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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.

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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,

[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.

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