboration between users and suppliers will be a key driver of technology integration throughout the technology life cycle, we expect a gradual increase in the relative intensity of collaboration between suppliers of complementary components from the emergence stage to the maturity stage of the technology:

Hypothesis 3. Technology integration-based R&D collaboration will evolve from predominantly vertical collaboration between users and suppliers to increasingly horizontal collaboration between suppliers of complementary components over the technology life cycle.

Finally, besides science-based and technology integration-based collaboration, the industry's R&D network also comprises co-opetitive collaboration among competitors. The motivation underlying co-opetitive collaborations may include learning from partners' distinct or complementary capabilities and generating economic efficiencies by pooling R&D resources with the partners (Sakakibara, 1997; Hagedoorn et al., 2000). Such collaborations provide an important strategic alternative for firms to manage progress throughout the technology's evolution (Powell et al., 1996; Hagedoorn, 2002). Hence, we do not expect the relative importance of co-opetitive collaboration to change over the course of the technology life cycle. However, given the distinct motivations of learning and resource pooling, it is possible that the motivation underlying co-opetitive collaboration may evolve over the course of the technology life cycle. We explore this pattern through supplementary network-based analysis after presenting our main results.

3. Collaborative R&D in the semiconductor manufacturing industry

We explore the interplay between technology evolution and the pattern of R&D collaboration in the context of the semiconductor manufacturing industry from 1990 to 2010. The industry's economic prominence, high R&D intensity, and the presence of a well-defined technological trajectory combine to present an ideal setting in which to examine the pattern of collaborative R&D over the technology life cycle. Technological progress in this industry is one of the most robust in the modern economy, with semiconductor manufacturers persistently reducing the size of the circuit and doubling the number of transistors in a semiconductor chip approximately every two years (Moore, 1995). From 1990 to 2010, the smallest circuit dimension (also referred to as minimum feature size) that semiconductor manufacturers could print decreased from 500 nanometers (nm) to 45 nm. This was enabled by the emergence of Deep Ultraviolet (DUV) lithography technology for semiconductor manufacturing in the late 1980s as a superior alternative to the existing I-line technology, and its subsequent evolution over the next two decades (Iansiti, 1998; Martin and Salomon, 2003; Kapoor and Adner, 2007). Fig. 2 plots the trend in the annual market share of DUV lithography equipment and the minimum feature size achieved by semiconductor manufacturers through using DUV technology.[9] While DUV lithography equipment was introduced in 1988, the technology was first implemented in production in 1992 to manufacture semiconductors with a minimum feature size of 350 nm. It was only in the timeframe of 1996 that the technology, now with a minimum feature size of 250 nm, started to gain market share. Since then, DUV technology has achieved rapid market growth and has continued to maintain its industry dominance. More recently, the industry has been transitioning from a matured DUV technology to Extreme Ultraviolet (EUV) technology that promises a minimum feature size smaller than 20 nm (Williamson, 2000; Lin, 2006). The EUV manufacturing equipment was introduced in 2010.

Underlying the industry's technological progress are R&D efforts by the different types of actors as illustrated in Fig. 3 (e.g., Henderson, 1995; Linden et al., 2000; Adner and Kapoor, 2010).

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[9] The information on minimum feature size using DUV technology was obtained from regularly published industry technology roadmaps by ITRS (www.itrs.net). The information on DUV lithography equipment market share data was obtained from VLSI Research Inc., a prominent industry consulting firm.

Complementary technological inputs from upstream suppliers of manufacturing equipment, materials and electronic design automation (EDA) software are integrated by semiconductor manufacturers into their production processes. Among the equipment suppliers are suppliers of lithography alignment equipment, as well as suppliers of metrology and processing equipment. The material suppliers include resist and mask suppliers. An attractive feature of the industry for the purpose of our study is that, due to the diversity and complexity of technological inputs, suppliers tend to be highly specialized (i.e., they manufacture a specific technological input such as the resist or the mask). This clear separation of firm boundaries with respect to technological inputs allowed us to make clear inferences regarding horizontal technology integration-based collaboration between suppliers of complementary technological inputs. In addition to suppliers and semiconductor manufacturers, R&D organizations are another important source of innovation in the industry. R&D organizations encompass both universities, such as University of California (Berkeley), as well as dedicated research institutes such as IMEC in Belgium. Finally, semiconductor manufacturers – in spite of their status as competitors – actually cooperate with each other through co-development alliances (e.g., Leiblein and Madsen, 2009) or through research consortia such as SEMATECH in the United States and SELETE in Japan.

3.1. Data

To investigate the pattern of collaborative R&D in the semiconductor industry, we assembled a novel dataset based on information in technical articles presented at industry conferences sponsored by SPIE, the primary professional association for semiconductor manufacturing.[10] Between 1990 and 2010, SPIE sponsored 147 global conferences in which a total of 12,834 articles were included. The technical conferences organized by SPIE have long served as an important avenue for actors in the industry to present outcomes of their technology development initiatives. These conferences are keenly followed by industry participants and are often discussed at length in trade journals (such as *Solid State Technology* and *EE Times*) and the business press. Moreover, the technical articles that are presented are typically updates on current projects; hence, this data source provides a contemporaneous account of industry's R&D efforts. The strong correspondence between SPIE conference data and the firms' collaborative R&D efforts was also confirmed to us by three industry veterans, who have also served as editors of the SPIE conference proceedings.[11]

This dataset affords significant, unusual advantages for our exploration of the interplay between technology evolution and the pattern of R&D efforts within an industry. To start, we are able to simultaneously identify both internal and collaborative R&D efforts over the DUV technology life cycle. We use the authors' affiliation information on an SPIE article to identify whether an article corresponds to internal or collaborative R&D, and to identify the type of collaboration.[12] While scholars have regularly used publicly reported alliance announcements (or databases such as SDC Platinum or MERIT-CATI that are created using these announcements) to identify pattern of collaborative R&D (e.g., Hagedoorn, 1995; Powell et al., 1996; Ahuja, 2000), this approach is particularly problematic for our analysis for two key reasons. First, a large proportion of R&D collaboration between firms as well as between firms and universities is not subject to public announcements (Hagedoorn et al., 2000). Second, public announcements seldom include information on the termination of alliances. Thus, while numerous scholars have skillfully leveraged alliance databases in their studies of R&D collaboration, the SPIE data offers us industry-wide comprehensiveness, and a contemporaneous account of internal and collaborative R&D efforts that these sources cannot provide.

Given the newness of the SPIE dataset, we took care to ensure its validity to answer our research question. We began by addressing the industry representativeness of the firms themselves, and confirmed through interviews with industry experts and through industry directories that all semiconductor manufacturers, their suppliers and research organizations pursuing R&D in lithography technology participate in SPIE conferences. We further verified with the experts that the technical articles presented at the SPIE conferences properly portrayed firms' internal and collaborative R&D activities. Although all SPIE submissions undergo a peer review process, rejections occur only infrequently (as confirmed to us in interviews with SPIE conference proceedings editors) and would result from clear violations of basic requirements, such as technical soundness, originality of research content, and being of a non-commercial nature.[13] To this end, it is also noteworthy that our SPIE dataset is unhindered by a "success bias" as it includes both articles that were presented and those that were displayed in the less advanced poster sessions at each SPIE conference included in our timeframe. As an important check regarding the appropriateness of SPIE conference articles as meaningful indicators of firms' R&D efforts, we compared, on an annual basis for several of the leading manufacturers and suppliers, the count of articles each firm presented with both their R&D expenditures, and also the number of their successful U.S. patent applications. Although these indicators are known to be noisy due to time lags and firm-level idiosyncrasies, we still found a very high correlation between them. For example, the correlation between the count of SPIE articles and R&D expenditures between 1990 and 2008 is 0.86 for Intel, a leading semiconductor manufacturer and is 0.94 for KLA-Tencor, a leading supplier of semiconductor manufacturing equipment. Similarly, the correlation between the count of SPIE articles and successful patent applications between 1990 and 2008 is 0.65 for Intel and is 0.80 for KLA-Tencor.[14] Lastly, as a final validity check regarding the use of the data to study industry's collaborative R&D efforts, we compared the inter-organizational collaborations indicated by the affiliation of authors of SPIE conference articles with the alliance relationships captured by SDC Platinum for three key industry players: ASML, Intel, and KLA-Tencor. For each of these firms, all of the SDC reported collaborations were captured by the SPIE conference dataset and, perhaps even more importantly, these collaborations were only a small subset of the collaborations identified in the

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[10] SPIE is a defunct acronym that originally stood for the Society of Photographic Instrumentation Engineers upon the group's formation in 1955. The society is now known as SPIE.

[11] There are a number of other technical conferences that are attended by engineers and scientists in the semiconductor industry. These conferences vary widely in their focus. Some are very broad in their scope. For example, the International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication (EIPBM) addresses a variety of technologies and applications (ranging from biology to solar energy) associated with the three primary energy beams (electron, ion and photon). Much more targeted are the technical conferences that focus on the domain of IC Design and semiconductor systems, which are dominated by IEEE. The semiconductor manufacturing domain is dominated by the SPIE conference.

[12] We note that several studies in the biopharmaceutical industry have also drawn on information on authors' affiliations in articles published in scientific journals to identify biopharmaceutical firms' R&D collaborations (e.g., Cockburn and Henderson, 1998; Gittelman and Kogut, 2003). In contrast to the scientists in the biopharmaceutical industry, engineers employed by the semiconductor manufacturers and suppliers frequently present at SPIE conferences but only seldom publish in the scientific journals.

[13] The details regarding SPIE's manuscript polices and review process are available at http://spie.org/x14099.xml (accessed 12.04.13).

[14] The somewhat lower correlation for Intel can be explained by the fact that SPIE conference articles represent Intel's R&D efforts in semiconductor manufacturing whereas patents represent Intel's R&D efforts in both semiconductor manufacturing and Integrated Circuit (IC) design.

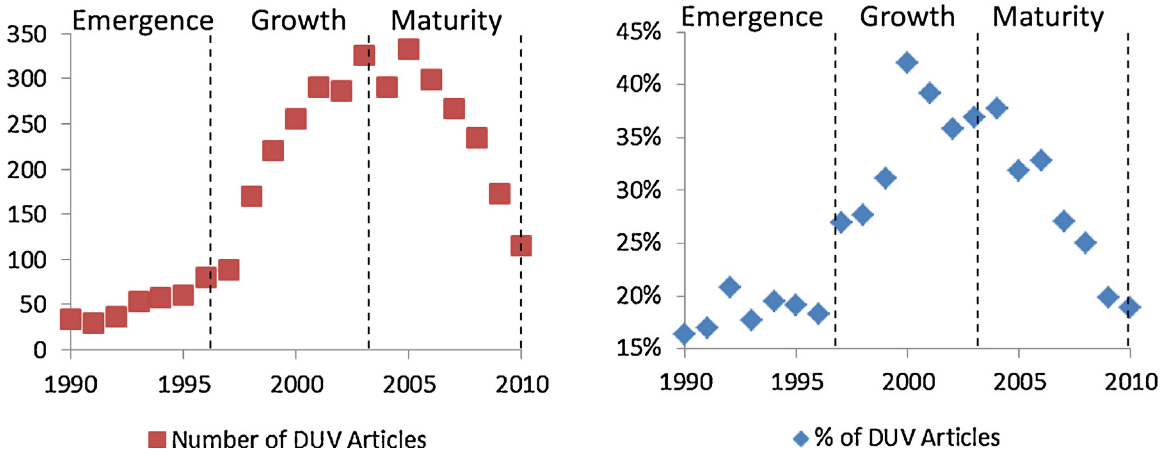

Fig. 4. Trends in the number and percent of DUV technical articles presented in SPIE conferences.

SPIE dataset. The above validity checks regarding the efficacy of our dataset gives us confidence in our analysis.

The complete list of 1571 unique firms and research organizations participating in the SPIE conferences from 1990 to 2010 was ascertained through the careful, extensive data cleaning efforts of several research associates. When classified by role type, 126 of these firms are semiconductor manufacturers, 740 are suppliers, 696 are research organizations, and 9 are research consortia. Firm roles were hand coded and assignments were made one-by-one based upon industry directories obtained from VLSI Research and SEMI as well as through confirmatory searches of company websites.

In order to identify SPIE conference articles that represent R&D efforts in DUV technology, we used a keyword approach (e.g., Adner and Kapoor, 2010). We conducted several interviews with industry experts to understand the evolution of the DUV technology and to develop a list of scientific keywords that can be used to categorize DUV-based technical articles. The keywords were: "DUV," "Deep Ultraviolet", "Deep UV", different wavelengths within the DUV spectrum ("248", "193", "157"), different sources of DUV energy ("KrF," "ArF," "F2") and "immersion." An article was categorized as being a DUV-based article if at least one of the keywords appeared in either the title or in the abstract. This procedure yielded a total of 3702 articles written by authors from 569 firms and research organizations. Fig. 4 plots the trend in the total number and the percentage of DUV articles presented at SPIE conferences. The pattern, as elaborated below, is very consistent with the trend in the semiconductor manufacturers' adoption of the DUV technology reported in Fig. 2. This provides an important validity check for the categorization procedure.[15]

3.2. Measures

3.2.1. Dependent variables

In Hypothesis 1, we predicted changes in the extent of collaborative R&D. Our dependent variable (*Collaboration*) takes a value of 1 if an article is written by authors affiliated with different organizations and 0 if it is written by authors from the same organization. Hypotheses 2 and 3 predict changes in the different types of collaborations and hence, the level of analysis is a collaborative relationship on an article. We consider any collaborative relationship with an R&D organization (i.e., a university or a dedicated research institute) on an article as a *Science-based* collaboration. Collaborative R&D efforts with respect to technology integration in the industry entail vertical collaboration between semiconductor manufacturers and their suppliers in order to integrate the technological inputs into the semiconductor manufacturing process (e.g., Chesbrough, 1999; Appleyard, 2002). Suppliers of complementary inputs also pursue technology integration efforts by collaborating with each other. Collaborations between a semiconductor manufacturer and a supplier or between two suppliers of complementary inputs (e.g., between a supplier of mask material and a supplier of EDA software) were identified as *Technology Integration-based* collaborations. To explore Hypothesis 3, we identified the collaborative relationship between suppliers of complementary inputs as *Horizontal Technology Integration-based* collaboration. 70% of all collaborative articles exhibited a dyadic collaborative relationship such that they were written by authors affiliated with two different organizations. For the remaining articles with more than two collaborative organizations, we coded each pair of collaborative relationships in the analysis such that a given article can have more than one type of collaboration. For example, a collaborative article with four different author affiliations, which include a semiconductor manufacturer, two different suppliers of complementary inputs and a research organization will be classified as having a science-based collaboration, a vertical technology integration-based collaboration and a horizontal technology integration-based collaboration. [16]

3.2.2. Independent variables

Our predictions concern how the pattern of collaborative R&D evolves over the emergence, growth and maturity stages of the technology life cycle. Accordingly, we categorize whether a given DUV article corresponds to R&D effort during the emergence, growth or maturity stages of the technology life cycle. As shown in Fig. 2, DUV technology was introduced in 1988, but it was not until 1992 that DUV was first implemented in manufacturing of semiconductors with a minimum feature size of 350 nm (NTRS, 1994). Only after 1996 did the DUV technology start to achieve significant performance improvement and market share growth, resembling a shift from the emergence to the growth stage. This parallels the trend in Fig. 4, wherein the number and percentage of DUV articles suggested a relatively low level of DUV R&D in the industry from

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[15] Articles in SPIE conferences also capture Industry's R&D efforts toward general productivity improvements as well as toward other established and emergent manufacturing technologies. This explains the somewhat lower peak value of 42% of all articles as DUV articles in the year 2000.

[16] 23% of collaborative articles are triadic and 5% are tetradic (i.e. authors for a particular article were affiliated with four different organizations). The results are robust to only including articles that exhibit dyadic collaborative relationship.

Table 1
Variables and their descriptions.

Variables	Description
Dependent variables	
Collaboration	Indicates whether the article was written by authors from different organizations (=1) or the same organization (=0). Used with Hypothesis 1.
Science-based collaboration	Set equal to 1 when the collaboration involves an R&D organization. Used with Hypothesis 2.
Technology integration-based collaboration	Set equal to 1 when the collaboration is between a semiconductor manufacturer and a supplier or between two suppliers of complementary inputs. Used with Hypothesis 2.
Horizontal technology integration-based collaboration	Set equal to 1 when the collaboration is between two suppliers of complementary inputs. Used with Hypothesis 3.
Independent variables	
Emergence stage	Set equal to 1 if the article was presented in a conference during the emergence stage of the DUV technology life cycle (1990–1996)
Growth stage	Set equal to 1 if the article was presented in a conference during the growth stage of the DUV technology life cycle (1997–2003)
Maturity stage	Set equal to 1 if the article was presented in a conference during the maturity stage of the DUV technology life cycle (2004–2010)
Control variables	
Number of R&D organizations	Number of R&D organizations active in DUV technology in a given year
Number of suppliers	Number of suppliers active in DUV technology in a given year
Number of manufacturers	Number of semiconductor manufacturers active in DUV technology in a given year
US affiliation	Set equal to 1 when any of the organizations associated with the observation are headquartered in the US
Europe affiliation	Set equal to 1 when any of the organizations associated with the observation are headquartered in Europe

1990 to 1996 followed by a period of rapid growth. Hence, we consider the articles presented from 1990 to 1996 as corresponding to R&D efforts during the *Emergence Stage* of the DUV technology.[17] The relative stabilization of technology's performance improvement as measured by minimum feature size in combination with a decreasing percentage of DUV technology articles after 2004 suggests an onset of the DUV technology's maturity and a reorientation of the industry's R&D efforts toward the new emerging technology, EUV. We therefore categorized articles presented during the 7-year period from 2004 to 2010 as corresponding to efforts during the *Maturity Stage* of the DUV technology life cycle.[18] Articles presented in the intermediate period (1997–2003) between emergence and maturity stages were considered as evidence of industry's R&D efforts during the *Growth Stage*.[19]

3.2.3. Control variables

We included a number of industry- and firm-level control variables. The observed pattern of collaboration may be influenced by the collaboration opportunity within the industry at a given period. To account for this possibility, we control for the *Number of R&D Organizations*, *Number of Suppliers*, and *Number of Manufacturers* active in the DUV technology in a given year. We also control for the geographic location of each article's authoring organizations. *US Affiliation* takes a value of 1 if any of the authors is affiliated with an organization headquartered in the United States; likewise, *Europe Affiliation* is set to 1 if any of the authors is affiliated with an organization headquartered in Europe. Given the high density of manufacturers, suppliers, and research organization in these regions, we expect that organizations located in the US and Europe to have a greater propensity to collaborate. Table 1 provides a brief summary of the variables using in the analysis.

3.3. Descriptive trends

Table 2 provides the trend in the percentage of collaborative articles during the emergence, growth and maturity stages of the DUV technology. During the emergence stage, 33% of all articles were a result of collaborative efforts between two or more organizations. This ratio increased to 43% during the growth stage and to 48% during the maturity stage. Hence, the trend provides some suggestive evidence that R&D efforts within the semiconductor manufacturing industry become increasingly collaborative over the DUV technology life cycle (Hypothesis 1). Note that while we observe a decreasing trend in the proportion of articles written by authors from the same organization, these internally oriented R&D efforts still represent more than half of all articles. Hence, while firms are increasingly pursuing collaborative R&D, they continue to invest in their internal R&D efforts. Such efforts not only

Table 2
Trends in the extent of collaboration on DUV articles.

	% of articles that are collaborative (total articles)		
	Emergence stage	Growth stage	Maturity stage
Industry	33%(352)	43%(1637)	48%(1713)
Manufacturers	32%(192)	50%(762)	59%(780)
Suppliers	43%(134)	56%(882)	58%(1077)

Table 3
Trends in the type of collaboration on DUV articles.

	% of collaborative articles[a]		
	Emergence stage	Growth stage	Maturity stage
Science	64%	41%	39%
Technology integration	28%	51%	55%
Vertical technology integration	27%	42%	41%
Horizontal technology integration	2%	15%	20%
Co-opetitive	21%	21%	17%

[a] Note that the totals for the respective collaboration categories within a stage are in excess of what may be expected. This is because of articles that had more than two collaborating organizations and that may represent different types of collaborations (e.g., Science and Technology Integration) within the same article.

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[17] Ideally, we would have preferred to also include DUV articles presented before 1990. However, our dataset was limited by the availability of information for the earlier conferences in the SPIE digital library.

[18] We note that while we characterize this period as the maturity stage, we do not imply that maturity corresponds to technology's stagnation. We expect and find that the maturity stage is indeed characterized by significant R&D efforts by industry participants which have enabled them to extend the performance of the DUV technology. In that respect, the maturity stage could perhaps be better referred to as the "post-growth" stage.

[19] While we identified three symmetric 7-year SPIE conference windows to study emergence, growth and maturity stages, we explored the robustness of our findings by first shrinking and then expanding each of the temporal windows by two years. The results of these robustness checks were very similar to our reported findings.

Table 4
Descriptive statistics and correlations for (a) all DUV articles and (b) for DUV collaborative articles.

(a)

		Mean	SD	1	2	3	4	5	6	7
1	Collaboration	0.46	0.50							
2	Growth stage	0.44	0.50	−0.01						
3	Maturity stage	0.46	0.50	0.06*	−0.83*					
4	No. R&D org.	35.21	9.33	0.07*	0.08*	0.37*				
5	No. suppliers	61.57	18.48	0.07*	0.16*	0.27*	0.86*			
6	No. manufacturers	27.24	6.01	0.08*	0.28*	0.16*	0.85*	0.87*		
7	US affiliation	0.49	0.50	0.31*	0.07*	−0.08*	−0.04*	−0.02	−0.02	
8	Europe affiliation	0.36	0.48	0.13*	−0.08*	0.10*	0.05*	0.04*	0.03*	−0.25*

(b)

		Mean	SD	1	2	3	4	5	6	7	8	9
1	Science	0.41	0.49									
2	Technology integration	0.52	0.50	−0.55*								
3	Horizontal technology integration	0.16	0.37	−0.22*	0.42*							
4	Growth stage	0.44	0.50	−0.01	−0.01	−0.03						
5	Maturity stage	0.50	0.50	−0.05*	0.06*	0.08*	−0.88*					
6	No. R&D org.	35.91	8.38	−0.07*	0.11*	0.06*	0.03	0.30*				
7	No. suppliers	62.90	17.00	−0.11*	0.13*	0.08*	0.14*	0.16*	0.83*			
8	No. manufacturers	27.72	5.41	−0.10*	0.12*	0.08*	0.26*	0.04	0.81*	0.85*		
9	US affiliation	0.66	0.47	0.03	0.10*	0.01	0.06*	−0.12*	−0.10*	−0.08*	−0.07*	
10	Europe affiliation	0.42	0.49	0.09*	0.08*	0.12*	−0.09*	0.10*	0.00	−0.01	−0.00	−0.11*

(a) $^{*}p < 0.05$, $N = 3702$ articles.
(b) $^{*}p < 0.05$, $N = 1717$ articles.

help firms develop knowledge but also build absorptive capacity to learn from their collaborative R&D efforts (Cohen and Levinthal, 1990; Mowery et al., 1996). We also explored the differences in the pattern of internal and collaborative R&D between semiconductors manufacturers and suppliers. Of the articles written by authors from semiconductor manufacturing firms, the proportion of collaborative articles increased from 32% in the emergence stage to 50% in the growth stage to 59% in the maturity stage. The proportion of collaborative articles written by authors from supplier firms increased from 43% in the emergence stage to 56% in the growth stage to 58% in the maturity stage. Hence, the evolution in the relative emphasis toward collaborative R&D seems to be more pronounced for semiconductor manufacturers than for suppliers.

Beyond the observed trend of increasing collaboration, we also observed changes in the pattern of collaboration. Table 3 provides a distribution of the different types of collaborations during the emergence, growth and maturity stages of the DUV technology. Science-based collaborations dominate the collaborative R&D efforts in the industry during the emergence stage of the technology, with 64% of all collaborative articles on DUV technology involving R&D organizations. As argued in Hypothesis 2, the distribution of collaboration shifts from predominantly science-based

Table 5
Logistic regression results for the effect of DUV technology life cycle on the extent and pattern of R&D collaboration.[a]

	(1) Dependent variable	(2)	(3)	(4)
	Collaboration (H1)	Science-based collaboration (H2)	Technology integration-based collaboration (H2)	Horizontal technology integration-based collaboration (H3)
Growth stage	0.447**	−1.088***	0.765**	2.398***
	(0.218)	(0.317)	(0.327)	(0.855)
Maturity stage	0.633***	−1.479***	1.014***	2.767***
	(0.227)	(0.327)	(0.335)	(0.852)
# R&D organizations	−0.005	0.056***	−0.020	−0.043**
	(0.010)	(0.014)	(0.014)	(0.022)
# Suppliers	−0.002	−0.015**	0.015**	0.001
	(0.005)	(0.007)	(0.007)	(0.011)
# Manufacturers	0.024	−0.039*	0.015	0.022
	(0.015)	(0.022)	(0.022)	(0.035)
US affiliation	1.756***	0.002	0.418***	0.090
	(0.104)	(0.129)	(0.127)	(0.191)
Europe affiliation	1.519***	0.530***	0.395***	0.019
	(0.111)	(0.128)	(0.126)	(0.192)
Constant	−2.677***	0.786**	−2.042***	−3.981***
	(0.227)	(0.331)	(0.346)	(0.894)
Log likelihood	−2050.62	−1001.16	−1036.24	−423.22
Chi-square	868.96***	242.85***	185.56***	259.65***
Articles	3604	1652	1629	891

Models 1–3 include manufacturer fixed effects. Model 4 includes fixed effects for the type of supplier. Standard errors in parentheses.

[a] The omitted category is the emergence stage.

* Significant at 10%.

** Significant at 5%.

*** Significant at 1%

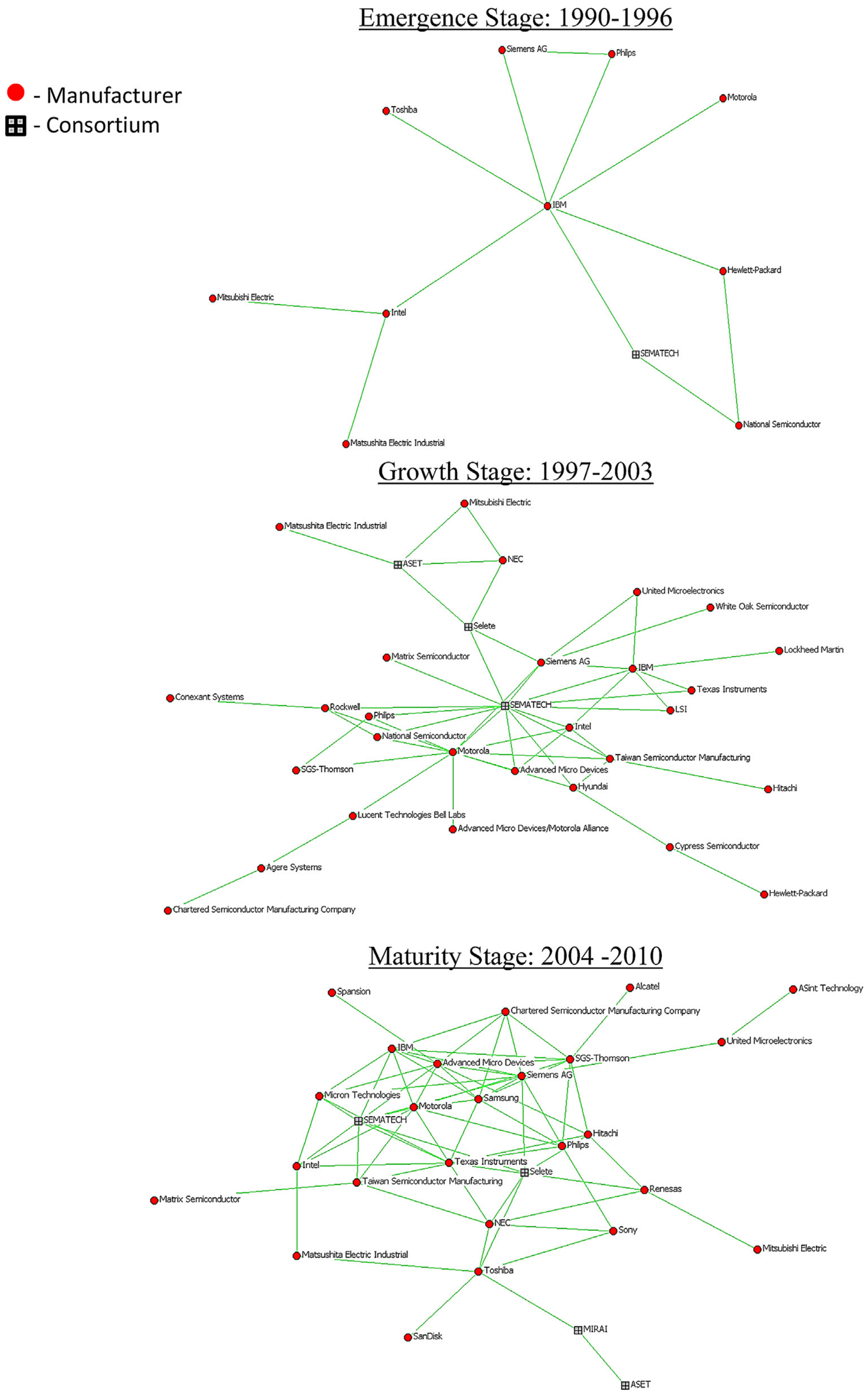

Fig. 5. Semiconductor manufacturers' co-opetitive collaboration network for DUV.

in the emergence stage to increasingly technology integration-based between manufacturers and suppliers during the growth and maturity stages. The proportion of technology integration-based collaborations increased from 28% during the emergence stage to 55% during the maturity stage. Note that the science-based collaborations still constitute about 39% of all collaborations within the maturity stage, suggesting the continuing important role of universities and research institutes even during the later stages of the technology life cycle (cf. Lim, 2009).

As the technology evolved from the emergence stage to the maturity stage, we also find that the nature of technology integration efforts evolved from predominantly vertical collaboration between manufacturers and suppliers to also include horizontal collaboration between suppliers of complementary technological inputs (Hypothesis 3). The proportion of articles involving such collaboration increased from 2% during the emergence stage to 20% during the maturity stage. Finally, we also explored the proportion of collaborative articles between competitors.[20] Co-opetitive collaborations exhibit a fairly stable pattern across the three stages (at 21%, 21%, and 17% of all collaborative articles for each period), which is suggestive of their importance throughout the technology's life cycle.

3.4. *Regression analysis*

Since our dependent variables are dichotomous, we use Logit models for our analysis. Table 4 shows the descriptive statistics and correlations for the variables and Table 5 reports the results from the regression analysis. The high correlation between the number of R&D organizations, suppliers and manufacturers is expected and reflective of the trend for the number of DUV articles. Greater the number of DUV articles in a given year, greater is the number of R&D organizations, suppliers and manufacturers. Different types of collaborations are likely influenced by the number of different types of organizations rather than the aggregate number of all organizations. Hence, we use the three different control variables in our analysis. As a test of robustness, we substituted the three variables with a single aggregate number of all organizations and found the results to be qualitatively similar.

Model 1 is used to test Hypothesis 1 with *Collaboration* as the dependent variable and is estimated using data on all DUV articles. Models 2–4 are used to test Hypotheses 2 and 3 with *Science-based, Technology Integration-based* and *Horizontal Technology Integration-based collaboration* as dependent variables and are estimated using data on DUV articles that are collaborative. Semiconductor manufacturers are the main drivers of R&D efforts in the semiconductor industry, and there is significant heterogeneity among the different manufacturers' R&D strategies. For example, Chesbrough (2003) and Brown and Linden (2009) discuss how semiconductor manufacturers such as IBM, Intel, Texas Instruments and Advanced Micro Devices differed in the extent to which they pursued internal and collaborative research. In order to account for such differences, we include manufacturer fixed effects in Models 1–3. In Hypothesis 3, we argue that technology integration-based R&D collaborations will evolve from predominantly vertical collaboration between manufacturers and suppliers to increasingly horizontal collaboration between suppliers of complementary inputs. This prediction is tested in Model 4 using data on only technology integration-based collaborations. Since different types of suppliers may have different opportunities to collaborate with complementary suppliers, we include fixed effects for the different types of suppliers in this model (e.g., EDA suppliers, mask suppliers, resist suppliers, etc.).[21]

Consistent with the descriptive trend, the estimated coefficients for the *Growth Stage* and *Maturity Stage* are each positive and significant in Model 1. Translating the coefficients to odds ratio, the estimates correspond to an article being 1.56 times more likely to be collaborative (versus internal) in the growth stage than in the emergence stage, and 1.88 times more likely to be collaborative in the maturity stage than in the emergence stage. The difference between the coefficients is also significant as tested using the Wald test ($p = 0.038$). Hence, we find strong statistical support for Hypothesis 1 that the likelihood of collaborative R&D increases over the life cycle such that it is lowest during the emergence stage and highest during the maturity stage. The coefficients for *US Affiliation*, and *Europe Affiliation* were each positive and significant suggesting that firms within these geographical clusters are more likely to pursue R&D collaboration.

In estimating the life cycle dynamics with respect to science-based and technology integration-based collaborations, the coefficients for *Growth Stage* and *Maturity Stage* are negative and significant for science-based collaboration and they are positive and significant for technology integration-based collaboration. The difference between the coefficients is also significant ($p = 0.002$; $p = 0.043$). Specifically, the science-based collaboration model (Model 2) suggests that the odds of a collaboration being science-based decrease by a factor of 0.34 in the growth stage versus the emergence stage, and decrease by a factor of 0.23 in the maturity stage versus the emergence stage. The estimates from technology integration-based model (Model 3) suggest that collaboration is 2.15 times more likely to be a technology integration-based collaboration in the growth stage than in the emergence stage, and is 2.76 times more likely to be a technology integration-based collaboration in the maturity stage than in the emergence stage. The findings from Models 2 and 3 jointly support Hypothesis 2 that the collaborative R&D efforts evolve from predominantly science-based during the emergence stage to increasingly technology integration-based during the growth and maturity stages of the technology life cycle. The estimates for the control variables were as expected. The likelihood of science-based collaboration increases with the number of R&D organizations. The likelihood of technology integration-based collaboration increases with the number of suppliers Given that, on average, suppliers and manufacturers tend to have a lower count for science-based collaboration articles, the likelihood of science-based collaboration decreases with the number of suppliers and manufacturers. The effect of US and Europe affiliation is positive but the coefficient for US affiliation is insignificant for science-based collaboration.

In Model 4, the coefficients for *Growth Stage* and *Maturity Stage* are positive and significant. The difference between the coefficients is also significant ($p = 0.06$). The estimates suggest that a technology integration-based collaboration is 11 times more likely to be of a horizontal type involving suppliers of complementary inputs in the growth stage than in the emergence stage, and is 15.91 times more likely to be of a horizontal type in the maturity stage than in the emergence stage. These results regarding the increasing prevalence of horizontal technology integration-based collaboration between suppliers of complementary inputs are dramatic, but as expected, in Hypothesis 3.

3.5. *Evolution of co-opetitive collaboration*

In contrast to science-based and technology integration-based collaborations and as reported in Table 3, co-opetitive

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[20] These include collaborations between semiconductor manufacturers or between suppliers of the same technological input (e.g., resist). Given that research consortia are by themselves co-opetitive organizational entities, we also consider articles written solely by authors affiliated with research consortia or by authors affiliated with semiconductor manufacturer and research consortia as being co-opetitive collaboration efforts among semiconductor manufacturers. We note that because of the high concentration of the different supplier segments (typically two dominant firms in each supplier category) and greater rivalry (due to lower product differentiation), co-opetitive R&D collaborations between suppliers were relatively scarce and included less than 5% of all co-opetitive collaborations in the dataset. Hence, we do not report suppliers' and semiconductor manufacturers' co-opetitive collaborations separately.

[21] Ideally, we would have preferred to also include supplier fixed effects in our analysis. However, we faced two challenges. First, by definition, supplier fixed effects perfectly explain technology integration-based collaboration. Hence, we are unable to use it for testing Hypothesis 2. Second, our sample of 891 articles with technology integration-based collaboration for testing Hypothesis 3 included 210 different suppliers, thus significantly reducing the degrees of freedom and making it very difficult to achieve precise estimates. Note also that we cannot use manufacturer fixed effects in Model 4 as they perfectly explain vertical technology integration-based collaboration.

collaborations exhibited a relatively stable trend throughout the DUV technology's life cycle. This observed persistence of co-opetitive collaborations, while emphasizing their importance toward industry's technological progress, potentially masks the evolutionary shift in the different motivations of learning and resource pooling that underlie such collaborations (Sakakibara, 1997; Hagedoorn et al., 2000). For example, firms in the pharmaceutical industry have extensively pursued co-opetitive learning-based collaborations during the emergence of biotechnology (e.g., Powell et al., 1996; Baum et al., 2000). As firms learn and accumulate knowledge, they may pool similar resources to share costs, avoiding duplicate investments and achieve economies of scale in R&D. Indeed, the great leaps in performance benefits attained early in the technology's evolution inescapably contract, and achieving even minimal progress requires ever-greater efforts. Moreover, as competitors continue to gain experience during the life cycle's evolution, any initial heterogeneity in their capabilities reduces. The increasing similarity amongst competitors' capability stocks further boosts the efficiency of pooling resources, as both competitors are then positioned to immediately and equitably contribute to the collaboration (Sakakibara, 1997). Hence, it is likely that the motivation underlying co-opetitive collaboration evolves from a learning orientation to an increasingly resource pooling orientation over the course of the technology life cycle. A precise exploration of such a pattern would ideally require detailed information through a survey instrument about the nature of collaboration between firms over the course of the DUV technology life cycle (cf. Sakakibara, 1997). This was beyond the scope of the research project. Instead, we leverage our collaboration dataset to identify the structural properties of the co-opetitive network, and we draw upon the literature on inter-organizational networks (Ahuja, 2000; Powell et al., 1996, 2005; Uzzi, 1997) to offer some preliminary insights.

A fundamental distinction in the networks literature has been made between "open" and "closed" networks (Ahuja, 2000; Walker et al., 1997). An extreme example of an open network is one that is highly centralized, oftentimes referred to as a star or hub-and-spoke structure (Wasserman and Faust, 1994). In this case, the central node is the quintessential broker, collecting information and accumulating knowledge from the peripheral, otherwise unconnected participants. The central player is well positioned to learn and innovate, since its position allows it to gather diverse knowledge; the peripheral players, however, also stand to benefit by their indirect access to these multitudinous sources of knowledge while maintaining only one direct tie to the center. For example, Powell et al.'s (1996, 2005) networks of learning are well characterized by these centralized structures. In contrast, closed networks, which are decentralized and have densely connected structures, provide a platform for the exchange and sharing of complex and valued resources that is facilitated through the participants' direct ties (e.g. Coleman, 1988; Hansen, 1999; Uzzi, 1996). Of course, such network structures come with the potential learning disadvantages of receiving redundant information in return and maintaining additional ties.

Given that co-opetitive collaboration among suppliers was rare, we focused on only semiconductor manufacturers for this analysis. Fig. 5 presents network graphs of the semiconductor manufacturers' co-opetitive R&D network for each of the three stages of the DUV technology. Each node in the network represents a semiconductor manufacturer or research consortium. Every line, or "tie," indicates the presence of a collaborative relationship between two organizations. During the emergence stage, the network is highly centralized. IBM, a pioneer in the DUV technology (Holmes et al., 1997), is the core hub at the center of this star-shaped network. During the growth stage, the network becomes less centralized as other organizations encroach on IBM's former dominance of the network core. Taking a more central role are the manufacturers Motorola and Intel, as well as the industry consortium SEMATECH, which was established to facilitate the pooling of semiconductor manufacturers' resources. Finally, during the maturity stage, the network becomes significantly decentralized with a much broader "core," consequently suggesting even greater resource pooling among semiconductor manufacturers toward DUV technology development. This evolution of the co-opetitive network offers some preliminary evidence regarding the evolutionary shift in the motivating driver of co-opetitive collaboration between semiconductor manufacturers from learning in the emergence stage to increasingly resource pooling in the growth and maturity stages of the DUV technology life cycle.

4. Discussion and conclusions

The study offers a rich characterization of how the pattern of R&D efforts among the industry community evolves over the technology life cycle. It provides an explicit consideration of the diversity of actors including research organizations, suppliers and users that contribute to the technological progress, and illustrates how the industry's locus of innovation interacts with the different evolutionary stages of the technology. In doing so, it unpacks the complexities that underlie a seemingly smooth S-shaped trajectory of technological progress and shows that technical advances are sculpted by a multiplicity of innovation actors who offer distinct but complementary responses toward pushing the technology forward.

The empirical exploration is conducted in the context of the semiconductor manufacturing industry from 1990 to 2010. During this period, the industry witnessed exponential technological progress that was fueled by the emergence of Deep Ultraviolet (DUV) manufacturing technology in the late 1980s and its subsequent evolution over the next two decades (Iansiti, 1998; Martin and Salomon, 2003; Kapoor and Adner, 2007). We draw upon a comprehensive archival dataset of 12,000 technical articles presented at 147 industry conferences, to capture the pattern of collaborative R&D pursued by semiconductor manufacturers (i.e., users), suppliers, universities and dedicated research institutes over the course of the DUV technology life cycle.

The early emergence stage of the technology is accompanied by high technological uncertainty during which firms build absorptive capacity, accumulate new knowledge and pursue technical or scientific breakthroughs (Sahal, 1981; Dosi, 1982; Cohen and Levinthal, 1990; Jiang et al., 2011). These motivations translated to R&D efforts having a somewhat stronger internal orientation and the externally oriented collaborative R&D efforts being channeled mainly through science-based collaborations involving universities and research institutes.

As the technology trajectory solidifies and experience is gained, R&D efforts during the growth stage evolve toward pursuing cumulative advances within the now established technological constraints and interdependencies. This changed the distribution of R&D collaboration from predominantly science-based during the emergence stage to increasingly technology integration-based involving users and suppliers during the growth and maturity stages of the technology. Technology integration-based collaborations come in two distinct flavors – the often emphasized vertical collaboration between users and suppliers (e.g., Clark and Fujimoto, 1991), and the somewhat less emphasized horizontal collaboration between suppliers of complementary components in which suppliers take a more active role in coordinating technological inputs (e.g., Mitchell and Singh, 1996; Kapoor, 2013a). As suppliers gain experience over the course of the technology life cycle, they develop the necessary architectural knowledge to assume some of the responsibilities underlying technology integration and create greater value from their efforts. This resulted in the evolution of technology integration-based R&D collaboration from predominantly vertical collaboration between users and suppliers to increasingly horizontal collaboration between suppliers of complementary components.

Finally, besides collaborating with research organizations and actors in the supply chain, focal firms also collaborate with each other. This was most evident in the co-opetitive collaborations among semiconductor manufacturers. Such collaborations could be motivated by firms learning from each other and accumulating knowledge as well as firms generating economic efficiencies in R&D by pooling their resources (e.g., Sakakibara, 1997; Hagedoorn et al., 2000). The evolution in the structure of co-opetitive collaboration from a highly centralized network during the emergence stage to increasingly decentralized network during the growth and maturity stages offered some initial evidence that co-opetitive collaborations evolve from a learning orientation to an increasingly resource pooling orientation over the course of the technology life cycle.

Taken together, these findings reinforce that technological progress in an industry is enabled by a collaborative network of diverse innovators including suppliers, users and research organizations (Freeman, 1991; Hagedoorn, 2002; Powell and Grodal, 2005). Beyond the recognition that the locus of innovation is indeed found in the network of collaborative relationships, we disentangle the different types of collaborative interactions that take place within the network and show how their relative importance evolves over the technology life cycle. In so doing, we contribute to the literature on interorganizational collaboration by not only generating dynamic insights, but also providing clarity on the importance and relevance of the different types of collaborative relationships (Ahuja et al., 2011). Given that technology life cycle has been a critical anchor for scholars studying the link between industry evolution and firm strategy (Tushman and Anderson, 1986; Nelson, 1994; Utterback, 1994), the study offers a novel characterization of how an innovating firm may reconfigure its cooperative R&D strategy as it pursues technical advances within an existing or a new technological regime.

Another important contribution of the study entails the use of technical conferences to examine the pattern of R&D collaboration. There are many industries and technological domains such as aerospace, automotive and energy where technical conferences are an important medium through which information regarding technology development and progress is disseminated. While scholars have successfully leveraged public announcements of alliances in the popular or industry press, such sources are severely limited in their ability to capture the broad spectrum of R&D collaborations, especially if they involve research organizations or if they tend to be less formal (Link and Bauer, 1989; Freeman, 1991; Hagedoorn et al., 2000; Hall et al., 2003). Technical conferences, on the other hand, provide a first-hand account of the R&D activities carried out by the firms' engineers and scientists. Technical conferences therefore offer scholars a much more comprehensive and contemporaneous account of firms' in-house and collaborative research efforts. While it is possible that a firm's reliance on secrecy can preclude the public disclosure of some of its R&D activities, the reputational and knowledge sharing benefits often offset these appropriability concerns and thus generate strong incentives for both firms and employees to participate in technical conferences (e.g., Hicks, 1995; Appleyard, 1996).

The findings have important implications for policy makers. While we expected that R&D collaboration within the industry will be predominantly science-based during the emergence stage of the technology, we were somewhat surprised to see a relatively high level of science-based collaboration even during the maturity stage (39% of all collaborative articles). This clearly suggests that universities and dedicated research institutes continue to be an important source of learning for firms throughout the technology's evolution. Hence, financing industry-relevant public research and facilitating collaborations between industry and research organizations are likely to be critical in shaping the competitiveness of regions and firms. Given the importance of suppliers especially during the growth and maturity stages of the technology life cycle, policy makers may need to ensure that technological advances are not halted by the suppliers' inability to invest in and undertake collaborative R&D. Finally, policies geared toward antitrust and cooperative research may explicitly need to account for the changing motivations for competitors to collaborate over the course of the technology life cycle.

The empirical evidence presented in the study also complements the recent study by Epicoco (2012); using network-based bibliometric techniques and drawing on patent citations information, she identified the key technological inventions and knowledge domains that underlie the evolution of the semiconductor industry. While Epicoco's emphasis was on integrated circuit (IC) and system design rather than on semiconductor manufacturing, her findings reinforced the importance of a broad set of actors that contributed to the technological advances in the semiconductor industry and, in particular, the critical role played by research organizations in generating some of the core inventions and initiating new knowledge domains. Our analysis of the evolutionary pattern of R&D collaboration among semiconductor manufacturers, their suppliers and research organizations also parallels another important evolutionary pattern in the semiconductor industry over the past two decades – the shift toward greater specialization with respect to semiconductor design and manufacturing activities (e.g., Macher et al., 1999; Brown and Linden, 2009; Kapoor, 2013b). This shift has not only resulted in an increased globalization of semiconductor manufacturing (Leachman and Leachman, 2004), but also provided firms with different strategic alternatives (i.e., make, buy or ally) for governing their manufacturing activities (Leiblein et al., 2002; Leiblein and Madsen, 2009). We note, however that our analysis and their interpretation are indifferent to whether the semiconductor manufacturer is a vertically integrated firm or a specialized manufacturing firm. They are both users of the DUV technology.

Although we have taken care in our examination, the study has a number of limitations. Our examination focuses on a specific technology in a given industry. Much more needs to be done to establish the generalizability of our findings in other contexts. For example, our findings may be more applicable in contexts where technological capabilities are broadly distributed among industry participants (i.e., users, suppliers, R&D organizations). Similarly, an important boundary condition for our findings related to technology integration-based collaboration (Hypotheses 2 and 3) is that these would be most applicable in contexts characterized by technological systems (Rosenberg, 1982; Hughes, 1983). Second, in relying on a unique dataset that draws on technical articles presented in industry conferences, we have assumed that these articles have a strong correspondence between internal and collaborative R&D efforts in the industry. While we have attempted to establish the validity of our data through interviews and comparisons with other data sources, it is likely that the dataset suffers from incomplete or delayed information for some internal R&D projects and for some collaborative R&D projects. For example, it is possible that engineers and scientists in the industry may have different incentives to participate in these conferences. It is also possible that different firms and R&D organizations may provide varying levels of encouragement to their employees to present their research in the industry conferences and maintain links with the wider scientific community (e.g., Henderson and Cockburn, 1994). Finally, our inferences regarding the evolution of co-opetitive collaboration from a learning orientation to increasingly resource pooling orientation are at best preliminary. We expect that such an evolutionary shift to have important implications for how firms manage co-opetitive collaborations over time, and hope that future research can more precisely identify this pattern and its resulting implications.

Despite these and other limitations, the study, drawing on a novel dataset, uncovers how the pattern of collaborative R&D within the industry community evolves over the technology life cycle. By viewing technological progress as shaped by the collective efforts of suppliers, users and research organizations, and by situating their internal and collaborative efforts in the context of the technology's evolution, it offers a rich characterization of how progress within an industry is sustained. In doing so, it offers a rare bridge between the literatures on technology evolution and networks of innovators, and shows why their joint consideration promises valuable insights for scholars, managers and policy makers.

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