

VALUE CREATION IN INNOVATION ECOSYSTEMS: HOW THE STRUCTURE OF TECHNOLOGICAL INTERDEPENDENCE AFFECTS FIRM PERFORMANCE IN NEW TECHNOLOGY GENERATIONS

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The success of an innovating firm often depends on the efforts of other innovators in its environment. How do the challenges faced by external innovators affect the focal firm's outcomes? To address this question we first characterize the external environment according to the structure of interdependence. We follow the flow of inputs and outputs in the ecosystem to distinguish between upstream components that are bundled by the focal firm, and downstream complements that are bundled by the firm's customers. We hypothesize that the effects of external innovation challenges depend not only on their magnitude, but also on their location in the ecosystem relative to the focal firm. We identify a key asymmetry that results from the location of challenges relative to a focal firm—greater upstream innovation challenges in components enhance the benefits that accrue to technology leaders, while greater downstream innovation challenges in complements erode these benefits. We further propose that the effectiveness of vertical integration as a strategy to manage ecosystem interdependence increases over the course of the technology life cycle. We explore these arguments in the context of the global semiconductor lithography equipment industry from its emergence in 1962 to 2005 across nine distinct technology generations. We find strong empirical support for our framework. Copyright © 2009 John Wiley & Sons, Ltd.

INTRODUCTION

A firm's competitive advantage depends on its ability to create more value than its rivals (Porter, 1985; Brandenburger and Stuart, 1996). Greater value creation, in turn, depends on the firms' ability to innovate successfully. To capture the returns from innovation, many firms strive to be technology leaders in their industry by being first to introduce new innovations to the market. A given innovation, however, often does not stand alone; rather, it depends on accompanying changes

in the firm's environment for its own success. These external changes, which require innovation on the part of other actors, embed the focal firm within an ecosystem of interdependent innovations (Adner, 2006).

Consider, for example, Airbus's monumental investment in pioneering the super-jumbo passenger aircraft with its A380 offer. Airbus, as the focal firm, faces substantial challenges in designing and manufacturing the core airframe of the airplane. Beyond this internal challenge, it also relies on a host of suppliers for subassemblies and components. Some of these suppliers are themselves confronted with significant innovation challenges to deliver components that meet Airbus's requirements (e.g., engine, navigation system), while others will not need to innovate at all (e.g., carpeting). Receiving these various components, Airbus

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faces the additional challenge of integrating these components with the airframe in order to deliver a functioning aircraft to its airline customers. In order for the aircraft to be used productively by airlines, however, a number of other actors in the environment, outside of Airbus's direct supply chain, confront additional innovation challenges as well. Complementors such as airports need to invest and develop new infrastructure to accommodate the oversized aircraft, regulators need to specify new safety procedures, and training simulator manufacturers need to develop new simulators on which aircraft crews can be trained. The A380 innovation ecosystem thus comprises not only Airbus as the core innovator, but also its upstream suppliers, and its downstream buyers and complementors. The key point is that it is not enough to consider whether and how Airbus will successfully resolve its internal innovation challenges; in order for the A380 offer to create value, all of the other ecosystem partners need to resolve their own innovation challenges as well.

Understanding firm performance in such 'innovation ecosystems' requires a change in the way in which the strategy and the innovation literatures have traditionally linked industry dynamics to firm performance. Most obviously, it requires an approach that is explicit not only about the innovation challenges that are faced by the focal firm (Cooper and Schendel, 1976; Tushman and Anderson, 1986; Henderson and Clark, 1990; Christensen, 1997), but one that is also explicit about the nature of innovation challenges confronted by the external partners. In addition, it requires an approach that extends beyond the focus on how different actors will bargain over value capture (Porter, 1980; Teece, 1986; Brandenburger and Stuart, 1996; Brandenburger and Nalebuff, 1997) to include an explicit consideration of the innovation challenges that different actors will need to overcome in order for value to be created in the first place.

The current paper presents an approach to analyzing the dynamics of value creation that focuses on the role of innovation challenges in a firm's ecosystem as potential bottlenecks to value creation. We show that no less important than the *magnitude* of innovation challenges in the ecosystem is the *location* of these challenges. We present a simple structure for locating challenges relative to the focal firm according to the flow of activities within the ecosystem and draw key distinctions

between challenges that need to be confronted by the focal firm, its upstream suppliers, and its downstream complementors.

Specifically, the current paper identifies asymmetries that arise from the positions of different counterparties relative to the focal firm. We show that a firm's ability to create value is impacted in very different ways depending on whether it is its upstream or downstream partners that face innovation challenges. The impact of high external innovation challenges on the focal firm depends on whether the challenges are confronted by suppliers, which affects the components that the firm needs to integrate in order to offer a complete product to its customers, or by complementors, in which case the firm can offer its complete product to the customer, but the customer cannot utilize it to its full potential. We link these asymmetries in value creation to their impact on value capture and competitive advantage. To our knowledge this is the first paper in the management literature to explicitly postulate or test the asymmetric effects of components and complements.

We use this ecosystem lens to consider two inter-related questions. First, how the structure of technological interdependence—the location of challenges relative to the focal firm—affects the benefit that accrues to technology leaders (i.e., firms that pioneer the introduction of new technology generations). Second, how the effectiveness of vertical integration as a strategy for managing technological interdependence changes over the course of a technology's life cycle.

The first mover advantage literature has identified important considerations under which technology leaders gain or lose from early entry into new markets. Both the applied and scholarly literatures are replete with studies, prescriptions, and caveats regarding the merits of pioneering opportunities (Lieberman and Montgomery, 1988; Mitchell, 1991; Golder and Tellis, 1993; Christensen, Suárez, and Utterback, 1998). Consistent with strong arguments for and against the benefits of leading in the introduction of new innovations, the empirical findings have been decidedly mixed, with some studies reporting significant pioneering advantages while others report disadvantages and non-effects (Kerin, Varadarajan, and Peterson, 1992; VanderWerf and Mahon, 1997).

The debates over the advantage accorded to technology leaders have tended to overlook the

nature of the technology challenges that leaders and their ecosystems must overcome. In so doing, they have neglected a key contingency. The current paper moves beyond the literature's traditional analysis of firms' positions relative to their rivals. We explicitly consider the innovation challenges that reside in the firm's environment and need to be confronted by external partners if the focal innovation is to succeed in the market. We develop a simple framework for characterizing the technological uncertainty associated with external innovation challenges. We argue that the location of challenges impacts the steepness of firms' learning curves, their rate of progress along these curves, and the extent of spillovers to rivals. We predict that challenges in components increase the performance advantage attributable to technology leaders, while challenges in complements decrease this advantage.¹ In so doing, we reveal how the structure and sequence of value creation affects the outcomes of competition for value capture.

We then consider firms' vertical integration of key components as a strategy to manage this interdependence. We integrate arguments from the research literatures on technology life cycles (Rosenberg, 1976; Sahal, 1981; Dosi, 1982) and transaction cost economics (Williamson, 1985), and suggest that while technological challenges tend to decrease as technologies mature, contractual challenges need not dissipate over time. Because vertical integration mitigates contractual hazards but not necessarily technological challenges, we posit that the shifting balance of technological and contractual uncertainty will act to increase the benefit from vertical integration over the course of the technology life cycle. Hence, vertical integration is likely to be more effective after a technology has reached a stage of maturity, rather than during its emergence.

We test these arguments in the context of the global semiconductor lithography equipment industry from its emergence in 1962 to 2005, a period during which the industry transitioned through nine distinct technology generations. While focal innovators faced significant challenges in each of these generational transitions, the extent

to which suppliers and complementors faced innovation challenges varied across these generations, providing us with an ideal setting in which to test the impact of ecosystem challenges on technology leaders. We construct a unique dataset to test our arguments. The data include a novel measure of ecosystem challenges for each of the nine technology generations, as well as information about every firm that ever sold lithography equipment for mainstream applications in the semiconductor industry.

Our study makes a number of contributions. First, it introduces a structured approach for analyzing technology interdependence. This approach offers a new perspective for understanding innovators' outcomes during periods of technological change by focusing not only on the internal challenges faced by the focal firms (Tushman and Anderson, 1986; Henderson and Clark, 1990) but also on the external challenges faced by partners in the ecosystem. By using an ecosystem lens to examine the benefits of technology leadership, we expand the scope of inquiry beyond its traditional focus on direct competitors to identify the underpinning mechanisms by which uncertainty in components and complements exercise opposing effects on the performance of technology leaders and laggards (Lieberman and Montgomery, 1998). By disaggregating the external environment into upstream and downstream constituents, we show that the location of challenges matters no less than their magnitude, and offer a finer-grained view of the interaction between organizations and their environments (Dess and Beard, 1984) and its implication for the dynamics of value creation (Brandenburger and Stuart, 1996; Adner and Zemsky, 2006). By linking the flow of activities among exchange partners to the distribution of innovation challenges across the ecosystem, we shed light on a key mechanism of joint value creation and contribute to the emerging research literature on ecosystem strategy (Moore, 1996; Iansiti and Levien, 2004; Adner, 2006). To the best of our knowledge, the current study is the first to operationalize the environment in this way. Finally, by explicitly considering the changing benefits of vertical integration over the course of the technology life cycle we contribute toward an understanding of how firms' boundary choices affect their performance outcomes over time (Stigler, 1951; Argyres and Bigelow, 2007; Novak and Stern, 2008).

¹ Note that our focus is *not* in specifying whether technology leaders will have a competitive advantage. Rather, our focus is on specifying whether competitive advantage from technology leadership is enhanced or eroded by the magnitude and location of external innovation challenges.

AN ECOSYSTEM PERSPECTIVE

The ecosystem construct, as a way of making interdependencies more explicit, has gained prominence in both business strategy (Moore, 1996; Iansiti and Levien, 2004; Adner, 2006) and practice (e.g., Intel Corporation, 2004; SAP Corporation, 2006). These approaches have focused on understanding coordination among partners in exchange networks that are characterized by simultaneous cooperation and competition (Brandenburger and Nalebuff, 1997; Afuah, 2000). Studies in this vein explore the challenges that arise when incentives across the ecosystem are not aligned (Casadesu-Masanell and Yoffie, 2007), the role of established relationships with ecosystem partners in shaping firms' motivations to compete for different market segments (Christensen and Rosenbloom, 1995), and the activities that focal firms undertake to induce exchange partners to favor their specific technology platforms (Gawer and Cusumano, 2002).

Notice, however, that these studies are primarily concerned with strategic interactions among firms, extending the focus on value capture from the context of bilateral partnerships (Teece, 1986) and industries (Porter, 1980) to the context of ecosystems (Jacobides, Knudsen, and Augier, 2006; Pisano and Teece, 2007). Thus, while the strategy literature has explored the role of co-specialization, bargaining power, and relationships between exchange partners in shaping firms' value capture, it has tended to assume away the question of how value is created in the first place.

Notice too, that while these research studies are clearly sensitive to the presence of different roles and actors along the value chain (i.e., drawing clear distinctions between suppliers, complementors, and buyers), the specific value chain position of a counterparty relative to the focal firm has had no impact on the resulting analysis;—that is, the impact of an exchange partner with high bargaining power on the focal firm's ability to capture value is exactly the same regardless of whether the counterparty is positioned as a complementor, a buyer, or a supplier.

Indeed, although the very imagery of a value chain (at the level of both firms and industries) suggests interdependencies characterized as an ordered arrangement of activities, the literature has largely neglected the impact of the relative locations of activities along the chain. This has left

the field in the odd position of highlighting the importance of complements, complementors, and complementary assets, (e.g., Teece, 1986; Milgrom and Roberts, 1990), claiming qualitatively distinct status for the role of complementors and suppliers, but unable to use its definition of these constructs² to distinguish between complements (e.g., software for hardware) and components (e.g., processors for computers) because improvements in either increase the attractiveness of the focal offer.

We depart from this literature by explicitly linking the dynamics of value creation and their implications for value capture to the structure of interdependence in a firm's ecosystem. The perspective that we propose and test in this study exploits the relative location of activities within the ecosystem to distinguish among the different roles played by various actors in the firm's environment. We identify roles according to the location in which activities are bundled in the ecosystem by following the flow of inputs and outputs of firms, and use this as the basic framework for our analysis.

Figure 1 shows the schema of our approach. The outputs of upstream suppliers serve as inputs to the focal actor. We refer to such inputs, which are bundled by the focal actor into its product, as components. The focal actor's product serves as an input to its customer. A customer may also need to bundle other offers alongside the focal actor's product in order to utilize it. We refer to such offers, which are bundled downstream by the customer, as complements. Thus, components and complements are defined according to where elements are bundled in the flow of activities relative

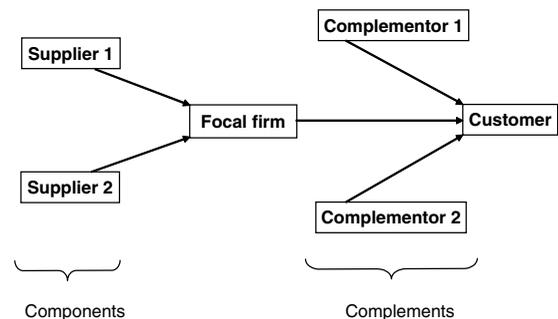


Figure 1. Generic schema of an ecosystem

²For example, 'The defining characteristic of these groups of complements is that if the levels of any subset of the activities are increased, then the marginal return to increases in any or all of the remaining activities rises' (Milgrom and Roberts, 1990: 514).

to the position of the focal product, not according to whether they are produced by a given firm or outsourced to another. For example, although Hewlett Packard produces both personal computers and printers, they remain separate offers that are brought together by the customer: the printer is a complement to the computer independently of whether it is offered by Hewlett Packard or Cannon. In the figure, as in our study, we examine only first-tier components and complements; clearly, this structure can be extended forward and backward along the activity chain to include higher-tiered actors (e.g., suppliers' suppliers; customers' customers). In the following section, we apply this approach in the context of innovations.

Innovation and the structure of interdependence

The majority of studies in the innovation literature have sought to characterize the magnitude and nature of the internal innovation challenges confronted by focal innovators.³ The magnitude of innovation challenges can be characterized by the extent to which they require changes to the current approach to problem solving. The nature of a challenge can be rooted in discovery, design, and development (Tushman and Anderson, 1986; Henderson and Clark, 1990); in integrating external components into firms' internal designs (Takeishi, 2002; Brusoni, Prencipe, and Pavitt, 2001); or in scaling up the production and delivery of the identified solution (Argote, 1999; Hatch and Mowery, 1998).

The success of an individual innovation, however, is often dependent on the success of other innovations in the firm's external environment. Hughes's (1983) rich description of the emergence of the electrical power network highlights the obstacles raised when some technological elements of an ecosystem lag behind others in resolving their challenges. He attributes the decline of direct current (DC) generation technologies to bottlenecks

³ Exceptions are Afuah's studies (Afuah and Bahram, 1995; Afuah, 2000), which have explored how firm performance is impacted when partners face technology challenges. These studies focus on the overall level of innovation challenges that partners must confront. In contrast, our study explicitly considers the impact of variations in both the level and the location of challenges within the ecosystem. In so doing, we are able to uncover new insights regarding the asymmetric impact of upstream and downstream uncertainty on innovators' outcomes.

in the development of distribution technology for the DC network. Conversely, Henderson's (1995) study of the semiconductor lithography industry (the same industry we examine in this paper) highlights the role that suppliers, customers, and complementors played in offsetting bottlenecks in optical lithography technology, thereby extending the dominance of optical lithography over nonoptical approaches. However, while the existence of external innovation dependencies in such systems of innovation has been well documented in the literature, it has been undertheorized.

The existence of bottlenecks in an ecosystem is evidence that challenges are distributed unevenly across ecosystem roles. While challenges in any location within the ecosystem will constrain the focal firm's ability to create value with its product, challenges located in different positions constrain its value creation and value capture in qualitatively different ways. Specifically, whereas upstream component challenges limit value creation by constraining the focal firm's ability to produce its product, downstream complement challenges limit value creation by constraining the customer's ability to derive full benefit from consuming the focal firm's product.

Figure 2 illustrates these distinctions. In the upper left hand quadrant, external component challenges and complement challenges are low, and the primary constraint on the focal firm is managing its own internal innovation challenges. An example might be DuPont developing a new plastic. The innovation literature has largely focused on the management of challenges in this quadrant. These internal challenges are an issue in all quadrants in Figure 2. In the other three quadrants, however, in addition to these internal challenges, external challenges also need to be overcome. In the upper right

		External complement challenges	
		Low	High
External component challenges	Low	Internal innovation challenges	Internal challenges + external constraint on consumption
	High	Internal challenges + external constraint on production	Internal challenges + external constraints on production and consumption

Figure 2. A framework for understanding the effect of ecosystem challenges on innovators

hand quadrant, upstream component challenges are high, and the focal firm faces an additional barrier to production rooted in the ability of its suppliers to overcome their own innovation challenges. For example, each new generation of hard disk drives has presented drive manufacturers with significant internal design challenges, but has also required significant innovation on the part of suppliers of components such as read-write heads, motors, and disk substrate materials. In the lower left hand quadrant, downstream complement challenges are high, and the focal firm's buyers are constrained in their ability to benefit from the firm's innovation, despite the firm's ability to overcome its own challenges. For example, although hardware platforms for electronic book readers have been available since the 1990s, the decade-long absence of compelling electronic book content hindered the ability of hardware providers to create value with their innovation.

Note that the upper right hand quadrant and the lower left hand quadrant both have high challenge on one external dimension and low challenge on the other. An analysis that examined only the magnitude of external innovation challenges, ignoring their location relative to the focal firm, would be blind to the asymmetric effects of upstream and downstream interdependence. Therefore, such an analysis would incorrectly characterize these quadrants as equivalent.

In the lower right hand quadrant, component and complement challenges are both high. An example is zero emission vehicles, which require significant innovation not only in car design, but also in the engine component and in the complement of the fuel delivery infrastructure. Nominally, this quadrant represents the highest state of environmental uncertainty. However, the effect of the simultaneous presence of high component and high complement challenges will likely depend on the specific order of uncertainty resolution—whether the characterization of ecosystem challenges will shift from the lower right hand quadrant to the upper right hand quadrant, or from the lower right hand quadrant to the lower left hand quadrant. The sequence will depend on the specific nature of challenges in the ecosystem.

We now consider how differences in the constraints on value creation due to the location of challenges in the ecosystem impact firms' competitive advantage.

TECHNOLOGICAL INTERDEPENDENCE AND INNOVATORS' PERFORMANCE

How do the magnitude and location of technological challenges in the ecosystem affect the benefits of technology leadership? Being first to introduce an improved technology to the market is a common managerial aspiration. Successful technology leaders, by virtue of having beaten their rivals to market, enjoy reduced competition when presenting their offer to customers. Whether this temporary exclusivity translates into a sustained competitive advantage over later entrants, however, depends on the leader's ability to exploit its window of opportunity. This capability will depend on the relative distribution of challenges across components and complements.

Component challenges

Innovations are often enabled by changes in components. In such cases, both firms and their suppliers may face considerable challenges in developing and integrating these new components into the focal offer (Fine, 1998; Iansiti, 1998; Brusoni *et al.*, 2001). How do component challenges affect the performance of technology leaders who pioneer technology generations?

A key driver of early mover advantage is the opportunity to exploit production and market experience to progress down the learning curve, increasing the firm's added value by improving the offer's performance or costs (Spence, 1981; Lieberman, 1984, 1989; Argote, 1999). Empirical studies of learning curves from the 1930s to the present day have found significant variance in learning potential. For example, in their review of 22 learning curve studies, Dutton and Thomas (1984) report progress ratios that vary from 55 percent (high learning opportunity) to over 100 percent (no learning opportunity).⁴

The extent to which progress down the learning curve can be a source of advantage is intimately linked to the potential for learning—greater advantage is rooted in greater learning potential. Hence, to understand learning as a source of advantage

⁴ The progress ratio measures the cost reduction associated with a doubling of production. A progress ratio of X percent implies that a doubling of production reduces cost of production to X percent of the initial cost.

we must consider what drives differences in the magnitude of the learning opportunity.

The magnitude of the learning opportunity depends both on the extent to which the innovating firm needs to change its current approach to problem solving and the scope it has for doing so. It is the emerging mastery of new routines that underpins a firm's progress down the learning curve. If very little change from the status quo is required, it follows that there is not much new for the firm to learn; hence, both the opportunity for and the relative advantage from learning will be relatively low. In contrast, when the innovating firm needs to overcome high uncertainty and complexity in order to bring its offer to market, the opportunity for learning will be higher, as will be the potential for learning to be a source of competitive advantage.⁵

When the focal innovation requires accompanying innovations in components, the focal firm's development challenges increase, as it now must overcome additional hurdles in specifying, sourcing, and integrating new components into its new designs. These challenges can impact both the technological as well as the organizational routines that must be mastered by the firm in order for it to bring the innovative offer to the market. In this way, component challenges increase the magnitude of the firm's learning opportunity, and hence the advantage it can gain from progressing down the learning curve in advance of its rivals.

Further, the increased requirements for closer coordination with suppliers (Dyer and Singh, 1998) and more frequent iterations through design and development cycles (Clark and Fujimoto, 1991) that accompany challenging components, contribute not only to increasing the benefits to the technology leader from greater experience with the new technology, but also to reducing the ease with which later rivals can imitate this progress (Lippman and Rumelt, 1982; Rivkin, 2000). For example, rivals have found it difficult to imitate

innovations that emerged from the extensive collaboration between Toyota and its key suppliers (Dyer, 1996; Dyer and Hatch, 2006).

Hypothesis 1: Greater technological challenges in components will increase the performance advantage of technology leaders.

The degree to which component challenges increase the performance advantage of technology leaders may be tempered by the extent of modularity between the component and the focal product. Two mechanisms stand out when interfaces are well specified. First, with regard to the focal firm, there may be less potential for learning because key developments are undertaken by the supplier. Second, with regard to the focal firm's rivals, there is the possibility that once the component has been developed for the technology leader, rivals can free ride on these investments and 'plug-and-play' the component directly into their own offers, thereby reducing the leader's period of exclusivity in the market.

We note, however, that while these factors can reduce the extent to which component challenges increase a leader's advantage, they are unlikely to reverse the direction of the effect. While modularity does reduce interdependence, it does not eliminate it. For example, Brusoni and Prencipe (2001) note that while modularity allows for the rise of specialist component suppliers, it also poses greater organizational and knowledge requirements on the focal firms in their role as system integrators. Similarly, Hoetker's (2006) study of outsourcing choices in the notebook computer market supports the argument that organizational coordination challenges exist even when technologies are highly modular.

Complement challenges

We have argued that component challenges can increase both potential for learning as well as barriers to imitation, and hence increase the advantages that accrue to technology leaders. How are the factors that support these advantages affected by challenges in complements? The resolution of component challenges is required in order for a firm to be able to produce its offer and present it to the market. However, the extent to which the offer can create value for users depends on

⁵ Balasubramanian and Lieberman (2006) report findings that are highly consistent with these arguments. This study considers 117 industries to examine how the relationship between experience and productivity depends on research and development (R&D) intensity (a proxy for industry development challenges). This study finds that greater R&D intensity is correlated with lower progress ratios (i.e., greater learning potential), which is consistent with our argument that greater learning potential should increase the relative benefits that accrue to firms with a head start in moving down the learning curve.

the availability of critical complements. For example, the Airbus A380's ability to create value for its airline customers is hampered until airports, as key complementors, undertake the modifications to their terminals that are required to handle the oversized aircraft.

Many innovations rely on the availability of complements to unlock their full value. Rosenberg (1972: 21) submits that a single innovation rarely constitutes a 'complete innovation,' and that the opportunities and challenges faced by users in adopting the innovation can be influenced by the state of development of complements. Hughes (1983) describes imbalances in the pace of development of complementary innovations as creating 'reverse salients' on the frontier of technological development. Ethiraj (2007) illustrates how complements constrained the value of products developed by suppliers to the personal computer industry. Goldfarb (2005) offers a qualitative examination of how challenges in complements delayed the adoption of electricity in the railroad and printing industries in the early 1900s.

Greater complement innovation challenges result in delays in the availability of the complement as complementors struggle to overcome their own technology hurdles. By reducing the value creation of the focal offer, delays in the availability of suitable complements act to slow the adoption rate of the new offer. These adoption delays impact the advantage from technology leadership in two distinct ways. First, they allow rivals more time to catch up and possibly imitate the leader before the market takes off. Second, because lower rates of adoption will reduce the firm's ability to gain experience (i.e., lower demand will lead to lower production quantities), the leader will make slower progress down the learning curve during its period of exclusivity. Hence, even without imitation, later entrants will confront a leader with a smaller competitive advantage. By acting to slow both adoption and the accumulation of experience, greater complement challenges erode the sustainability of the technology leader's competitive advantage.

Hypothesis 2: Greater technological challenges in complements will decrease the performance advantage of technology leaders.

The impact of complement challenges on technology leaders is likely to be affected by the extent to which complements are open vs. proprietary.

When complements are open, such that they can be used with the offer of any firm, laggards will benefit from any progress that had been made in the market to advance the leader's offer; that is, spillovers will be higher and technology leaders will see their advantage eroded.

When complements are proprietary, such that they can only work with the offer of a particular firm, spillovers will be reduced. However, the leader need not necessarily be better off: to the extent that there is a new race to be won in the development of suitable complements, whether the first firm in the market with the focal offer will also win the race to be first to market with the key complement will depend on a number of case-specific factors. What is clear, however, is that even when complements are proprietary, high complement challenges forces firms to compete in a second race for leadership. Hence, regardless of whether complements are open or proprietary, complement challenges erode the benefit of technology leadership in the focal offer.

The balance of uncertainty: technology vs. opportunism

Our discussion is focused on innovation challenges that arise in ecosystems, in which focal offers need to be combined with components and complements if they are to present a value-creating solution to customers. We have argued that in such contexts the distribution of technological challenges across the ecosystem is an important driver of firms' outcomes. We now consider vertical integration as a governance strategy to manage such interdependence.⁶

A key benefit of vertical integration is the ability to mitigate contractual hazards. These contractual hazards arise when firms and their suppliers make asset-specific investments under conditions of uncertainty (Williamson, 1985). When contracting with suppliers for innovative components with high development challenges, the focal firm faces two specific kinds of uncertainty. The first is the technological uncertainty surrounding

⁶ In our empirical setting, a subset of firms integrate into component production, but no firms integrate into complements. Hence, because we are only able to test arguments regarding vertical integration into components, we do not hypothesize about the benefits of integration choices with respect to complements. This question, although fascinating, is beyond the scope of this paper.

whether and when suppliers will discover appropriate solutions to their development challenges (Clark, 1985). The second is what Williamson (1985: 58) terms behavioral uncertainty regarding whether and when suppliers will behave opportunistically (Jap and Anderson, 2003; Sutcliffe and Zaheer, 1998).

The resolution of technological uncertainty determines value creation—if the supplier cannot produce appropriate components, the firm cannot bring the desired product to market. The resolution of behavioral uncertainty determines value capture—if the supplier renegotiates the contract terms opportunistically, the firm cannot appropriate the expected rents.

Early in a technology's life cycle, technological uncertainty is at its peak. As development takes place, knowledge is accumulated and progress becomes more predictable. Although development continues throughout the life cycle, and innovation challenges are always present, within a given trajectory the level of technological uncertainty tends to decrease over time (Dosi, 1982; Sahal, 1981).⁷

In contrast to technological uncertainty, which decreases with time, the trend for behavioral uncertainty as technology matures is ambiguous. On the one hand, increased experience and repeated interactions can allow firms to specify better formal contracts and extend relational contracts with their suppliers, such that behavioral uncertainty may decrease over time (Mayer and Argyres, 2004; Argyres, Bercovitz, and Mayer, 2007). On the other hand, it is also possible for behavioral uncertainty to increase over the technology life cycle: as firms continue to work with suppliers to

improve their offers, the level of co-specialization, transaction-specific assets, and supplier switching cost can increase. Similarly, as the market for the offer grows, so may the opportunity cost to the firm of switching suppliers, increasing the incentive for suppliers to behave opportunistically. For example, the classic episode of General Motors (GM) and Fisher Body as discussed by Klein (1988, 2000) suggests that the rapid increase in demand for closed metal bodies created significant contractual hazards for GM and led GM to acquire Fisher Body.

Vertical integration mitigates the effects of behavioral uncertainty but not of technological uncertainty.⁸ If the level of technological uncertainty decreases more rapidly than behavioral uncertainty over the technology's life cycle, then the *relative* importance of behavioral uncertainty rises. Under these conditions the benefit from vertical integration will be greater at later stages of the technology life cycle.

Hypothesis 3: The performance advantage from vertical integration will increase over the course of the technology life cycle.

EMPIRICAL CONTEXT

We test our hypotheses in the context of the semiconductor lithography equipment industry. Semiconductor lithography is a key process used by semiconductor manufacturers to create integrated circuits. Improvements in lithography tools have been the main driver of progress in semiconductor manufacturing, enabling the production of higher performance chips at lower marginal cost (Moore, 1995). From its emergence in 1962 to 2005, the semiconductor lithography industry has witnessed the commercialization of nine different technological generations. From the beginning, lithography tool manufacturers have regarded technology leadership to be a key source of competitive advantage. Being among the first to introduce a new technology generation offers technology leaders significant learning advantages as well as the opportunity to lock in customers due to high switching costs.

⁸ Vertical integration may also allow firms to develop a better understanding of the interactions between the focal components and the product architectures (Kapoor and Adner, 2009), and to apply such firm-specific knowledge to facilitate improvements over the technology life cycle (Novak and Stern, 2008).

⁷ The literature has distinguished among industry life cycles (i.e., the time span between an industry's emergence and its decline), technology life cycles (i.e., within a given industry, the time span between a new technology's emergence and its decline), and product life cycle (i.e., within a given technology, the time span between the emergence of a new product and its decline). The current study focuses on the introduction of new technology generations, and so conducts its analysis at the level of technology life cycles. We note that the distinction between the technology and product life cycles can be fuzzy depending on the context and whether product performance or product sales are being plotted on the Y-axis. However, in our context this distinction is quite clear. Within the semiconductor lithography industry, which emerged in 1962 and continues to the present day, we are examining technology life cycles, such as the period from emergence of the I-line technology generation in 1985 to its decline in the face of the rising dominance of the subsequent technology generation. We do not focus on the product life cycle that governed the rise and decline of specific product models within the I-line generation.

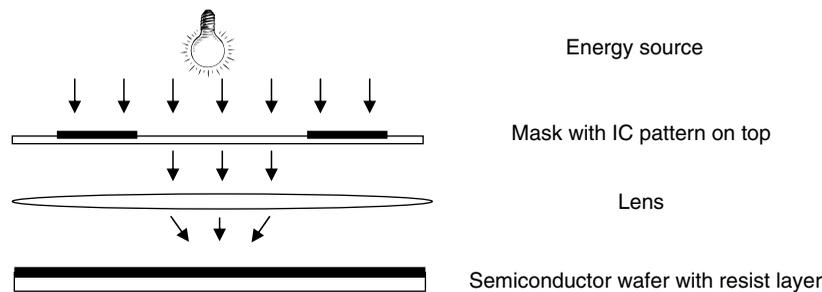


Figure 3. Basic schema of the semiconductor lithography process

In each of the nine technology generations, the manufacturers of lithography tools had to overcome significant innovation challenges. Although suppliers and complementors were always critical to enabling each new technology generation, the magnitude of their challenges varied across generations—whereas in some generations it was possible to simply reuse existing elements, other generations required suppliers and complementors to completely reinvent their offers.

Semiconductor lithography

Semiconductor lithography is the process by which a circuit design is imprinted on a semiconductor wafer. The basic principle of lithography is illustrated in Figure 3. After the design of an integrated circuit (IC) is finalized (i.e., the wiring, the gates, and the junctions), the circuit blueprint is transferred to a *mask*. The lithography process takes place when beams of energy originating from an *energy source* are directed onto the mask. The pattern on the mask allows a portion of the energy to pass through, with or without an optical *lens* system, onto the wafer. The wafer is coated with an energy sensitive *resist*. The resist undergoes a chemical reaction wherever the mask has allowed the energy to pass through. This chemical reaction changes the structure of the resist and allows its selective removal from the wafer. Another chemical process is then initiated in which the exposed parts of the wafer are etched. Finally, the remaining resist is removed, creating a final circuit that replicates the initial design. A single wafer can go through this process a number of times as multiple layers of circuits are etched onto it. For example, in 2006, a one gigabit dynamic random access memory chip could be etched with as many as 60 circuit layers.

The key performance attribute of a lithography tool is its resolution, the smallest geometry on which the tool can focus on the wafer surface. Resolution determines the extent of miniaturization that can be achieved by the semiconductor manufacturer. A semiconductor manufacturer will use scores of lithography tools in a single production line, often one for each circuit layer. With modern tools costing over \$20 million each, investments in lithography equipment represent a substantial portion of the cost of a fabrication facility. Lithography ‘production recipes,’ which are customized to specific tool models, masks, and resists, are regarded as a key source of advantage for semiconductor manufacturers who invest significant resources in optimizing their production lines (Iansiti, 1998). To maintain competitiveness semiconductor manufacturers continuously reinvest in their facilities and look to new lithography technology generations to allow them to offer products with higher performance at lower cost.

The current study’s focal firms design and assemble the lithography tool. The key components that these toolmakers need to integrate into their offers are the energy source and the lens. Their customers are semiconductor manufacturers who use the lithography tool in their fabrication plants. The mask and the resist are the key complements that these customers must integrate with the lithography tool. A schema of the lithography tool ecosystem is presented in Figure 4.

The development of a new generation of lithography tool technology poses significant challenges for tool manufacturers to achieve finer and finer resolutions. A new technology generation can also impose substantial challenges on other ecosystem elements: the energy source may need to operate at a new wavelength; the lens may need to be manufactured from a new material; the mask, which needs to be etched with thinner lines, may need to

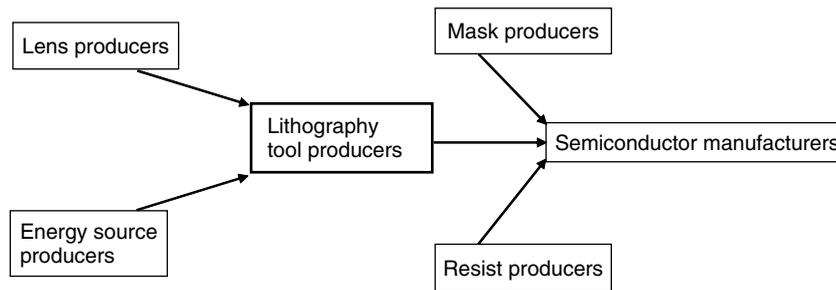


Figure 4. The semiconductor lithography equipment ecosystem

be manufactured in a new way, possibly from new materials; the chemical resist may need to be reformulated to enable greater control of the chemical reactions as energy wavelengths become smaller and geometric resolutions become finer.

Despite undergoing nine generational transitions, the structure of interdependence in the ecosystem—the components that need to be integrated by the focal tool manufacturers and the complements that their customers, the semiconductor manufacturers, need to combine with the tool offer—has remained unchanged throughout the 44-year period that we study. All tool manufacturers integrate the source and lens components and leave it to their customers to integrate the mask and the resist complements with the tool. This choice of what to bundle and what to exclude in the tool offer is rooted in a lack of synergies on both the supply and demand sides. On the supply side, there is little overlap between the knowledge bases and resources required to succeed in developing and assembling lithography tools (highly complex batch assembly), creating new resists (producing vats of very specialized chemical solution), and mask production (essentially a custom printing service business). More importantly, on the demand side, the big semiconductor manufacturers (the toolmakers' most important customers) have had little interest in fully bundled solutions—they regard their proprietary production recipes for putting together tool, mask, and resist as a key source of their own competitive advantage (Kapoor and Adner, 2009), and view a move to bundled lithography solutions as inviting a loss of differentiation.⁹ Where tool manufacturing

firms have differed is in their strategy for managing their interdependence with lens components: some firms are vertically integrated into lens production whereas others rely on external suppliers.

Thus, the industry allows us to examine a well-defined technological ecosystem that comprises focal firms, their suppliers, and their complements, in which the location and magnitude of ecosystem innovation challenges vary across technology generations. The industry is also appealing because it provides a natural set of controls for two key factors that have already been examined in the innovation literature. First, all the transitions across technology generations can be characterized as sustaining innovations (nondisruptive in the Christensen [1997] sense) in that all technology generations were targeted at existing customers, enhanced performance on the same set of key performance attributes (resolution, accuracy, and throughput, in particular), and commanded significant price premiums over earlier generations. Second, the value of complementary assets—sales force, manufacturing, brand, service, and support competence—was preserved throughout (Mitchell, 1989; Tripsas, 1997).

Technology transitions in the semiconductor lithography equipment industry

The key measure of progress in semiconductor lithography is improvement in tool resolution. Finer resolutions enable the semiconductor manufacturers to use the lithography tool to pack more circuits onto a chip and more chips onto a wafer. These improvements allow semiconductor manufacturers to offer chips with higher performance at lower marginal cost.

For the lithography tool manufacturers, improving resolution is a top priority. Tool manufacturers increase resolution using a combination of three

⁹Such stability in activity flows is a common characteristic across many industries. For example, disk drive producers have always bundled motors and heads; their customers, the computer assemblers, bundle the drive with processors and software.

levers. The first is to reduce the wavelength of light that is transmitted by the energy source. The second is to increase the size of the lens. The third is to improve the design of the tool itself. The industry distinguishes among technology generations according to the design of the tool and the wavelength of energy that it transmits. Incremental improvements to the tool design and the lens are core drivers of product advances within a technology generation. When further improvements become untenable due to a combination of physical and economic constraints the industry shifts to a new design or to a smaller wavelength, which heralds the emergence of a new lithography technology generation.

In transitioning across technology generations, tool manufacturers always face significant design challenges. Consider, for example, the industry's transition from I-line generation steppers to deep ultraviolet (DUV) 248 nm generation steppers. The core approach to increasing resolution in this transition was to decrease the energy wavelength from 365 nm to 248 nm, which would allow tool resolution to improve from 0.8 μm to 0.45 μm . The relationship between reduced wavelength and finer resolution is straightforward in theory.¹⁰ Realizing this improvement in a commercial setting, however, requires a corresponding improvement in tool design (e.g., in terms of factors such as alignment, repeatability, reliability, and throughput). Overcoming these design challenges requires tool manufacturers to experiment and iterate, often for years, in order to come up with a suitable offer (Henderson and Clark, 1990).¹¹

¹⁰ The resolution capability of lithography technologies that employ a lens system is given by the Rayleigh criterion:

$$\text{resolution} = k_1 \times (\text{wavelength}/\text{numerical aperture}),$$

where wavelength is the wavelength of the light being transmitted by the source, numerical aperture is the measure of the size of the lens, and k_1 is a process-specific constant.

¹¹ Henderson's studies of the industry have highlighted that in confronting new technology generations, firms may face both engineering challenges in creating new designs as well as cognitive challenges in recognizing the subtleties of change (Henderson and Clark, 1990; Henderson, 1993). In particular, these studies highlighted the unique cognitive challenges that confront incumbents when generational changes affect the architectural links among only core design concepts. The focus of our paper is on external challenges; however, we account for incumbency effects in our empirical specification.

When a new technology generation requires innovation in components, the tool manufacturers face greater challenges in specifying, sourcing, and integrating the new components into their designs. The transition to DUV 248 nm, for example, required fundamental changes in the energy source and the lens. Mercury lamps, which had been used in all earlier generations, were not able to provide sufficient energy at a wavelength of 248 nm to cause adequate chemical reactions in the resist. This challenge was overcome by the development of excimer lasers using krypton fluoride (KrF) gas. In addition, the conventional glass material that had been used to make lenses faced absorption problems with the 248 nm wavelength. The only material that could be used was fused silica, and this required major changes to the lens manufacturing process. These required changes created significant challenges in components, which, in turn, served to increase the design and integration challenges that confronted the tool manufacturers.

In order for the new generation of lithography technology to be used effectively by customers, significant challenges needed to be overcome in the development of complements as well. Mask makers needed a new material that would provide improved transmission of the new wavelength which, in turn, required changes to the mask manufacturing process. Finally, the existing novolac resists could not absorb enough energy from the 248 nm wavelength to cause an adequate chemical reaction. To solve this challenge, a new chemically amplified resist had to be developed.

Table 1 summarizes the major technological innovations required to overcome the challenges in the tool, lens, source, mask, and resist in each technology generation. Readers interested in a more detailed overview of each of the technology transitions are referred to Kapoor and Adner's (2007) study, which explains how ecosystem challenges impacted the sales evolution of different technology generations.

METHODOLOGY

Data

We used both primary and secondary data sources for this study. We began by developing a detailed

Table 1. Major technological innovations by the lithography equipment ecosystem to overcome the challenges accompanying new technology generations

Technology generation (year of first sale)	Resolution (μm)	Tool	Source	Lens	Mask	Resist
Initial solution (pre-1962)			Mercury lamp.	None.	Manually cut mask.	Negative resist.
Contact printer (1962)	7.00	Circuit design is transferred to wafer by putting mask in direct contact with the resist on the wafer and then shining the light energy from the mercury lamp energy source.	—	—	Introduction of Step & Repeat Camera for mask making.	—
Proximity printer (1972)	3.00	The mask is separated from the wafer by a small gap. Eliminating direct contact reduces defect rates.	—	—	Substitution of emulsion plates by chrome on glass.	—
Projection scanner (1973)	2.00	A reflective lens system is incorporated into the tool to allow for greater concentration of light energy to be transferred through the mask onto the wafer.	—	Development of reflective lens system.	Use of electron beam systems for high-quality IX masks.	—
E-beam writer (1976)	0.5	Move an electron beam through a preprogrammed path to create the circuit pattern directly on the resist without use of lens or mask.	Development of thermionic and field emission methods and final convergence to Schottky emitter.	—	—	New developments with PMMA-based resist.

Table 1 (Continued)

Technology generation (year of first sale)	Resolution (μm)	Tool	Source	Lens	Mask	Resist
X-ray printer (1978)	0.3	Change wavelength from 435 nm to 10 nm and project energy from an X-ray source without use of a lens.	Development of synchrotron for providing a high energy source.	—	Development of new mask materials such as SiC/Ta. Development of new mask making techniques to provide smaller geometries.	— Change in resist from standard negative resist to novolac resist.
G-line stepper (1978)	1.25	Step-and-repeat technology allows a single wafer to be etched through multiple exposures as the mask is shifted across the wafer in steps. A refractive lens system allows for the circuit dimensions on the mask to be 5–10 times larger than the dimensions etched onto the wafer.	—	Development of refractive lens system.	—	Change in resist from standard negative resist to novolac resist.
I-line stepper (1985)	0.80	Wavelength derived from the mercury lamp energy source is reduced from 435 nm to 365 nm.	—	Development of new lens material for reduced wavelength.	—	—
DUV 248 nm stepper (1986)	0.45	Wavelength is reduced from 365 nm to 248 nm.	Development of krypton fluoride (KrF) excimer laser.	Change in lens material to fused silica.	Change in mask material to quartz.	Change in resist to chemically amplified resist.
DUV 193 nm stepper (1996)	0.15	Wavelength is reduced from 365 nm to 248 nm.	Development of argon fluoride (ArF) excimer laser.	Change in lens material to calcium fluoride.	Introduction of RET masks for 193 nm.	New versions of chemically amplified resist.

historical understanding of the semiconductor lithography equipment industry during a 20-month field study. We conducted multiple interviews with over 30 industry experts, most of whom have been associated with the industry for more than 20 years. The interviewees came from a variety of positions within the ecosystem: toolmakers, semiconductor manufacturers, suppliers, complementors, industry associations, and consultants. The interviews were semi-structured and lasted two hours on average. We identified ecosystem structure by first asking what elements needed to be integrated by tool manufacturers in order for them to produce their offers; and second, asking what elements needed to be integrated by the tool customers in order for the tool to be used productively. There was unanimous agreement that the energy source and the lens were the key components to be integrated into the tool by the manufacturer, and that the mask and the resist were the key complements to be integrated with the tool by the customer. We used the information from the interviews to develop an understanding of the ecosystem challenges that governed the emergence of the different technology generations. We consolidated this information in a document that mirrors Table 1 and sent it back to our interviewees for written and verbal comments. We incorporated these comments and then sent the table out for a second review. All the experts agreed with our final characterization.

We searched every issue of *Solid State Technology* from 1961 to 2001 for articles relating to ecosystem innovation challenges. *Solid State Technology* is a leading industry journal whose mission is to cover the key trends and issues that confront the industry. It has been publishing technical articles on challenges facing the semiconductor industry since its founding in 1957. Using this source, we created measures (discussed below) that characterize the extent of challenges in the key components and complements for each of the technology generations.

Finally, we obtained detailed market data from the leading industry consulting firm, VLSI Research, which has been following the industry since the 1970s. The VLSI data included sales by technology generation for every firm that competed in the lithography equipment industry from 1974 to 2005. Rebecca Henderson generously shared her data on the contact printing generation. Our final dataset consists of an unbalanced panel of 64

firm-technology generations. The average number of observations per group is 10.4. Our data are comprehensive and include information on each of the 33 firms that ever sold a semiconductor lithography tool for mainstream semiconductor applications.¹²

Variables

The definitions of the variables used to test our hypotheses are summarized in Table 2 and detailed below.

Dependent variable

Our dependent variable, *generation share*, is a firm's market share in a given technology generation in a given year. This measure is consistent with prior research studies that examine firm performance in new technology generations (Mitchell, 1991; Henderson, 1993; Tripsas, 1997). Further, industry participants and observers (e.g., VLSI Research, Gartner Dataquest) regularly use market share in a generation as a measure of firm success.

Our main analysis considers a firm's market share in a given technology generation in a given year. As a test of robustness for Hypotheses 1 and 2, reported in the Appendix, we also consider a firm's cumulative market share over the entire life of the technology generation.

Independent variables

Our measures of component and complement challenges were created using a count of *Solid State Technology* articles that discuss ecosystem challenges. Our industry sources confirmed that a count of published articles that address technical problems regarding an ecosystem element is a good proxy for the level of technology challenges that surrounded the development of different lithography generations. Through our field work we developed a list of keywords that we used to guide the article search.¹³

¹² The current analysis excludes two firms from our sample because, although they produced lithography tools, they were competing in different markets. These firms entered the given lithography generation during its declining phase and were targeting niche markets such as thin film heads, pressure sensors, and biotech applications rather than the mainstream applications of semiconductor manufacturers.

¹³ The keywords were: lithography, microphotographs, mask, photomask, resist, laser, UV, DUV, Deep UV, optical, lens,

Table 2. Variable descriptions

Variables	Description
Dependent variable	
Generation share	Firm's market share in a given generation in a given year.
Key variables in study	
Technology leadership	Entry timing for the firm in the new generation. Leadership position is defined as one for the first entrant and subsequent entry is measured with respect to the lag in years from the first entry.
Component challenge	Number of technical articles that refer to lens and source innovation in the given generation that appear in the industry journal no later than five years after the emergence of the new generation.
Complement challenge	Number of technical articles that refer to mask and resist innovation in the given generation that appear in the industry journal no later than five years after the emergence of the new generation.
Vertical integration	Dummy = one for a firm with a separate business unit performing manufacturing of lens component for the generation.
Technology maturity	Count of number of years between a technology generation's year of first sale and the given year.
Control variables	
Incumbent	Dummy = one for a firm that sold lithography tools in an earlier technology generation.
Conglomerate	Dummy = one for a firm that was active in multiple industries.
Generation sales growth	Annual sales growth rate of the generation.
Number of firms	Number of firms active in the generation in a given year.

We identified a total of 181 lithography-related articles that appeared from 1961 to 2001. We then identified articles that discussed ecosystem challenges in a given generation. We used the article titles to identify the match between the generation and the ecosystem element. If there was insufficient information available in the title, we read the abstract and the conclusion to ascertain if the article addressed the innovation challenges in the ecosystem for a given generation. A small subset of articles discussed the ecosystem innovation challenges for multiple generations, and for these articles we read the relevant sections for each generation in order to create a match. This procedure reduced our set to 102 articles.

Finally, since our primary concern is with respect to innovation challenges that confront technology leaders as they pioneer technology generations, we further reduced our set to include only those articles that were published no later than five years after the commercialization of the first tool in a generation. Another reason to choose the five-year post-commercialization window was to present a balanced view of upstream

and downstream ecosystem challenges. The articles published after the close of this five-year window were almost entirely dedicated to discussing complement challenges. This is not surprising, since by the fifth post-commercialization year, much progress would have necessarily been made on the component side. Our final dataset consisted of information from 56 articles that discussed 78 ecosystem innovation challenges. We tested robustness with three- and seven-year windows and the results are consistent with those reported here.

We constructed the *component challenge* measure as the sum of the number of articles that discussed innovation challenges in the lens ($innov_{lg}$) and the source ($innov_{sg}$) for technology generation g .¹⁴

$$component\ challenge_g = innov_{lg} + innov_{sg}$$

¹⁴ As validation of the article count measure, we tested its consistency with the qualitative descriptions revealed in our interviews and reported in Table 1. We coded the entries and non-entries in Table 1 with values of one and zero respectively, and then compared them to the article count data. The correlation is 0.91 for source, 0.83 for lens, 0.92 for mask, and 0.89 for resist innovation challenges. This high correlation increases our confidence in the measure.

stepper, aligner, mercury, illuminator, exposure, printer, and the names of the different generations.

Similarly, *complement challenge* was constructed as the sum of the number of articles that discussed innovation challenges in the resist ($innov_{rg}$) and the mask ($innov_{mg}$).

$$\text{complement challenge}_g = innov_{rg} + innov_{mg}$$

We measure a firm's *technology leadership* as the time of its entry into a new technology generation relative to its rivals. We define entry as the first occurrence of revenue for a firm in a given generation. The first firm to enter the generation was assigned a technology leadership value of one. Subsequent firms were assigned values with reference to the years elapsed since the first entrant (e.g., a firm entering a generation three years after the leader was assigned a technology leadership value of four).

To assess the effects of vertical integration on firm performance, we construct the variable *vertical integration*. The variable takes a value of one if the firm produced its own lens component in a given technology generation and zero otherwise. During the history of the industry no tool manufacturer produced its own energy source.

We define the variable *technology maturity* as the number of years that have lapsed since the first commercial sale of a tool in the given technology generation, where the first year of commercial sales is coded as one.

Control variables

We control for a number of firm- and industry-level effects. Henderson and Clark (1990) and Henderson (1993) identified important differences between incumbents and entrants during technology transitions in the semiconductor lithography equipment industry. We control for this effect using the variable *incumbent*, which takes a value of one if a firm had sold lithography tools in an earlier technology generation.

We control for firm size through the variable *conglomerate*, which takes a value of one if the firm was active in industries other than semiconductor manufacturing equipment and zero otherwise. We include two industry level controls. The first is *generation sales growth*, a measure of change in tool sales (in dollars) in a given generation in a given year, which represent the growth opportunities that may influence choices regarding investment in new technology generations. The

second is *number of firms*, which controls for the competitive density in the generation in a given year.

Statistical analysis

We use panel data for our empirical analysis. Each panel corresponds to a *firm in a given technology generation*. The use of panel data helps to control for potential sources of unobserved heterogeneity and enables us to test how the benefits of vertical integration change over time during the course of a given generation. While both the random- and the fixed-effects models allow for explicit consideration of the unobserved effects, the random-effects model makes an additional assumption that the unobserved effect is uncorrelated with the independent variables. Although a fixed-effects approach would require fewer assumptions than the random-effects approach, it cannot be used if the explanatory variables do not vary within the experimental group (Baltagi, 2005: 13). In our analysis, component challenges and complement challenges are the key explanatory variables, but they do not exhibit intertemporal variation for a firm within a given generation. For this reason, we use a random-effects model. We control for unobserved differences across firms by including firm dummies in a firm-generation panel (Wooldridge, 2002: 288). We also include year dummies to control for unobserved year-specific effects. We estimate the following equation:

$$y_{igt} = \beta_0 + \mathbf{X}_{igt}\boldsymbol{\beta} + \mathbf{D}_i\boldsymbol{\lambda} + \mathbf{T}_t\boldsymbol{\delta} + a_{ig} + u_{igt}$$

where y_{igt} is firm i 's market share in a generation g in year t ; \mathbf{X}_{igt} is the vector of independent and control variables; \mathbf{D}_i is the vector of dummies for each firm; \mathbf{T}_t is the vector of dummies for each year; a_{ig} is the unobserved heterogeneity for a firm in a generation that is assumed to be uncorrelated with the explanatory variables; and u_{igt} is the error term.

RESULTS

Descriptive relationships

Figure 5 illustrates the varying degrees of component and complement challenges in each of the nine technology generations. As can be seen from

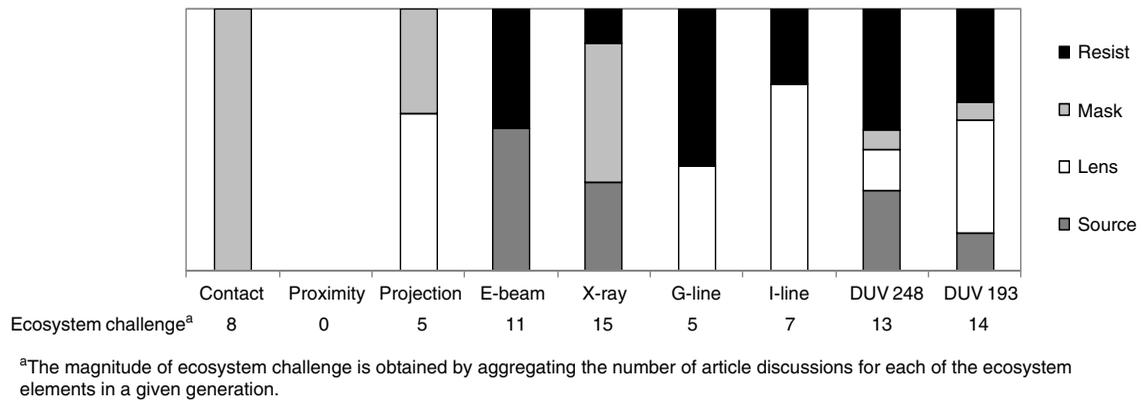


Figure 5. Distribution of challenges among ecosystem elements in nine semiconductor lithography equipment generations

the figure, each of the technology generations presented a distinct combination of ecosystem challenges. This is a key source of variance that we exploit in this study.

The descriptive statistics and pairwise correlations for the variables used in the study are presented in Table 3. The statistically significant negative correlation between technology leadership (where lower values indicate earlier entry timing) and generation share suggests that early entry is rewarded with higher market share in the semiconductor lithography equipment market. Since component challenges and complement challenges are moderately correlated, we estimate their coefficients in separate models, as well as in a combined model, to alleviate concerns regarding multicollinearity.

Tests of the hypotheses

Our hypotheses predict the impact of external ecosystem challenges on the entry timing advantage that accrues to technology leaders, and the impact of vertical integration decisions on firm performance over the course of the technology life cycle. We test Hypotheses 1 and 2 by interacting firms' technology leadership with measures of ecosystem challenges. We mean centered the variables in the interaction terms. The mean centering of continuous variables helps to reduce potential multicollinearity and facilitates the interpretation of the estimated coefficients (Aiken and West, 1991). We test Hypothesis 3 by interacting firms' vertical integration status with the generation's technology maturity. Consistent with prior empirical studies examining market share performance in new

technology generations (Henderson, 1993; Tripsas, 1997), we use a semi-log specification to test our hypotheses.

Table 4 reports our regression results. Model 1 is our baseline model. Consistent with conventional wisdom in the industry, the coefficient for technology leadership is statistically significant and negative, indicating benefits to technology leadership. We find that incumbency has a negative effect, which is consistent with Henderson's (1993) empirical findings. The coefficient for vertical integration is statistically significant and positive, suggesting that in-house component manufacturing is a source of advantage in this industry. The coefficient for complement challenge is also statistically significant and positive. While not hypothesized, this finding indicates that on average, the market share of a firm is greater when complement challenges are high than when complement challenges are low. Given that an increase in a firm's market share translates to a decline in rivals' market shares, the result suggests that greater complement challenges may result in lower variance among the firms' market shares so as to increase the mean market share level of the population. We computed the coefficient of variation for a firm's market share at different values of complement challenges and consistent with the above finding, the correlation between complement challenges and the coefficient of variation was negative.¹⁵ Among the industry-level controls, the coefficient for number of firms is negative and statistically significant,

¹⁵ We note that when we exclude the X-ray and e-beam generations in Model 6 (below) the direct effect of complement challenge remains positive but is statistically insignificant.

Table 3. Descriptive statistics and correlations

Variables	Mean	Std. dev.	Min	Max	1	2	3	4	5	6	7	8	9	10	11	12
1 Ln(generation share)	-1.83	1.26	-6.21	0.00												
2 Technology leadership * component challenge	-0.64	7.69	-30.18	22.91	-0.05											
3 Technology leadership * complement challenge	1.90	8.79	-22.47	32.71	0.24	-0.20										
4 Vertical integration * technology maturity	2.66	5.63	0.00	27.00	0.23	0.10	-0.02									
5 Technology leadership ^a	3.55	2.93	1.00	13.00	-0.35	-0.34	0.24	-0.07								
6 Component challenge ^a	3.57	2.44	0.00	8.00	-0.03	-0.01	-0.36	0.09	-0.09							
7 Complement challenge ^a	4.13	2.67	0.00	10.00	0.13	-0.38	0.09	-0.15	0.24	0.32						
8 Vertical integration	0.23	0.42	0.00	1.00	0.22	0.10	-0.03	0.85	-0.12	0.15	-0.13					
9 Incumbent	0.48	0.50	0.00	1.00	-0.05	0.03	-0.26	0.28	0.15	0.39	0.06	0.31				
10 Conglomerate	0.49	0.50	0.00	1.00	0.23	0.07	-0.08	0.48	-0.34	0.23	-0.10	0.56	0.21			
11 Generation sales growth	40.78	106.11	-76.02	874.05	-0.07	0.06	-0.03	-0.08	-0.09	0.12	0.06	0.04	0.10	0.03		
12 Number of firms	4.92	2.38	1.00	11.00	-0.45	0.07	-0.19	-0.03	-0.03	0.06	-0.17	0.00	-0.09	0.06	0.10	
13 Technology maturity	11.26	6.68	1.00	32.00	0.16	-0.10	0.18	0.23	0.22	-0.15	-0.12	0.01	-0.11	-0.01	-0.33	-0.24

N= 676, Correlations greater than 0.08 are significant at p<0.05.

^aVariable is mean centered (mean, min, and max are shown for the precentered values).

Table 4. Coefficient estimates from random effects OLS regressions; dependent variable = Ln(generation share)

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6 ^a
Technology leadership * component challenge		-0.040*** (0.009)			-0.042*** (0.009)	-0.044*** (0.013)
Technology leadership * complement challenge			0.022** (0.009)		0.020** (0.008)	0.020* (0.011)
Vertical integration * technology maturity				0.034** (0.016)	0.041*** (0.016)	0.029* (0.017)
Technology leadership	-0.146*** (0.022)	-0.148*** (0.019)	-0.163*** (0.020)	-0.142*** (0.022)	-0.158*** (0.018)	-0.156*** (0.024)
Vertical integration	0.406*** (0.156)	0.245 (0.151)	0.398** (0.156)	0.047 (0.231)	-0.205 (0.227)	0.012 (0.281)
Component challenge	-0.036 (0.047)	-0.045 (0.044)	-0.001 (0.048)	-0.052 (0.049)	-0.033 (0.047)	-0.035 (0.115)
Complement challenge	0.102*** (0.025)	0.074*** (0.022)	0.086*** (0.024)	0.104*** (0.025)	0.061*** (0.023)	0.028 (0.031)
Technology maturity	0.003 (0.017)	-0.025 (0.018)	0.014 (0.017)	-0.011 (0.019)	-0.033 (0.020)	-0.029 (0.040)
Incumbent	-0.609*** (0.124)	-0.757*** (0.127)	-0.423*** (0.144)	-0.658*** (0.127)	-0.655*** (0.151)	-0.769*** (0.253)
Conglomerate	0.875 (0.585)	-0.215 (0.579)	0.397 (0.541)	2.845*** (0.310)	2.697*** (0.355)	2.812*** (0.447)
Generation sales growth	-0.000 (0.000)	-0.001 (0.000)	-0.000 (0.000)	-0.000 (0.000)	-0.001 (0.000)	-0.000 (0.000)
Number of firms	-0.183*** (0.020)	-0.181*** (0.020)	-0.179*** (0.020)	-0.189*** (0.020)	-0.184*** (0.020)	-0.178*** (0.024)
Constant	-1.066 (0.867)	0.194 (0.951)	-1.393 (0.860)	-3.190*** (0.613)	-2.407*** (0.655)	-2.401** (1.126)
Firm dummies	Included	Included	Included	Included	Included	Included
Year dummies	Included	Included	Included	Included	Included	Included
R-squared (within)	0.17	0.17	0.17	0.19	0.19	0.19
R-squared (between)	0.77	0.83	0.78	0.77	0.83	0.83
R-squared (overall)	0.58	0.61	0.60	0.59	0.62	0.62
Observations	676	676	676	676	676	521

Robust standard errors in parentheses clustered for intra-panel correlation, * significant at 10%; ** significant at 5%; *** significant at 1%.

^a Model 6 excludes observations from X-ray and e-beam generations.

confirming the negative effects of competitive density on firms' market share performance.

In Model 2 we interact technology leadership with component challenge to test Hypothesis 1. In Model 3 we interact technology leadership with complement challenge to test Hypothesis 2. In Model 4 we interact vertical integration with technology maturity to test Hypothesis 3. Model 5 is the fully specified model.

Hypothesis 1 predicted that greater component challenges will increase the performance advantage accorded to technology leaders. The hypothesis is supported in Models 2 and 5. The coefficient of the interaction term between tech-

nology leadership and component challenge is negative and statistically significant. Hence, the greater the challenges in components, the greater the market share benefit that accrues to technology leaders.

Hypothesis 2 predicted that greater complement challenges will decrease the performance advantage accorded to technology leaders, and is supported in Models 3 and 5. The coefficient of the interaction term between technology leadership and complement challenge is positive and statistically significant. Therefore, complement challenges in the firms' ecosystem erode the benefits that accrue to technology leaders.

Hypothesis 3 predicted that the advantage from vertical integration will increase over the course of the technology life cycle. The positive and significant coefficient of the interaction term between vertical integration and technology maturity in Models 4 and 5 supports the hypothesis.

Robustness tests

We tested the robustness of our results in a number of ways. First, we considered the X-ray and electron-beam (e-beam) generations as possible anomalies. These were the only technology generations not to achieve market dominance even in their peak sales years. This however, was only evident *ex post*. *Ex ante*, these two generations had garnered very strong interest and support among industry participants who believed that these generations represented the future of lithography technology. As a robustness test, we present Model 6 in Table 4, which excluded the X-ray and e-beam technology generations and whose results are fully consistent with our predictions.

Second, as a test of robustness for Hypotheses 1 and 2, we include Table A1 in the Appendix, which shows results from a cross-sectional specification estimated using ordinary least squares (OLS) regression for a firm's cumulative market share in a given generation. The results are fully consistent with our predictions. As an additional test of robustness for Hypotheses 1 and 2, we reconfigured our panel data from grouping by 'firm in a generation' to grouping by 'firm.' This specification allowed us to estimate a traditional fixed-effects specification. However, it required that we right censor observations of firms' participation in older generations beginning in the year in which they introduce their new generation products (because the panel can only have one observation per firm per year). In addition, because the fixed-effects estimation requires temporal variance within a panel, it effectively excludes firms that participated in only one technology generation. These exclusions reduced the number of observations from 676 to 406. The results of this more conservative test are fully consistent with our main results and are reported in Table A2 in the Appendix.

Third, we split component and complement challenges into their individual elements of source, lens, mask, and resist, to ensure that our results are

not driven by a specific element. Again, the results are fully supportive of our predictions.

Fourth, it is possible that vertically integrated firms may systematically enter a generation late and ramp up much faster than their nonintegrated rivals. We checked for this possibility by comparing the technology leadership values for vertically integrated firms with those of nonintegrated firms. We did not find a significant difference between the two subgroups ($t = 0.90$, $p = 0.37$). Finally, in our context, the first two years are typically characterized by ramp-up challenges. For this reason we performed a robustness test by excluding the data for the first two years of each firm's participation in a new technology generation. Our predicted relationship continued to be statistically significant.

DISCUSSION

Firms face considerable challenges in resolving the uncertainty that surrounds the development and production of an innovation. Extant innovation research has provided a rich set of dimensions to characterize the innovators' internal challenges and to explain performance outcomes (Tushman and Anderson, 1986; Henderson and Clark, 1990; Christensen, 1997). However, the challenges that accompany an innovation are often situated not only within a focal firm but also in the firm's ecosystem of upstream suppliers and downstream customers and complementors. In this study, we move beyond the literature's traditional analysis of an innovating firm's internal challenges to also consider the external challenges confronted by partners in its ecosystem.

In considering external innovation challenges, we present a structured framework based on the flow of activities in the ecosystem to distinguish between those challenges whose resolution depends on suppliers and those whose resolution depends on complementors. We examine how such external innovation challenges affect the benefit that technology leaders derive from pioneering a new innovation. We find that, depending on their location, challenges in the external ecosystem can either enhance or erode a firm's competitive advantage from technology leadership. Specifically, we find that while the advantage from technology leadership increases with component challenges, it decreases with complement challenges. Challenges in components increase the technology leader's

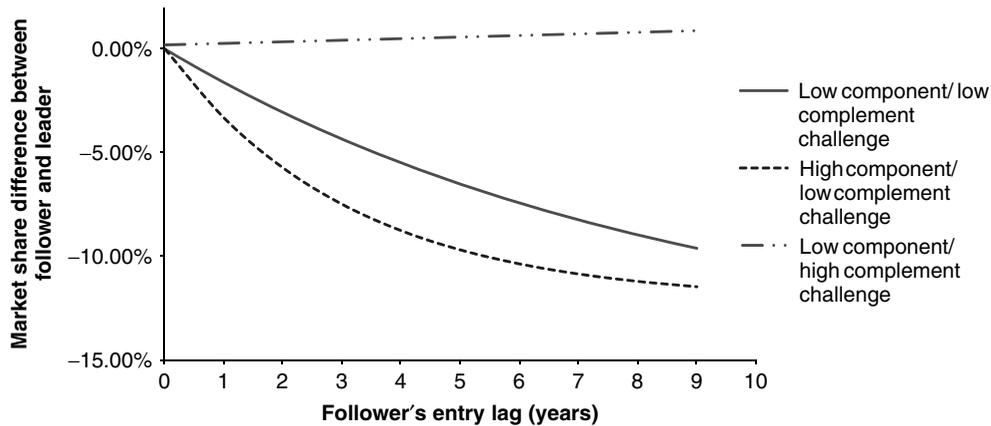


Figure 6. Difference in expected market share between a technology leader and a follower as a function of ecosystem challenge and the follower's entry timing lag

competitive advantage by increasing the potential for learning and by increasing barriers to imitation. In contrast, challenges in complements reduce the technology leader's competitive advantage by slowing its advance down the learning curve and by increasing opportunities for rivals to catch up.

Figure 6 uses the estimates from Model 5 to plot the effect of technology leadership on firms' market share performance for different combinations of ecosystem challenges. The vertical axis measures the difference in average annual market share between the technology leader and a follower. The horizontal axis is the lag, in years, between the entry times of the leader and the follower, where a value of zero denotes simultaneous entry. We plot three component-complement challenge scenarios, where high (low) corresponds to a +1 (-1) standard deviation above (below) our sample mean. The baseline case, 'low component-, low complement-challenge' shows a downward sloping curve indicating that when ecosystem challenges are low, the technology leader is advantaged relative to the follower. As discussed above, this finding is highly consistent with the established beliefs in the semiconductor lithography equipment industry. In the case of 'high component-, low complement-challenge' we find that the slope is even more negative, indicating that technology leaders enjoy an even greater competitive advantage. To get a sense for the economic magnitude of these differences, consider that in 2004 a one percent market share difference in the DUV 248 generation corresponded to \$28.7 million in sales. Finally, in the 'low component-, high complement-challenge' case we find a weakly upward sloping

curve. This finding indicates that when complement challenges are high, technology leadership is less beneficial; indeed, in our specific context, we find that the leader is at a slight disadvantage to later followers.

The implication of Figure 6, as an illustrative summary of our arguments and findings, for the debates regarding early mover advantages is a strong one. Moving beyond the debate of existence vs. nonexistence of first mover advantages (e.g., Golder and Tellis, 1993; Lieberman and Montgomery, 1988, 1998), we have identified specific contingencies that determine the extent of technology leadership. Further, the mechanisms that we identify regarding the opposing effects of component and complement challenges expand the analysis of first mover advantage beyond the traditional firm-centered focus to incorporate specific features of the external environment.

Beyond environmental contingency, we also examine vertical integration as a strategy for managing ecosystem challenges. We suggest that when contracting with suppliers for innovative components, the focal firm faces two specific kinds of uncertainty. The first is the technological uncertainty surrounding whether and when suppliers will discover appropriate solutions to their own development challenges. The second is the behavioral uncertainty regarding whether and when suppliers will behave opportunistically to renegotiate agreements and reset terms in their own favor. We note that while technology uncertainty is resolved and reduced over the course of the technology life cycle, behavioral uncertainty does not necessarily decrease over time. This asymmetry suggests

that the balance between technological uncertainty and behavioral uncertainty will tend to tilt toward the latter over time. As such, we argue and find that the benefits derived from vertical integration should increase over the course of the technology life cycle. This empirical finding is consistent with recent studies conducted in the context of the automotive industry (Argyres and Bigelow, 2007; Novak and Stern, 2008).

Distinguishing between innovation challenges that reside upstream and downstream of a focal firm reveals important asymmetries in their effect on the firm's ability to create value with its offer. The impact of upstream component challenges, which prevent the firm from offering its innovation to the market, are qualitatively different from downstream complement challenges, which prevent the focal firm's customers from utilizing the innovation to its full potential. Although both result in bottlenecks to value creation, they have opposite effects on the firm's ability to capture value and create competitive advantage. This finding supports recent calls in the literature that argue for the importance of understanding the dynamics of value creation as a precursor to the analysis of value capture (Brandenburger and Stuart, 1996; Adner and Zemsky, 2006).

By expanding the scope of inquiry beyond the traditional firm boundaries, the current paper offers an additional lens for understanding technology evolution and firm performance. The ecosystem dynamics that we explore seem to characterize a large, and growing, number of innovation environments. Prior research literature has often linked the resolution of technological uncertainty to the emergence of dominant designs (Utterback and Abernathy, 1975; Anderson and Tushman, 1990) and industry standards (Cusumano, Mylonadis, and Rosenbloom, 1992). The ecosystem perspective presented here suggests that the readiness of complements can play a similar role, no less decisive, in the resolution of this uncertainty.

Further, our findings hold a potential managerial implication regarding managing investments in new technologies. Investing to accelerate commercialization cycles in the pursuit of first mover advantage makes most sense in settings characterized by high component innovation challenges and low complement innovation challenges; such investments are likely to be less beneficial in settings characterized by high

complement challenges. In many settings, relative challenge levels across the ecosystem can be identified well in advance of the commercialization of the innovation. For example, in the context of the semiconductor lithography equipment industry, we found articles discussing ecosystem challenges that appeared in print up to six years before the technology generation was actually commercialized. Our interviews confirm this perspective.

Finally, we contribute to the research literature in organizational theory that examines the interactions between the firms and their environments (Lawrence and Lorsch, 1967; Dess and Beard, 1984). While prior studies have highlighted the importance of environmental uncertainty in affecting firms' internal structures, decision processes and performance, they have not given a clear structure in which to assess the impact of distinct elements of the environment. In the absence of such structure, the research literature's characterization of uncertainty in the external environment has tended to remain at an aggregated level—for example, distinguishing between stable vs. variable (Lawrence and Lorsch, 1967), low vs. high velocity (Eisenhardt, 1989), and smooth vs. abrupt development (Suárez and Lanzolla, 2007). Although these aggregate characterizations have yielded important insights, we believe that a finer-grained level of analysis can offer additional findings.

Our results also suggest a modification to current approaches to analyzing networks. Network theory has concentrated on how the social structure of exchange relationships influences firm outcomes (Burt, 1992). A common operationalization is to examine the structure of ties among actors in a network, distinguishing between direct and indirect relationships. The current study introduces a sensitivity to the flow of activity within such networks, differentiating between upstream and downstream roles. This distinction raises a new set of questions regarding the impact of network ties to different roles within a network: we expect that the implications of direct ties will differ depending on whether one is considering a focal firm's direct upstream tie to its supplier or direct downstream tie to its customer; similarly, we expect the implications of indirect ties to depend on whether the link is upstream, to a supplier's supplier or downstream, to a complementor.

In considering our findings with regard to early mover advantage, the question arises: Shouldn't firms, in recognizing the effect of complement innovation challenges in delaying market adoption of new technologies, change their strategies and forgo early entry? Our field interviews suggest that firms, at least in our setting, are generally more focused on managing component challenges than complement challenges. Since the delivery of the firm's product is so dependent on the performance of suppliers, managerial attention seems to be especially focused on identifying any and all potential sources of production bottlenecks. In contrast, complement challenges command less attention—while it is clear that technology managers are largely responsible for production, who is responsible for complementors? Marketing and sales managers are the natural candidates, but their mandate is to focus on direct customer needs. In general, when customers discuss obstacles and opportunities with representatives of the focal firm, they tend to discuss the issues over which the firm has actual control (e.g., performance, delivery times, service levels, etc.) rather than external factors over which the firm is relatively powerless (e.g., progress of complements). This distinction raises an additional set of questions regarding how firms' external coordination requirements are reflected in their internal organizational structures.

The current study, of course, has a number of limitations. While we have taken care in our estimation and included firm and year dummies to account for unobserved differences across firms and time periods, there are several potential concerns with respect to endogeneity. Our focus is on the effect of component and complement challenges that arise during technology transitions. During these transitions, focal firms also faced innovation challenges in their core activities, but due to nonavailability of data we were unable to measure their extent. This omission could bias our results if focal innovation challenges were correlated with external challenges. However, descriptive evidence suggests that there is no systematic correlation between the core innovation challenge and challenges in components and complements. For example, in the proximity generation, while the tool manufacturers faced significant challenges in designing and manufacturing the new architecture, there were no major changes required anywhere else in the ecosystem. For completeness, we do control for the fact that incumbents are likely to

face greater challenges across the technological transitions than entrants as discussed by Henderson and Clark (1990) and find support for this argument.

In addition, although we characterize the location relationships among ecosystem actors, we have no visibility as to the history and nature of specific exchange relationships among these actors and how these might affect their interactions (Argyres and Liebeskind, 2002). Future studies could address these limitations by incorporating how actors coordinate through mechanisms such as alliances and relational contracts within the context of innovation ecosystems.

Finally, the current study is conducted in the context of a single industry, such that its replication in other contexts would extend its generalizability. Although we believe that the underpinning drivers we have identified hold across settings, it is quite possible that their effects can be drowned out by other factors that can dominate in other settings (e.g., strategic interactions, the specific nature of technological change, demand uncertainty, modes of cross-firm coordination, etc.). As such, we view this study as presenting a baseline structure upon which other factors and considerations can be overlaid. In this regard, we are careful to characterize our hypotheses and findings as regarding the extent, rather than the absolute level of early mover advantages.

This study has presented an ecosystem lens to examine the conditions under which technology leadership yields competitive advantage. We have argued and shown that the benefit of technology leadership depends on both the location and the magnitude of uncertainty within the ecosystem. We have examined the effectiveness of vertical integration as a strategy to manage ecosystem uncertainty and have identified the impact of the technology life cycle in determining its benefits.

Ecosystem settings raise a new set of issues for both researchers and managers to consider. Choices regarding both business model design and organization design need to be revisited in the light of joint value creation. Questions regarding development incentives (Casadesus-Masanell and Yoffie, 2007), positioning and coordination choices (Iansiti and Levien, 2004; Gawer and Cusumano, 2002), customer expectations (Adner, 2004), and value chain configuration (Jacobides and Billinger, 2006) all become more visible and more important in the context of ecosystems. We hope that our

developed framework and analysis can offer additional avenues along which such questions can be fruitfully addressed.

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APPENDIX: ROBUSTNESS TESTS

Table A1. Test of Hypotheses 1 and 2 using OLS regression; dependent variable = Ln(firm's cumulative market share in a given technology generation)

	Model 7	Model 8	Model 9	Model 10	Model 11 ^a
Technology leadership * component challenge		-0.044* (0.023)		-0.049** (0.019)	-0.049** (0.021)
Technology leadership * complement challenge			0.048* (0.027)	0.052** (0.025)	0.053* (0.027)
Technology leadership	-0.125 (0.081)	-0.153** (0.067)	-0.136 (0.083)	-0.168** (0.075)	-0.155* (0.089)
Component challenge	-0.107 (0.106)	-0.107 (0.105)	-0.074 (0.104)	-0.072 (0.102)	-0.099 (0.149)
Complement challenge	0.259*** (0.084)	0.239*** (0.073)	0.245*** (0.082)	0.220*** (0.072)	0.161 (0.110)
Vertical integration	1.553*** (0.269)	1.681*** (0.274)	1.439*** (0.277)	1.574*** (0.286)	1.878*** (0.409)
Incumbent	-0.483 (0.689)	-0.502 (0.636)	-0.403 (0.766)	-0.419 (0.707)	-0.406 (1.029)
Conglomerate	1.474** (0.648)	1.368** (0.659)	1.370* (0.683)	1.242* (0.694)	1.111 (0.950)
Constant	-3.821*** (0.393)	-3.818*** (0.396)	-3.834*** (0.361)	-3.832*** (0.365)	-4.010*** (0.589)
R-squared	0.36	0.39	0.40	0.43	0.43
Observations	64	64	64	64	50

Standard errors in parentheses, clustered by firm, * significant at 10%; ** significant at 5%; *** significant at 1%.

^a Model 11 excludes observations from X-ray and e-beam generations.

APPENDIX (CONTINUED): ROBUSTNESS TESTS

Table A2. Test of Hypotheses 1 and 2 by modifying the panel from 'firm in a given generation' to 'firm' and using the firm fixed effects estimation approach; dependent variable = Ln(firm's market share in its most recent technology generation)

	(1)	(2)	(3)	(4)
Technology leadership * component challenge		-0.027*** (0.009)		-0.030*** (0.009)
Technology leadership * complement challenge			0.013 (0.009)	0.017** (0.009)
Technology leadership	-0.103*** (0.022)	-0.106*** (0.022)	-0.108*** (0.023)	-0.114*** (0.023)
Component challenge	0.056 (0.043)	0.084* (0.043)	0.065 (0.043)	0.099** (0.044)
Complement challenge	0.101*** (0.027)	0.077*** (0.028)	0.088*** (0.029)	0.058** (0.030)
Incumbent	-0.844*** (0.158)	-0.848*** (0.156)	-0.746*** (0.170)	-0.720*** (0.169)
Generation sales growth	-0.001 (0.000)	-0.001 (0.000)	-0.001 (0.000)	-0.001 (0.000)
Number of firms	-0.178*** (0.024)	-0.173*** (0.024)	-0.175*** (0.024)	-0.170*** (0.024)
Constant	-0.719*** (0.148)	-0.757*** (0.147)	-0.792*** (0.156)	-0.858*** (0.155)
R-squared (within)	0.24	0.26	0.24	0.27
Observations	406	406	406	406

Standard errors in parentheses.

* significant at 10%; ** significant at 5%; *** significant at 1%.