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What Firms Make vs. What They Know: How Firms' Production and Knowledge Boundaries Affect Competitive Advantage in the Face of Technological Change

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Product innovation often hinges on technological changes in underlying components and architectures, requiring extensive coordination between upstream component development tasks and downstream product development tasks. We explore how differences in the ways in which firms are organized with respect to components affect their ability to manage technological change. We consider how firms are organized in terms of both division of labor and division of knowledge. We categorize product innovations according to whether they are enabled by changes in components or by changes in architectures. We test our predictions in the context of the global dynamic random access memory industry from 1974 to 2005, during which it transitioned through 12 distinct product generations. We find that vertically integrated firms had, on average, a faster time to market for new product generations than nonintegrated firms. The performance benefit that firms derived from vertical integration was greater when the new product generation was enabled by architectural change than when it was enabled by component change. We also find that although many nonintegrated firms extended their knowledge boundaries by developing knowledge of outsourced components, the performance benefits from such knowledge mostly accrued to "fully nonintegrated" firms (i.e., those that did not vertically integrate into any upstream component), rather than "partially integrated" firms (i.e., those that vertically integrated into some components but not others). Our study makes a strong case for the value of integrating the knowledge- and governance-based theoretical perspectives to broaden our examination of how firms organize for innovation and to uncover the technological and organizational sources of performance heterogeneity.

Key words: firm boundaries; vertical integration; knowledge integration; time to market; architectural innovation
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Introduction

In many industries, firms' ability to sustain their competitive advantage depends on their ability to manage technological change. A well-established body of work within the innovation literature has explored the ways in which technological change affects the performance of incumbent firms (e.g., Cooper and Schendel 1976, Tushman and Anderson 1986, Henderson and Clark 1990, Christensen 1997). Relatively neglected in this literature, however, is the exploration of how the relationship between technological change and firm performance is affected by ways in which firms are organized with respect to upstream components.

This gap is somewhat surprising because several of the foundational studies in the literature have explicitly considered the systems view of technology, clarifying the ways in which technological changes in products are driven by changes in components (Rosenberg 1982, Clark 1985, Henderson and Clark 1990, Christensen 1992). Scholarly work has been confined to a handful of theoretical papers proposing a match between firms' vertical integration choices and the type of technological change (Teece 1988, 1996; Wolter and Veloso 2008) and an empirical study by Afuah (2001) that examines the relationship between vertical integration and firm performance in the computer workstation industry during the shift from complex instruction set computing to reduced instruction set computing technology.

One possible reason for this limited attention could be the distinct intellectual origins of the two theoretical perspectives that are relevant to this line of inquiry—transaction cost economics (Williamson 1975, 1985) and the knowledge-based view (e.g., Nelson and Winter 1982, Kogut and Zander 1992, Teece et al. 1997). Transaction cost economics, although very influential in explaining why a given transaction may be more efficiently governed through either the market or the hierarchy, has not explicitly considered evolutionary processes within an industry (Williamson 1985, Jacobides and Winter 2005, Argyres and Bigelow 2007). The knowledge-based view, although very influential in explaining firm heterogeneity and competitive advantage as industries and technologies evolve, has not explicitly considered the comparative logic of markets versus firms (Williamson 1999, Nickerson and Zenger 2004). Another possible reason for the lack of empirical work is the challenge of obtaining detailed historical data that not only characterize product innovations according to the different types of technological change but also characterize focal firms according to how they are organized with respect to upstream and downstream activities (Wolter and Veloso 2008).

In this study, we draw on recent theoretical advances that have extended the comparative logic of transaction cost economics to the knowledge-based view (Nickerson and Zenger 2004), as well as advances that have broadened the traditional view of firm organization as implied by transaction cost economics, to consider not only the division of labor but also the division of knowledge (Brusoni et al. 2001, 2009; Takeishi 2002). In so doing, we are able to consider a broader menu of choices to explore how firm organization interacts with different types of technological change to shape performance outcomes.

We follow Nickerson and Zenger's (2004) problem-solving perspective to the theory of the firm. Their theory argues that the efficient choice of market versus hierarchy depends on the complexity of the problem that the firm is trying to solve. We consider the commercialization of new product innovation as the problem that the firm is trying to solve. We assess the effectiveness of firm boundary choices in solving this problem according to the speed with which firms solve this problem. We extend Nickerson and Zenger's (2004) theoretical framework in two ways: first, by arguing that firms pursuing the market form of governance may benefit from their investments in the knowledge of outsourced activities; and second, by linking problem complexity to the nature of technological change underlying product innovation.

To conduct our study, we assembled a unique data set from the global dynamic random access memory (DRAM) industry between 1974 and 2005. During this period, the industry transitioned through 12 distinct product generations. The data set characterizes technological changes that underlie each of the 12 product generations and includes information on firms' market performance, vertical integration choices, and knowledge with respect to upstream components. We measured firm performance as the time to market for a new product generation, a key driver of competitive advantage in this industry (Integrated Circuit Engineering 1983, Methe 1992, Enz 2003). The main difference among product generations was that some of them were enabled by changes in components, whereas others were enabled by changes in architecture (Henderson and Clark 1990). An appealing feature of the DRAM industry is that it offers natural controls for a number of factors that have been the focus of extant literature on technological change. Each new product generation had superior technical performance compared with the previous generation (Foster 1986) and along the performance dimension that consumers demanded (Christensen 1997), was not competence destroying for the incumbents (Tushman and Anderson 1986), and preserved the value of complementary assets (Mitchell 1989). These natural controls make the DRAM industry an ideal setting in which to explore our research question.

We find that, in the context of the DRAM industry, vertically integrated firms had, on average, a faster time to market for new product generations than nonintegrated firms. Moreover, the performance benefit that firms derived from vertical integration was greater when the new product generation was enabled by architectural change than when it was enabled by component change. We also find that although many nonintegrated firms extended their knowledge boundaries by developing knowledge of outsourced components, the performance benefits from such knowledge mostly accrued to "fully nonintegrated" firms (i.e., those that did not vertically integrate into any upstream component within the architecture), rather than "partially integrated" firms (i.e., those that vertically integrated into some components but not others). We conducted a number of unstructured interviews with industry participants that enabled us to corroborate our findings and discuss their implications.

Although we are cautious in interpreting our findings in light of examining only one industry and using a specific measure of firm performance, our study makes a strong case for the value of integrating the knowledge- and governance-based theoretical perspectives to broaden our examination of how firms organize for innovation and to uncover the technological and organizational sources of performance heterogeneity.

Theory and Hypotheses

Product innovations are enabled by changes in components and architectures (e.g., Henderson and Clark 1990). Managing such technological changes requires close coordination between the activities that underlie the development of components and the activities that underlie the integration of those components into a final product. This is especially true when component technologies advance at nonuniform rates (Rosenberg 1982, Hughes 1983) or have technological interdependencies that require experimentation and learning for their potential to be realized (e.g., Iansiti 1998, Loch and Terwiesch 1998).

In their quest to attain competitive advantage with product innovations, firms face important trade-offs regarding their vertical scope (e.g., Teece 1988, 1996; Mahoney 1992; Argyres 1996; Poppo and Zenger 1998; Baldwin and Clark 2000; Leiblein and Miller 2003; Hoetker 2005; Novak and Stern 2008). Vertical integration offers a firm greater control over its innovation process and greater opportunities to accumulate knowledge about components and architectures, but it requires large capital investments and a broad set of technological capabilities. Outsourcing enables a firm to focus on its core capabilities, exploit a broader supplier base, and reduce capital investments, but it may hamper learning and adaptability. In industries characterized by rapid technological changes, these trade-offs are amplified because investments in production and technological capabilities must be made under greater uncertainty. However, control and adaptability are even more important as components and architectures evolve rapidly.

An alternative mode by which firms can organize for innovation and manage these trade-offs has been put forward by scholars who distinguish between division of labor and division of knowledge (Patel and Pavitt 1997; Fine 1998; Prencipe 2000; Brusoni et al. 2001, 2009; Takeishi 2002). According to this research stream, instead of vertical integration on the production side, firms' may choose to pursue "knowledge integration" such that they may develop knowledge of upstream components even as the production function is outsourced. Evidence of such differences between firms' production and knowledge boundaries has been presented through a multi-industry analysis of the world's largest corporations (Patel and Pavitt 1997), as well as through detailed expositions of firms in the aerospace, automotive, and metal-forming industries (Prencipe 2000, Ahmadjian and Lincoln 2002, Brusoni et al. 2001, Takeishi 2002, Parmigiani and Mitchell 2010).

How do investments in vertical integration and knowledge integration shape firms' effectiveness in managing technological change and commercialize new product generations? The answer to this question requires a theoretical approach that blends the comparative assessment of markets versus hierarchies (e.g., Williamson 1985, 1991) with the nature of coordination challenges associated with upstream component development tasks and downstream product development tasks in the face of a technology transition (e.g., Clark and Fujimoto 1991).

We build on the work of Nickerson and Zenger (2004), who, drawing from the knowledge-based and transaction cost perspectives, propose a problem-solving approach to the theory of the firm. They consider a firm as a problem-solving entity searching for solutions that require a combination of distinct knowledge sets. This is consistent with the innovation literature that treats new product development as a problem-solving exercise and the success of such an exercise as requiring a combination of component and architectural knowledge (Henderson and Clark 1990). Firms conduct experiments, or trials, to search for the solution which may entail the use of experience-based and cognitive-based search processes (Cyert and March 1963, Gavetti and Levinthal 2000). In searching for the solution, firms require extensive knowledge sharing and a coordinated pattern of trials between the different parties. However, such interactions may be subject to knowledge formation hazards, because parties may act opportunistically by not sharing knowledge (Arrow 1973) or by shaping trials and solution search in ways to extract greater personal benefits. The extent of these hazards affects the speed with which valuable solutions are discovered and the cost of doing so.

Nickerson and Zenger (2004) argue that the relative effectiveness of markets versus hierarchies in the search for solutions depends on the nature of the problem that the firm is trying to solve. They follow Simon's (1962) typology of complex systems to characterize problems as decomposable, nearly decomposable, or non-decomposable. They suggest a correspondence between problem complexity and mode of governance whereby markets are more effective at finding solutions to more decomposable problems, whereas hierarchies are better suited to finding solutions to less decomposable problems.

We extend Nickerson and Zenger's (2004) theoretical framework in two ways: first, by considering the role of knowledge integration for firms pursuing market form of governance; and second, by linking problem complexity to the nature of technological change underlying product innovation. We consider the commercialization of a new product generation as the problem that the firm is trying to solve. We assess the relative effectiveness of the different modes of organization according to the firms' time to market for the new product generation. A faster time to market is an important driver of competitive advantage (Lieberman and Montgomery 1988, Stalk and Hout 1990, Brown and Eisenhardt 1995) and is frequently used as a key indicator of success by the new product development literature (Wheelwright and Clark 1992, Brown and Eisenhardt 1995).

Managing technological changes underlying a new product generation requires extensive knowledge sharing as well as coordination of efforts between firms and their component suppliers (Clark and Fujimoto 1991, Takeishi 2002).[1] Given the uncertainty of technological change, firms are subject to hazards associated with insufficient knowledge exchange between them and their component suppliers as well as hazards associated with suppliers underinvesting in component development tasks. Hierarchies mitigate such hazards by granting firms the decision rights over the investments required for solution search (Grossman and Hart 1986, Williamson 1991) and by facilitating the development of communication channels and codes to ease knowledge exchange (Arrow 1974, Kogut and Zander 1992, Monteverde 1995).

Compared with a nonintegrated firm, a vertically integrated firm will have superior knowledge exchange during the commercialization of product innovation and greater control over the activities underlying component and product development. Hence, we predict that vertically integrated firms will have a time-to-market advantage over nonintegrated firms in a new product generation.

Hypothesis 1 (H1). *A vertically integrated firm will have a time-to-market advantage over a nonintegrated firm in a new product generation.*

Although vertical integration may facilitate knowledge exchange and coordination of tasks between firms and component suppliers, we should not necessarily expect all firms to vertically integrate. The literature has identified a number of constraints that may disincline firms from choosing to vertically integrate. They may need to balance the benefits against the cost of integration (Walker and Weber 1984, Williamson 1985). If firms do not enjoy significant economies of scale and scope from their investments in vertical integration, they may be better off procuring those components from external suppliers.[2] This constraint is exacerbated in industries characterized by rapid technological change as capital investments in vertical integration would bear a greater risk due to the likelihood of technological obsolescence (Balakrishnan and Wernerfelt 1986, Afuah 2001). The choice to vertically integrate may also require consideration of the relative differences between firms' capabilities and those of the suppliers (e.g., Argyres 1996, Williamson 1999). If suppliers possess superior capabilities, firms may be further inclined toward outsourcing.

Firms that do not vertically integrate into production may nonetheless pursue an alternative mode of coordination. An emerging research stream has proposed viewing firm organization through the lens of division of knowledge rather than just through the traditional lens of division of labor (Patel and Pavitt 1997; Brusoni et al. 2001, 2009; Takeishi 2002). This stream considers the possibility that firms may invest in knowledge integration by developing knowledge of externally produced components.

Although Nickerson and Zenger's (2004) problem-solving perspective did not consider firms that use market form of governance but pursue knowledge integration, their arguments are equally applicable to this mode of organization. In their theoretical framework, they consider two types of hazards that firms are subjected to during solution search: hazards associated with inadequate exchange of knowledge between parties and hazards associated with parties influencing the pattern of trials for their own personal benefit. These hazards have a direct correspondence with the nature of benefits that innovating firms may derive from knowledge integration.

In the context of product innovation, knowledge integration will allow firms to craft superior contracts and create more effective monitoring mechanisms (Mowery 1983, Mayer and Salomon 2006, Argyres and Mayer 2007, Tiwana and Keil 2007). This will help mitigate hazards associated with suppliers making choices to increase their own personal benefits, e.g., underinvesting in component development tasks that may be specific to a firm. Second, it will also help mitigate knowledge exchange hazards between firms and their suppliers by improving the quality of communication. For example, Ahmadjian and Lincoln (2001, p. 689) provide evidence of how Toyota's investment in knowledge of electronics improved the quality of its communication with its key electronics supplier, Denso:

> Some supporting evidence comes from our interviews with Toyota engineers who stated that the quality of Toyota's discussions with Denso about parts design and manufacturing had risen since Toyota's investment in electronics learning began. Before, they said, Toyota people sometimes asked silly or naive questions in procurement negotiations with Denso. Now that Toyota was acquiring a solid knowledge base in the technology, the communication between the companies has improved.

Hence, knowledge of the external component can help firms using the market form of governance to improve knowledge exchange between them and their suppliers and better coordinate component development and product development tasks. Such knowledge will act as a "shift parameter" for the nonintegrated firm's effectiveness in the discovery of the solution and improve its time-to-market performance in a new product generation.

Hypothesis 2 (H2). *A nonintegrated firm's knowledge of the external component will improve its time-to-market performance in a new product generation.*

Product innovations can be categorized based on changes in components and architectures (Henderson and Clark 1990). Some product innovations are enabled by changes in components while preserving the architectural links and interactions among components. Other product innovations are enabled by changes in components as well as changes in the links and the interactions among them. According to Henderson and Clark (1990, p. 12), such architecture-enabled innovations are "triggered by a change in a component—perhaps size or some other subsidiary parameter of its design—that creates new interactions and new linkages with other components in the established product." Business and technology historians have provided numerous instances in which change in a given component creates "disturbances" in the rest of system that are eventually resolved through modifications in other parts of the system (Rosenberg 1982, Hughes 1983). These modifications may entail changes in other components as well as changes in the links and the interactions among components.

Nickerson and Zenger (2004) suggest that the relative efficiency with which a firm finds a solution to a problem depends on the fit between the problem complexity and the firm's governance mode. They draw on Simon's (1962) work on complex systems and characterize problem complexity according to whether problems are decomposable, nearly decomposable, or non-decomposable. As problem complexity increases from decomposable to nearly decomposable to non-decomposable, the value of solutions to the problems is increasingly influenced by the interaction between actors. In the case of decomposable problems, the discovery of a valuable solution can be made by actors conducting independent trials. However, in the case of non-decomposable problems, the discovery of a valuable solution requires extensive knowledge sharing and coordination of trials between actors.

An innovation that is enabled by a change in architecture requires extensive interactions between the product development and component development tasks. Such an architecture-enabled innovation represents the case of a non-decomposable problem (Nickerson and Zenger 2004), in which a change in any one component will impact other components in an unpredictable way, requiring extensive experimentation and knowledge sharing for the discovery of the desired solution. In contrast, product innovation that is enabled by changes in components while preserving the interactions and the links between them requires less extensive coordination between the product development and component development tasks. Hence, such a component-enabled innovation represents the case of a nearly decomposable problem in which a change in any one component will impact other components in a more predictable way, requiring less extensive experimentation and knowledge sharing for the discovery of the desired solution.

Compared with nearly decomposable problems, non-decomposable problems subject firms to greater hazards associated with insufficient knowledge exchange between them and their component suppliers, as well as with suppliers underinvesting in component development tasks (Nickerson and Zenger 2004). As a result, a hierarchy-based governance form should have a greater advantage over the market when product innovation is enabled by architectural change (non-decomposable problem) than when it is enabled by component change (nearly decomposable problem).

This prediction is also consistent with Teece's (1996) proposition that integrated firms would fare better in innovations requiring significant readjustments to other parts of the system. He defines such innovations as systemic innovations and provides insights into some of the key mechanisms driving this relative superiority of integrated firms:

> What is needed to successfully develop and commercialize systemic innovations are institutions with low-powered incentives, where information can be freely shared without worry of expropriation, where entities can commit themselves and not be exploited by that commitment, and where disputes can be monitored and resolved in a timely way. This is precisely what multi-product integrated firms achieve. (Teece 1996, p. 219)

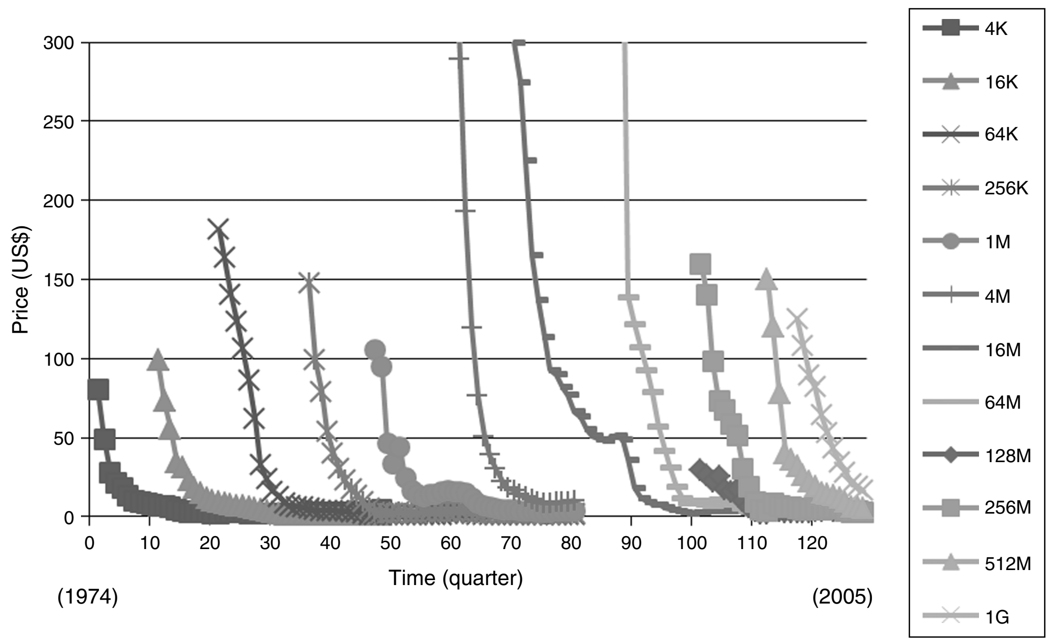
Hence, we expect that the time-to-market advantage for vertically integrated firms over nonintegrated firms will be greater when the new product generation is enabled by architectural change than when it is enabled by component change.

Hypothesis 3 (H3). *A vertically integrated firm will have a greater time-to-market advantage over a nonintegrated firm when the new product generation is enabled by architectural change than when it is enabled by component change.*

Innovation in the Global DRAM Industry

We test our predictions in the context of the global DRAM industry. This industry presents an ideal setting in which to explore how firm boundaries shape performance during periods of technological change. First, it is a highly competitive industry, with firms aggressively competing to introduce new product generations and expand capacity (Methe 1992, Salomon and Martin 2008). From 1974 to 2005, 12 distinct DRAM product generations were introduced into the market. Once a new generation is introduced, a steep learning curve and intense competition combine to result in sharp price erosion (Irwin and Klenow 1994, Hatch and Mowery 1998). Figure 1 shows the price trend for the different DRAM generations. For this reason, faster time to market for a new product generation has been an important source of competitive advantage in the industry (Integrated Circuit Engineering 1983, Methe 1992, Enz 2003). Second, throughout the industry's history, the key component technologies have been characterized by a high degree of coordination between component suppliers and product firms. Despite the coordination challenges, firms in the industry have exhibited significant differences in their vertical scope. Third, each firm introduces the new DRAM generation with essentially the same product characteristics as required by industry standards. Hence, firms' product innovations for a given generation represent functionally equivalent solutions. Comparing differences in firms' time-to-market performance for a given product generation is less likely to suffer from biases as a result of unobserved differences in product characteristics (e.g., Martin and Salomon 2003). Note, however, that although DRAMs of a given generation are similar

Figure 1 Price Trend for the Different DRAM Generations



along some key characteristics, the manufacturing processes behind them are highly idiosyncratic and proprietary. It is the challenge of managing the manufacturing processes that underlie the physical product that makes this a highly relevant setting for us.

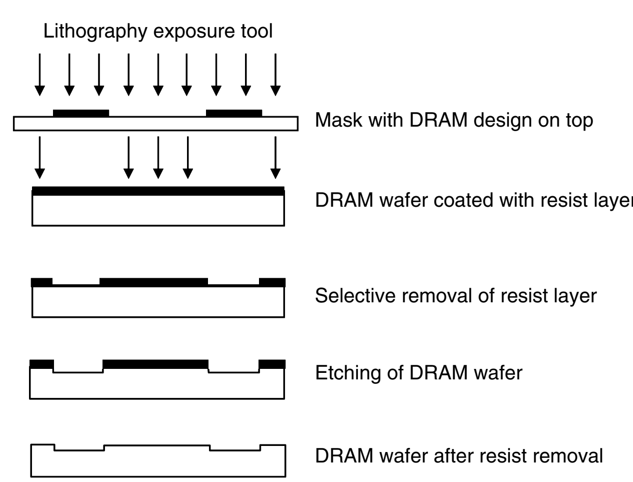
Component Technologies and Technological Change in the DRAM Industry

Since its emergence in the late 1960s, the DRAM industry has been viewed as the main engine of growth for the entire semiconductor value chain. Because of advances in computing applications, the industry is under continuous pressure to introduce new product generations that increase the memory density of the DRAM chip.[3] Of the many processes required to manufacture a DRAM chip, the lithography process, illustrated in Figure 2, plays the most critical role in allowing for the introduction of new DRAM generations (Moore 1995, Martin and Salomon 2003).

Components can be physical elements within the product architecture (e.g., Henderson and Clark 1990) or, as is the case here, inputs to the production process (e.g., Henderson and Cockburn 1994). The three key component technologies that are integrated in the lithography process are the *mask*, the *resist*, and the *alignment equipment*. The lithography process takes place when beams of ultraviolet (UV) light from the alignment equipment are directed onto the mask. The mask bears the blueprint of the DRAM chip design. Because the DRAM chip is made up of several stacked layers, each characterized by a unique circuit design, several unique masks are used to create a single DRAM chip. The mask allows a portion of the light to pass through onto the semiconductor substrate. The substrate, a silicon wafer, is coated with a layer of energy-sensitive chemical resist. The resist undergoes a chemical reaction wherever the mask allows the light to pass through. This chemical reaction changes the structure of the resist and allows its selective removal from the wafer through a developing process. Another chemical process is then initiated in which the exposed parts of the wafer are etched. The remaining resist is then removed, creating a final circuit that replicates the initial DRAM design. A typical DRAM chip goes through this process a number of times to sequentially build integrated circuits with different mask designs.

DRAM firms' commercialization of new generations depends in large part on the progress in the alignment equipment, resist, and mask component technologies.

Figure 2 Schema of Semiconductor Lithography Technology



Although all three component technologies have progressed at fast rates, their progress has not been uniform, giving rise to technological bottlenecks (Adner and Kapoor 2011) and creating significant coordination challenges for firms in the DRAM industry. Moreover, the integration of these component technologies during the commercialization stage requires extensive experimentation and firm-specific learning. For example, a manager from a supplier of mask technology commented,

> We can offer our technology to our customer, but how that technology works in the customer's facility is very much a function of how the customer integrates the different technologies, and we typically go back and forth until the technology is implemented in production.

Component Technologies and Interactions. For a DRAM firm, the commercialization of a new product generation requires close collaboration among personnel in the product design, process technology, and manufacturing engineering groups. This collaboration between the design and manufacturing activities is consistent with the concept of "unstructured technical dialog" discussed by Monteverde (1995). In DRAM production, the mask represents the blueprint of a firm's product design and is used to develop and scale up the manufacturing process. The mask is thus the bridge through which this unstructured technical dialog takes place. Mask production is normally located in close geographic proximity to semiconductor manufacturing. This is because of the combination of intense pressure to be early to market with a new DRAM innovation and the complex iterations between DRAM firms and their mask suppliers. Our interviews with industry experts confirmed this aspect of coordination. For example, a technical manager with a leading semiconductor manufacturer commented,

> From lab to production, there are typically three to four mask redesigns.... Your designers come to you and say, "We are going to change the chip design," and you should be able to implement it [the new mask design] very quickly.

The development of a new product generation also includes extensive experimentation with different types of resist. The suitability of resist is evaluated based on its coating uniformity on the semiconductor substrate, its interaction with the alignment tool, and its stability during the chemical processes of developing and etching. A DRAM manufacturer invests significant amounts of effort and resources over many months in finalizing its choice of resist for a new DRAM production process. Once a particular resist is finalized in a firm's process "recipe," changes are time consuming and extremely costly. In addition, DRAM firms invest in dedicated equipment for downstream processes in their manufacturing lines that may be specific to a given resist chemistry.

The alignment equipment is the final component technology within the lithography architecture. As with the resist component, firms invest significant resources in selecting alignment equipment from a limited number of suppliers. In addition, firms incur dedicated investments for integrating the equipment into their manufacturing lines and creating the infrastructure for maintenance.

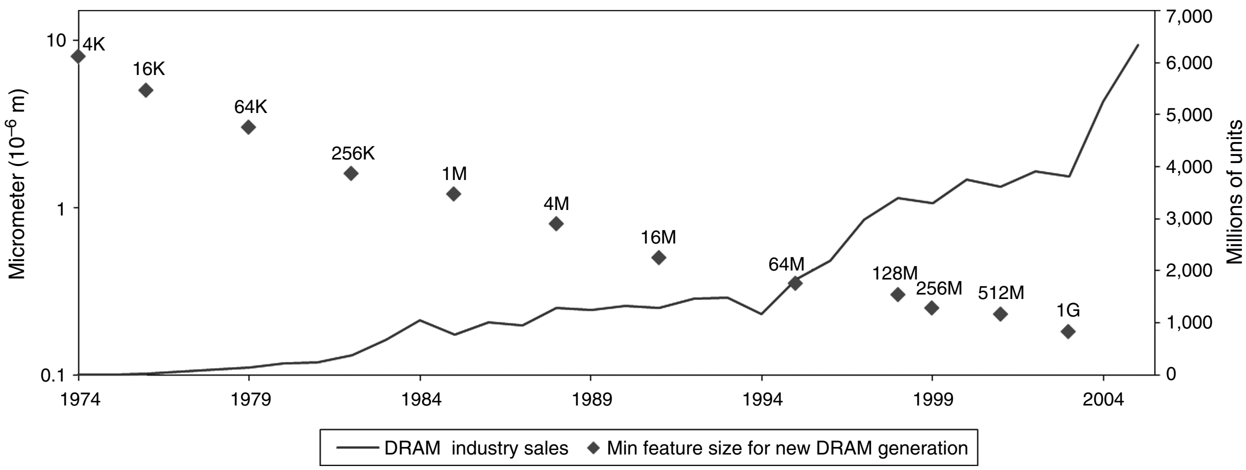
Component Technologies and Firm Boundaries. All three lithography component technologies exhibit a high degree of interaction with a DRAM firm's product development activities. For this reason, vertical integration of these components should yield superior coordination of the activities that underlie the commercialization of a new product innovation. However, the decision to vertically integrate is also dependent on production costs and firm capabilities (e.g., Walker and Weber 1984, Argyres 1996). During the time period we studied, some DRAM firms integrated into the production of masks, no firm integrated into the production of resist, and only one firm (Hitachi) integrated into alignment equipment.

Although there are high coordination requirements between the resist component development and DRAM development, the internalization of resist production imposes significant requirements in terms of investment and capabilities. The fact that all DRAM manufacturers outsource resist production can be seen as an indicator of the dominance of the latter set of concerns over the former. In particular, because chemical compositions are continuously changing, resist producers are required to incur large recurring investments to keep up with the pace of technological change. These costs are best borne by producers who are able to deploy these investments over a sufficiently large customer base. Historically, only large specialized chemical suppliers such as Kodak, Hoechst, and Shipley, which benefit from economies of both scale and scope through their participation in other chemical markets, have manufactured resist for semiconductor manufacturing.

As with the resist, the lack of vertical integration into alignment equipment is also explained through differences in production costs and capabilities between firms and their suppliers. Because the development and production of alignment equipment requires advanced capabilities in optics and mechanics, this market has historically been dominated by specialist suppliers. Not only do these specialist firms (e.g., Nikon and Canon) possess superior optics and mechanics capabilities but they also benefit from economies of scope through participation in multiple imaging-based markets such as consumer cameras, medical imaging, and optoelectronics.

We found that some of the DRAM firms that did not integrate into the production of key components nevertheless invested in the knowledge of such components. As discussed below, our examination of patents granted to DRAM firms showed that they invested in the knowledge of components even when they outsourced their

Figure 3 Introduction of New DRAM Generations, Minimum Feature Size, and DRAM Industry Sales



production. This finding is consistent with prior examination of knowledge boundaries (Patel and Pavitt 1997, Brusoni et al. 2001, Takeishi 2002), and we explore how such knowledge of external components affects firms' time-to-market performance in new product generations.

New DRAM Generations and the Nature of Technological Change. Since the emergence of the DRAM industry with the introduction of the 1-kilobit (1K) DRAM, there have been 12 new generations from 1974 to 2005. Each new generation was enabled by DRAM firms' reduction of the minimum feature size, the smallest circuit dimension printed on a DRAM chip. This reduction was largely attributable to progress in the lithography technology. Figure 3 plots the introduction of different DRAM generations and the minimum feature size in micrometers (μm, equal to 10^{-6} m) that was achieved through improvements in the lithography process.

Although the new DRAM generations were commercialized through improvements in the alignment equipment, resist, and mask, there were important differences in the nature of the technological changes across these generations (Kapoor and Adner 2007). Table 1 lists the different DRAM generations, the minimum feature size, and the key changes in the lithography technology that enabled the commercialization of each new product generation. As depicted in the table, all generations entailed changes to the core lithography technology. However, whereas some generations entailed changes to the individual components without a significant change in the critical interactions among components, others entailed changes to both the individual components and the critical interactions among them. We characterize the former as component-enabled innovations and the latter as architecture-enabled innovations.

For example, in the 64K DRAM generation there was a change in lithography technology from the proximity printing to the projection printing method. Projection printing entailed gradually scanning the energy field across the wafer, which differed from earlier approaches that exposed the entire wafer all at once. This was an architectural innovation that required changes not only in the design of the alignment equipment but also in the relationship between the alignment equipment and the mask. Whereas in the previous DRAM generations the principal driver of the productivity of the lithography process had been the alignment equipment, the introduction of projection printing shifted the emphasis from the alignment equipment to the mask. To meet this change, mask producers had to significantly improve their production process to deliver "perfect" masks and closely interact with DRAM manufacturers during the development stage to minimize any productivity losses. In contrast, the commercialization of the 1-megabit (1M) DRAM generation was achieved through changes in components within the same technology architecture as the previous product generation.

Methodology

Data

We used both primary and secondary data for this study. The data were collected during an 18-month field study from the fall of 2006 to the spring of 2008. The primary data were collected through a series of interviews with more than 20 industry experts. The interviews were semistructured and lasted two hours on average. The information from the interviews helped us to develop an understanding of the technology (architecture and key components), the extent of coordination challenges during new technology development between DRAM firms and their suppliers, the drivers of vertical integration, and the differences in the nature of technological changes underlying new product generations. We frequently followed up on our discussions through e-mails or phone calls. These allowed us to better match the context with our constructs and enabled us to corroborate our findings.

Table 1 Changes in Lithography Technology for Each DRAM Generation

DRAM generation (Year)	Minimum feature size (μm)	Description of major changes in components	Description of major changes in interactions among components	Type of technological change
1K (1970)	>8	N.A.		N.A.
4K (1974)	8.0	Change in the alignment equipment from the contact printing method, in which the entire wafer is in contact with the mask, to the proximity printing method, in which the mask is separated from the wafer with a tiny gap to improve process yield.		Component enabled
16K (1976)	5.0	Improvements in mask-making process and resist chemistry to print smaller circuits.		Component enabled
64K (1979)	3.0	Change in the alignment equipment from the proximity printing method, in which the entire wafer is exposed to the UV light all at once, to the projection printing method, in which the UV light is passed through the reflective lens system of the alignment equipment and through the mask onto the wafer.	Change in the interaction between the mask and the alignment equipment. Manufacturing performance is now driven by mask capability instead of alignment equipment capability.	Architecture enabled
256K (1982)	1.6	Change in the alignment equipment such that UV light is projected through a refractive lens system onto only a part of the wafer at any time; the mask is shifted across the wafer in steps such that multiple exposures are made across the wafer to complete the lithography process. The pattern on the mask is 5–10 times the DRAM circuits.	Interaction between the mask and the alignment equipment changes from scanning to stepping. Minimum feature size is now driven by the interaction between the alignment equipment and resist.	Architecture enabled
1M (1985)	1.2	Improvement in the resist chemistry to achieve smaller feature size.		Component enabled
4M (1988)	0.8	Improvement in the alignment equipment (increasing the size of the lens) and resist chemistry.		Component enabled
16M (1991)	0.5	Change in the wavelength of UV light emitted by the alignment equipment from 435 nm to 365 nm, accompanied by changes in the resist chemistry to absorb lower wavelength light.	Smaller wavelength changed the extent of transmission of UV through the alignment equipment lens and mask as well as the extent of absorption by the resist.	Architecture enabled
64M (1995)	0.35	Improvement in the alignment equipment by increasing the size of the lens; improvements in mask-making process and resist.		Component enabled
128M (1998)	0.30	Improvement in the alignment equipment by increasing the size of the lens; improvements in mask-making process and resist.		Component enabled
256M (1999)	0.25	Change in the wavelength of UV light emitted by the alignment equipment from 365 nm to 248 nm, accompanied by changes in the resist and mask material to absorb lower wavelength light.	Smaller wavelength changed the extent of transmission of UV through the alignment equipment lens and mask and the extent of absorption by the resist. New mask techniques such as the phase-shift mask and optical proximity correction are employed to obtain smaller features.	Architecture enabled
512M (2001)	0.23	Improvement in the alignment equipment by increasing the size of the lens; improvements in mask-making process and resist.		Component enabled
1G (2003)	0.18	Improvement in the alignment equipment by increasing the size of the lens; improvements in mask-making process and resist.		Component enabled

Table 2 Description of the Secondary Data Used for the Study

Secondary data sources	Data
Gartner Dataquest	Quarterly DRAM shipment by firm, quarterly DRAM price, DRAM feature size
VLSI Research	DRAM firm annual sales
U.S. Patent and Trademark Office	Patents granted to DRAM firms
Rose Reports	DRAM firms' participation in mask production
Reynolds Consulting	DRAM firms' participation in mask production
Grenon Consulting	DRAM firms' participation in mask production
IC Knowledge	DRAM feature size
SPIE Conference Proceedings (technical articles)	Changes in component technologies of alignment equipment, resist, and masks for DRAM generation; changes in relationships between different components; DRAM feature size
Industry articles by analysts	Changes in component technologies of alignment equipment, resist, and masks for each DRAM generation

Notes. We had to use multiple sources for firms' make-or-buy decisions for the mask technology because industry analysts providing such services operated at different time periods of the study. We used the overlapping years to check that the data between different sources were consistent. We found no discrepancies among the three sources. This is expected, because internal mask production was a "commonly" known fact in the industry.

The secondary data were collected from semiconductor industry analysis firms, industry publications, and the U.S. Patent and Trademark Office. Table 2 provides details of the sources of secondary data that we used to carry out the quantitative analysis in the study. Our sample includes every firm that ever sold a DRAM on the open market. We identified 36 firms in the DRAM industry that competed in 12 distinct DRAM generations, ranging from 4K to 1-gigabit (1G) memory density, between 1974 and 2005. In this study, we consider only the performance of incumbent firms (that is, we include firms as of their second generation of DRAM production). We do this because characterizing the effectiveness of a firm's transition across technology regimes requires an observation of the firm both before and after the change, and new entrants, by definition, do not have a prior state to observe. We also note that, in the context of the DRAM industry, incumbent firms have always been the leading innovators in the industry.

Measures

Dependent Variable. Our measure of firm performance is based on a firm's timing of the commercialization of a new DRAM generation, a key driver of competitive advantage in this industry (e.g., Integrated Circuit Engineering 1983, Methe 1992, Enz 2003). Research in strategy has considered firms' time of entry into new markets as an important driver of competitive advantage (Lieberman and Montgomery 1988). In addition, studies on innovation have used firms' timing of new product innovations as a key measure of performance (e.g., Schoonhoven et al. 1990, Brown and Eisenhardt 1995, Gatignon et al. 2002). The measure is also appropriate for testing a firm's ability to coordinate technological changes in its vertical chain so as to minimize delays in the commercialization of a new product innovation.

We measure a firm's *time to market* for a given DRAM generation as 1 plus the difference in the number of quarters (three-month periods) between the first shipment by the firm and first shipment in the industry. Hence, the first firm that commercializes the new generation takes the value of 1, and a firm that commercializes the generation three quarters after the first firm takes a value of 4. It is possible that the first shipment may represent a delivery of samples that may not meet all of the customers' requirements. Hence, the quarter in which the first shipment is recorded for a new DRAM generation may inappropriately characterize an early "sampler" as a full-fledged market pioneer. To check for this bias, we used two alternative commercialization thresholds in which the time to market was measured as the first quarters in which the firm shipped 100,000 and 250,000 units of the new DRAM generation. The results were robust to these alternative time-to-market measures.

Because DRAM firms introduce new product generations with similar characteristics (e.g., memory capacity, physical dimensions) as required by industry standards, our interpretation of results is unlikely to suffer from unobserved differences in product quality or attributes across firms. Furthermore, because no firm in the industry has ever "skipped" a technology generation, strategic nonparticipation is not an issue in our context. Finally, we examine all firms that have participated in the industry since its beginnings, and hence we do not face any left-censoring issues. The only generation for which we have potentially incomplete data is the 1G generation that emerged in 2003, into which three incumbents had yet to enter by 2005. Our econometric analysis accounts for these right-censored observations.

Independent Variables. The binary choice variable *outsource mask* takes a value of 1 if the DRAM firm outsourced the production of mask technology and a value of 0 if the firm is vertically integrated into mask technology in the year prior to its commercialization of the new DRAM generation. We measured a firm's knowledge in mask and resist technologies using patent data. We used Delphion's Corporate Tree feature to match different patent assignee names to specific DRAM firms. This step helped us to ensure that we are able to match patents to a specific firm even if they are filed under a different assignee name (subsidiaries, acquired firms, or typographical errors). We asked industry experts who have been associated with mask and resist research and development (R&D) to provide us with the most prominent technology subclasses associated with the two components. We identified the patent subclass 430/5 as the key technology subclass for mask technology and patent subclasses 430/270.1, 430/191a, 430/192a, 430/326, 430/325, 430/281.1, 430/190, and 430/311 as key technology subclasses for resist technology. We also confirmed the validity of the subclasses as a proxy for the knowledge underlying the components by examining the patents granted to specialized mask and resist manufacturers. The subclasses mentioned above dominated the patents for all specialized firms. The variables *mask knowledge* and *resist knowledge* are operationalized as the number of successful mask- and resist-related patent applications, respectively, filed by a DRAM firm in the three years preceding the firm's commercialization of a new DRAM generation. Similar patent-based measures have been used in prior studies to examine firm knowledge in a given technology (e.g., Henderson and Cockburn 1994, Hoetker 2005, Cattani 2005). As a robustness check, we included a five-year window for the patent-based measures of component knowledge. Because the primary subclass may underrepresent the knowledge that underlies the patent granted to a firm, we also included component knowledge measures using patents in which the mask or resist subclass is not restricted to the primary subclass. The results were robust to these alternative component knowledge measures.

Finally, we characterize the nature of technological change for each of the generations. The classification of these generations as either component enabled or architecture enabled is a key aspect of this study. To obtain this classification, we discussed the details of each technology transition with a number of industry experts, read technical articles from the annual lithography conference organized by the International Society for Optical Engineering (SPIE) since 1976, and read articles written by industry analyst firms such as Integrated Circuit Engineering, VLSI Research, and IC Knowledge. We identified the significant changes in the individual components of lithography technology—alignment equipment design, mask production process, and resist chemistry—that enabled each new DRAM generation. Such changes were present in every product generation (see the third column of Table 1). We also identified significant changes in the interactions among the alignment equipment, masks, and resist. Such changes were present in some generations but not others (see the fourth column of Table 1).

We tabulated these descriptions, circulated them among our industry experts, and made changes based on their feedback. We then recirculated the resulting table among our experts. All of the experts agreed with our final characterization of the changes in components and their interactions for the different DRAM generations.

With Table 1 complete and validated, we then coded the different DRAM generations according to whether the generation entailed changes in the critical relationships among key components (i.e., architectural change) or not. We defined the variable *architectural innovation* as taking a value of 1 if the new DRAM generation is enabled by an architectural change and 0 if it is enabled by component change.

Control Variables. We controlled for *firm size* as measured by the natural log of a firm's annual sales (in millions of dollars) in the year prior to its commercialization of a new generation. Firms in our sample vary in their degree of dependence on the DRAM market. Besides DRAMs, some of these firms are also active in other semiconductor markets. Burgelman's (1994) account of Intel's participation in both the DRAM and microprocessor markets suggests that the firm's market scope may influence its resource allocation toward the development of new product innovations. We controlled for this effect using the variable *non-DRAM sales*, measured as the percentage of a firm's sales in non-DRAM markets in the previous year. We also controlled for the product generation's minimum feature size. The variable *DRAM feature size* is defined as the natural log of the smallest circuit dimension printed on a DRAM chip in a given year. Because producing chips with smaller feature size entails a greater number of manufacturing steps and significantly increases the interaction between the manufacturing and designs tasks, DRAM feature size is a proxy for the complexity of a product generation (e.g., Hatch and Mowery 1998, Lieblein et al. 2002, Macher 2006, Salomon and Martin 2008).[4] Producing smaller feature sizes also requires the use of increasingly expensive manufacturing equipment. Because this increases the levels of capital investment required to produce not only the DRAM chips but also masks, DRAM feature size is also a proxy for the required degree of capital investment in a new product generation (Allen 2000, Muzio and Seidel 2000, Weber and Berglund 2005).[5] DRAM feature size thus increases both coordination requirements (because of greater complexity) and investment requirements (needed for capital equipment purchases). Although we are unable to tease apart the complexity effect from the required scale of investment effect, the DRAM feature size measure ensures that these potential explanations are controlled for across generations.

Analysis

We use event history analysis to test our predictions. Because we are interested in estimating a firm's time to market, we use an accelerated failure time (AFT) class of models (Cox and Oakes 1984, Mitchell 1989, Schoonhoven et al. 1990). The basic AFT model is of the form

$$t_i = \exp(X_i \beta_x)\tau_i,$$

or

$$\ln(t_i) = X_i \beta_x + \ln(\tau_i),$$

where t_i is the firm's observed time to market for a new product generation, X_i is a vector of covariates, β_x is a vector of coefficients, and τ_i is the random disturbance term that has a specific distribution depending on the parametric assumption about the baseline hazard function. Several parametric forms of the hazard function are possible. We follow the procedure described by Cleves et al. (2008) to select the parametric form for our analysis. We initially used a flexible three-parameter generalized gamma distribution for our analysis. The gamma distribution is typically employed to evaluate an appropriate parametric model for the data. We used the Wald test to compare the results from the nested models and the Akaike information criterion to compare the results from the nonnested models. We found the Weibull distribution to be the most suitable parameterization of the hazard rate for our data (e.g. Mitchell, 1989, Bayus 1998). We also performed sensitivity analysis with the parametric lognormal model, piecewise exponential model, and semiparametric Cox proportional hazards models, and the results were robust to these alternative specifications. We used clustering to adjust the standard errors for possible within-firm correlation. Three of the incumbents had yet to commercialize the most recent 1G DRAM generation, and we treated these observations as right-censored.

A potential concern with the event history analysis is that we are unable to account for unobserved differences across firms that may systematically affect their decisions to outsource mask as well as their time-to-market performance. We explore three alternative estimation approaches to alleviate concerns that our estimates may be biased because of unobserved firm-specific effects. First, we use fixed-effects ordinary least squares (OLS) panel regression to help account for the time-invariant firm-level endogeneity. Given the limitation of OLS estimation for handling right-censored observations (Allison 1995), we exclude the final DRAM generation, 1G, from this analysis. Second, we use the instrumental variable quantile regression model to estimate firms' time to market while accounting for the endogeneity of firms' vertical integration choices (Koenker and Geling 2001, Abadie et al. 2002). Third, we explore the use of difference-in-differences estimation to identify the effect of firms' vertical integration on the time to market.[6] We discuss these additional analyses in the robustness checks section and report the results in Figure A.1 and Tables A.1 and A.2 in the appendix. The results were robust to these alternative approaches.

Results

The descriptive statistics and correlations for variables used in the regression analysis are reported in Table 3.

Table 4 provides results from the event history models. Model 1 includes control variables, *mask knowledge*, and *outsource mask* to test Hypothesis 1. Model 2 replicates Model 1 but uses data only from those firms that outsource mask production to test Hypothesis 2. Model 3 includes the effect of resist knowledge to test Hypothesis 2 for the full sample. Model 4 adds the direct effect of architectural innovation. Model 5 is the fully specified model that includes the interaction between *architectural innovation* and *outsource mask* to test Hypothesis 3.

We first discuss the estimates of the control variables and then the estimates of the independent variables. The effect of *firm size* is negative and significant. Hence, the larger the DRAM firm, the faster is its time to market. The effect of *non-DRAM sales* is positive but only moderately significant in Model 5, suggesting that greater participation in non-DRAM markets could potentially slow a firm's new DRAM technology development, because resources would need to be shared across multiple product lines. The effect of *DRAM feature size* is negative and significant. As feature size gets smaller, technology development becomes more complex, and firms, on average, take longer to commercialize new product generations.

The coefficient estimate for *outsource mask* is positive and significant in all models, suggesting that DRAM firms that do not integrate into mask production tend to commercialize new product generations later than their vertically integrated rivals. The result strongly supports Hypothesis 1, that vertically integrated firms will have a time-to-market advantage over nonintegrated firms in a new product generation. In Model 2, the coefficient estimate for *mask knowledge* is negative and significant. Among firms that outsource mask production, the greater a firm's mask knowledge, the faster its time to market for a new product generation. However, the estimated coefficient for *resist knowledge* (recall that all DRAM firms outsource the resist component) is negative but insignificant. Hence, although we find support for Hypothesis 2 with respect to the mask knowledge for firms that outsource mask production, we did not find support for Hypothesis 2 with respect to the resist knowledge for all firms that outsource resist production. The direct effect of *architectural innovation* on firm's time to market is positive and weakly significant in Model 4 but insignificant in Model 5. The coefficient estimate for the interaction term between *outsource mask* and *architectural innovation* is positive and significant. DRAM firms that outsource mask production have a greater time-to-market disadvantage compared with firms that integrate into mask production when the new product generation is enabled by architectural change than when it is enabled

Table 3 Descriptive Statistics and Correlations

	Log(*Time to market*)	*Mask knowledge*	*Resist knowledge*	*Architecture enabled*	*Firm size*	*Non-DRAM sales*	*DRAM feature size*
Entire sample ($N = 166$)							
Mean	1.58	4.84	3.66	0.40	6.73	0.64	−0.29
SD	0.92	9.28	7.43	0.49	1.55	0.35	1.19
Min	0.00	0.00	0.00	0.00	3.58	0.00	−2.41
Max	3.14	46.00	45.00	1.00	9.35	0.99	2.08
Correlations							
Mask knowledge	−0.31						
Resist knowledge	−0.32	0.52					
Architectural innovation	0.15	−0.14	−0.15				
Firm size	−0.48	0.48	0.45	−0.10			
Non-DRAM sales	−0.09	−0.33	−0.23	0.05	−0.05		
DRAM feature size	0.06	−0.53	−0.47	0.11	−0.58	0.56	
In-house mask ($N = 99$)							
Mean	1.28	4.24	4.68	0.41	7.20	0.78	−0.07
SD	0.91	7.24	8.54	0.50	1.32	0.22	1.09
Min	0.00	0.00	0.00	0.00	4.09	0.00	−2.21
Max	2.94	27.00	45.00	1.00	9.35	0.99	2.08
Outsource mask ($N = 67$)							
Mean	2.03	5.73	2.15	0.37	6.04	0.42	−0.61
SD	0.73	11.66	5.10	0.49	1.62	0.40	1.28
Min	0.00	0.00	0.00	0.00	3.58	0.00	−2.41
Max	3.14	46.00	20.00	1.00	9.00	0.99	2.08

Note. All correlations above 0.2 are significant at $p < 0.05$.

by component change. This result provides strong support for Hypothesis 3.

The interpretation of the estimated coefficients in Model 5 suggests that the time to market for firms that outsource mask production is 1.36 times longer than that for integrated firms when product generation is enabled by component change. This ratio increases to 1.89 times longer when product generation is enabled

Table 4 Accelerated Failure Time Estimates for Firms' Time to Market for New Product Generation

	(1)	(2)	(3)	(4)	(5)	(6)		(7)[a]	(8)[a]	
	All firms	Outsource mask	All firms	All firms	All firms	In-house mask	Outsource mask	All firms	In-house mask	Outsource mask
(1) *Outsource mask* (H1)	0.520***		0.454***	0.446***	0.310**			0.265*		
	(0.120)		(0.129)	(0.129)	(0.137)		(0.156)			
(2) *Mask knowledge* (H2)	−0.027***	−0.026***	−0.026***	−0.026***	−0.025***	−0.036***	−0.013***	−0.025***	−0.033**	−0.014***
	(0.007)	(0.005)	(0.007)	(0.007)	(0.007)	(0.011)	(0.003)	(0.007)	(0.014)	(0.002)
(3) *Resist knowledge* (H2)			−0.007	−0.006	−0.007	0.005	−0.053***	−0.007	0.004	−0.052***
			(0.009)	(0.009)	(0.009)	(0.011)	(0.005)	(0.009)	(0.011)	(0.004)
(4) *Outsource mask* × *Architectural innovation* (H3)					0.331***			0.307***		
					(0.117)			(0.115)		
(5) *Architectural innovation*				0.119*	−0.017	−0.014	0.286***	0.025	0.012	0.278***
				(0.065)	(0.084)	(0.099)	(0.063)	(0.075)	(0.099)	(0.063)
(6) *Firm size*	−0.187**	−0.115**	−0.194***	−0.199***	−0.203***	−0.267**	−0.124***	−0.209**	−0.274**	−0.116***
	(0.074)	(0.052)	(0.074)	(0.072)	(0.074)	(0.123)	(0.040)	(0.089)	(0.139)	(0.031)
(7) *Non-DRAM sales* (%)	0.195	0.056	0.164	0.191	0.211*	0.568*	0.146	−0.023	0.312	0.030
	(0.140)	(0.138)	(0.132)	(0.123)	(0.116)	(0.303)	(0.107)	(0.173)	(0.378)	(0.126)
(8) *DRAM feature size*	−0.202***	−0.157***	−0.225***	−0.234***	−0.233***	−0.281***	−0.175***	−0.211***	−0.231***	−0.189***
	(0.057)	(0.056)	(0.061)	(0.061)	(0.062)	(0.098)	(0.048)	(0.051)	(0.082)	(0.041)
Constant	2.868***	3.061***	2.974***	2.934***	3.007***	3.120***	2.961***	3.166***	3.306***	2.949***
	(0.479)	(0.268)	(0.481)	(0.475)	(0.478)	(1.011)	(0.182)	(0.625)	(1.161)	(0.147)
Observations	169	70	169	169	169	99	70	144	89	55
Time at risk	1,117	682	1,117	1,117	1,117	435	682	904	372	532
Weibull shape parameter	1.819	2.471	1.827	1.847	1.872	1.609	3.138	1.850	1.603	3.280
Log likelihood	−164.82	−47.14	−164.11	−163.20	−159.42	−107.61	−33.80	−138.27	−96.82	−24.07

Note. Standard errors are in parentheses, clustered by firm.
[a]Data exclude final product generation for firms that exited the industry.
*Significant at 10%; **significant at 5%; ***significant at 1% (two-tailed *t*-test).

by architectural change. Based on our data, this implies that, on average, integrated firms lead outsourcing firms by 2.37 quarters in commercializing component-enabled innovations and 5.85 quarters in commercializing architecture-enabled innovations. In assessing the economic significance of these commercialization lags, consider the steep price erosion in the industry as illustrated in Figure 1. The average quarterly price decline over the first two years of a new product generation is 21%. Early entrants into the market benefit from the higher prices and margins that hold before the market shifts to intense competition and commoditization. In addition, Irwin and Klenow (1994) provide evidence that early commercialization allows a pioneering DRAM firm to go down a steep learning curve and reduce its production cost compared with late entrants. They estimated a learning rate of about 20% for each of the DRAM product generations introduced between 1974 and 1992. Thus, the economic significance of time to market, affected by the combination of higher prices and lower costs, is quite meaningful.

Exploration of the Difference Between Firms That Integrate into Mask Production and Firms That Outsource Mask Production

The lack of support for Hypothesis 2 with respect to resist knowledge, in which we predicted that all DRAM firms will derive benefits from their investment in resist knowledge, was surprising to us, especially given that we found strong support for the hypothesized effect with respect to mask knowledge.

To explore this further, we split the sample between firms that vertically integrate into masks and firms that outsource mask production. The results are reported in Model 6. The coefficient estimate for mask knowledge was negative and significant for firms that produce masks as well as for firms that outsource mask production. However, the estimated coefficient for resist knowledge is negative and significant *only* for firms that outsource mask production, but it is insignificant for firms that integrate into mask production. Hence, resist knowledge seems to improve the time-to-market performance for firms that outsource both mask and resist components but not for firms that integrate into masks. We discuss this unexpected finding in the next section. The interpretation of coefficients in Model 6 suggests that for firms that outsource both mask and resist components, a one-standard-deviation increase in mask (resist) knowledge lowers their time to market by 14.1% (23.7%). For an average firm, this implies a reduction in time to market by 1.36 (2.29) quarters.

Finally, the estimated coefficient for architectural innovation is positive and significant for firms that outsource mask production. In contrast, the nature of technological change does not seem to affect the time-to-market performance for firms that are vertically integrated into mask. This finding supports the proposition that firms that outsource mask production face greater challenges than firms that integrate into mask production when the new product generation is enabled by architectural change than when it is enabled by component change.

Robustness Checks

Because many DRAM firms exited the industry between 1974 and 2005, we checked for the possibility of survival bias. We did this by excluding data for each firm's last product generation prior to its exit from the industry. To the extent that the "final" generation may be a firm's weakest attempt to enter the new product generation, this revised specification should help to account for this possibility. The coefficient estimates, reported in Models 7 and 8, continue to have similar magnitude and significance levels as our main results. We also explored whether there are systematic differences in the exit patterns between firms that integrate into mask production and those that outsource mask production. We compared the industry tenure of firms in the two groups. The mean industry tenure for the 10 firms that integrated into mask production and exited the industry was 16 years. The mean industry tenure for the 15 firms that outsourced mask production and exited the industry was 13.3 years. The difference in industry tenure between the two groups was statistically insignificant ($p = 0.36$). Hence, we do not find support for a systematic difference in the survival propensity of the two groups.

We also tested for the sensitivity of our results to three alternative estimation techniques. First, we use firm-effects panel regression to account for time-invariant unobserved differences across firms, and the results are reported in the appendix. We note that only 7 of the 36 firms in our data switched their mask production strategy over the period of the study, and these switches were never reversed. This limited within-firm variance makes the fixed-effects estimation for the outsource mask variable relatively imprecise. Hence, we report results from both the random-effects and fixed-effects models to test Hypothesis 1. We use log-transformed time to market as the dependent variable. Although the coefficient estimate for outsource mask is positive, it is significant only in the random-effects model. We performed a Hausman test comparing the estimates from the random-effects and the fixed-effects models. We were unable to reject the null hypothesis that the firm effects are random ($\chi^2 = 5.20,\ p = 0.74$), suggesting that the estimates obtained using the random-effects model are consistent. Finally, the results for mask knowledge, resist knowledge, and architectural innovation obtained using fixed-effects models were similar to our main results obtained using hazard models. Second, we explore the use of difference-in-differences (DD) estimation to identify the effect of vertical integration on firms' time to market. To perform DD estimation, we created dummy variables for firms that were treated (switched their vertical integration strategy) versus untreated (did not switch) and for the pre- and post-treatment generations. Given that no two switches in the same direction took place during the same generational transition, we extracted seven different subsamples of treated and untreated firms for the pre- and post-treatment generations from our main data set. For example, the subsample where treatment was vertical integration (nonintegration), the untreated firms included all nonintegrated (vertically integrated) firms. We report the results for each of the seven subsamples identified by the treated firm in the appendix. Despite a small number of observations, making it difficult for us to obtain precise estimates, we found support for our prediction in three of the seven subsamples. Standard errors were too large to reject the null hypothesis in the remaining subsamples. We note that an important assumption for DD estimation is that the treatment is exogenous (e.g., Bertrand et al. 2004). In our context, this assumption implies that a firm's decision to switch its vertical integration strategy is uncorrelated with its time-to-market performance. This assumption may only partially hold, because firms may choose to vertically integrate to improve their time to market, or firms that are facing poor performance may choose to economize by divesting their mask-making operations.[7] Finally, we use quantile regression with instrumental variables to assess the robustness of our findings. Quantile regression methods have been applied to survival analysis by Koenker and Geling (2001) and Koenker and Bilias (2001), where the dependent variable is log-transformed time to event. This approach not only allows for the effect of covariates to vary over quantiles but also allows for greater flexibility regarding the effect of covariates on the time-to-market distribution. To account for the endogeneity of regressors in quantile regression, scholars have developed instrumental variable techniques (Abadie et al. 2002). We use the number of mask suppliers as a "generation-varying" instrument for each firm. Prior research has identified small-numbers bargaining hazards resulting from the number of suppliers as being an important source of contractual hazards that firms may consider in their choice to vertically integrate (Pisano 1990, Leiblein et al. 2002). However, the number of suppliers is unlikely to affect firms' time to market for two reasons. First, firms typically work with one mask supplier during the technology development stage and may use multiple suppliers only when the technology has matured. Second, the number of suppliers may affect the extent of R&D investments in mask technology and the pace of progress of the industry as a whole, but it does not necessarily affect relative performance differences across individual firms. We follow the standard approach in the literature to report results from quantile regression by plotting the coefficient estimate against the quantile (see the appendix). Consistent with our main results, the estimated coefficient for *outsource mask* is uniformly positive and significantly different from 0.

Discussion and Conclusion

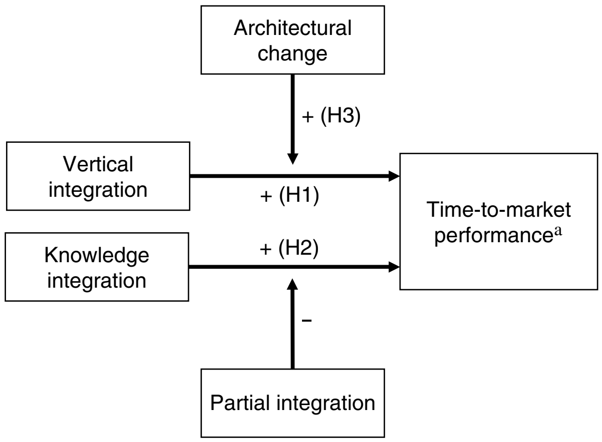
Product innovations are enabled by technological changes in components and architectures. We examine how differences in the ways firms are organized with respect to components affect their ability to manage technological change. We view firm organization based on both the division of labor and the division of knowledge (Brusoni et al. 2001). We categorize product innovations according to whether they are enabled by changes in components or by changes in architectures (Henderson and Clark 1990).

We build on Nickerson and Zenger's (2004) arguments that the efficient choice of market versus hierarchy depends on the complexity of the problem that the firm is trying to solve. We consider the commercialization of new product innovation as the problem that the firm is trying to solve. We extend Nickerson and Zenger's (2004) theoretical framework in two ways: First, we consider not only vertical integration but also knowledge integration (i.e., firms investing in knowledge of externally produced components). Second, we link the extent of problem complexity to the nature of technological change. Figure 4 summarizes our findings through a simple model of how component-level organizational choices (vertical integration and knowledge integration) and system-level contingencies (nature of technological change and partial integration) influence firms' time-to-market performance in a new product generation.

We conduct our analysis in the context of the global DRAM industry from 1974 to 2005. During this period, the industry transitioned through 12 distinct product generations, some of which were enabled by changes in components, whereas others were enabled by changes in architecture. We examine the determinants of firms' time to market for a new product generation, a key driver of competitive advantage in this industry.

We find that in the DRAM industry, vertically integrated firms achieve a time-to-market advantage over nonintegrated firms. In linking problem complexity with the nature of technological change, we argue that component-enabled product innovations present firms with nearly decomposable problems, whereas architecture-enabled product innovations present firms with non-decomposable problems. Consistent with our prediction, we find that the performance benefit from vertical integration is greater when the new product generation is enabled by architectural change than when it

Figure 4 A Simple Model Summarizing Our Findings in the DRAM Industry



[a]Higher firm performance implies a lower value for the firm's time to market.

is enabled by component change. Hence, the nature of technological change presents an important exogenous contingency for the relationship between vertical integration and firm performance.

We also find that although higher costs or the lack of capabilities may deter firms from vertical integration, many firms' pursued knowledge integration by developing knowledge of externally produced components (e.g., Brusoni et al. 2001, Takeishi 2002). The importance of knowledge of outsourced components was validated in our interviews with industry participants. For example, a manager in a firm that outsourced both mask and resist production commented on how knowledge of mask and resist facilitates the governance of supplier activities (e.g., Argyres and Mayer 2007):

> The expertise in resist and mask helps us to select suppliers but more importantly, it helps us to manage the ongoing process of evaluation and feedback with the supplier during technology development iterations…expertise in mask and resist helps you to design contracts…the actual people that do purchasing work very closely with engineers to create specifications when they create contracts…the last two [monitoring and writing of contracts] are more important aspects and gives more bang for your buck for investment in expertise.

A surprising result of our study was that firms' knowledge of external components seems to improve the time-to-market performance of lean firms (firms that outsource both mask and resist) but does not affect the performance of partially integrated firms that outsource resist but produce masks themselves. Hence, the scope of firm's vertical integration in a multicomponent technology may present an important contingency for the relationship between knowledge integration and firm performance.

Why is it that a firm that does not integrate into any of the components of lithography technology benefits more from knowledge of external components than a firm that partially integrates into the technology? We posed this question to our industry experts, and the following quote from an industry consultant captures their perspective on the observed difference:

> Firms that outsource critical technologies have more incentive to develop supplier capabilities than firms that own technologies…. You do see [in the industry] that certain firms are much better in managing technology development with suppliers than others. These are the firms that rely on suppliers for most of their technology needs.

It is possible that firms with greater reliance on external suppliers build superior capabilities to manage these suppliers and therefore enjoy greater benefits from their knowledge of external components. Just as there are scope benefits to R&D through knowledge spillovers (Henderson and Cockburn 1996), and to vertical integration through coordinating efficiencies (Novak and Stern 2009), so too can there be scope benefits to outsourcing through the development of superior governance capabilities. It is also possible that firms that are vertically integrated into some of the components within a product architecture may follow different product development routines than firms that outsource all of the key components. For example, a manager with a resist supplier commented,

> Companies that don't have their own internal mask shop will be running a balancing act between their mask supplier, their resist supplier and their tool supplier during new technology development…those with internal mask shop tend to put more weight on the mask development and play less of a balancing act between the different elements.

The result that the knowledge of outsourced components speeds up the time to market of nonintegrated firms suggests a potentially important extension to Nickerson and Zenger's (2004) framework; i.e., the knowledge of activities carried out through the market can act as a shift parameter for the effectiveness of a market-based governance form. The nonfinding regarding the effect of resist knowledge on the time-to-market performance of partially integrated firms (i.e., those that were vertically integrated into mask but not into resist) suggests that the extent of the shift may be endogenous to the firm's overall scope of production with respect to a given technology. Although preliminary, this result certainly echoes Brusoni et al. (2009) in suggesting that future research should aim at examining the micromechanisms that underlie differences in the ways firms manage and benefit from knowledge integration (e.g., Dyer and Singh 1998, Kale et al. 2002). It raises an interesting link between knowledge sourcing strategies and internal development incentives (e.g., Kapoor and Lim 2007) that bears further exploration.

The finding that vertically integrated firms derive a greater performance advantage over nonintegrated firms when product innovation is enabled by architectural change than when it is enabled by component change also helps to potentially resolve the mixed findings in the innovation literature. Although Henderson and Clark (1990) provide convincing evidence from the semiconductor lithography alignment equipment industry that architectural innovation was a major reason for the failure of incumbents during technology transitions, subsequent research in other contexts has been less consistent. For example, Christensen and Rosenbloom (1995) show that in the disk drive industry, incumbents were successful in commercializing new architectural innovations as long as the innovation was developed and deployed within the same value network. However, as Chesbrough (2001) notes, incumbents in the semiconductor lithography alignment equipment industry were operating in the same value network and were still adversely affected by architectural innovation.

We suggest that this inconsistency in the innovation literature can potentially be resolved through closer examination of the interaction between firms' vertical integration choices and the nature of technological change. In the semiconductor lithography alignment equipment industry, three of the four architectural transitions changed the relationship between the lens and other components of the system (Henderson and Clark 1990, p. 23). Incumbent firms that relied on external lens suppliers to commercialize the innovation exited the industry when confronted with architectural innovations.[8] However, the one firm that produced its own lens (Canon), despite facing significant challenges associated with the architectural innovation, continued to be an important industry participant during and after the transition. Similarly, in the disk drive industry, the two technological innovations in which existing value networks were preserved and incumbents were able to successfully commercialize architectural innovations were the change from removable disk pack drives to 14-inch Winchester drives and the transition from 3.5- to 2.5-inch drives. In both cases, vertically integrated incumbents such as IBM, Control Data, Toshiba, Hitachi, and Fujitsu, which manufactured their own key components of magnetic disk and drive heads, were successful (Christensen 1993, Christensen and Rosenbloom 1995, Christensen et al. 2002). Hence, it does seem that across both industry settings, firms that were vertically integrated in the production of key components performed better with architectural innovations.

Finally, our analysis makes an important empirical contribution to the literature on knowledge integration, which has, to date, focused primarily on product component technologies (e.g., Brusoni et al. 2001, 2009; Takeishi 2002). By focusing on process component technologies, we are able to extend their relevance to industries characterized by the separation of product design from product manufacturing, such as apparel, construction, and the fabless/foundry model in the semiconductor industry (Macher and Mowery 2004).

Although we have taken care in our examination, the present study has a number of limitations. The sample is restricted to a single industry, and there is a need to explore the generalizability of our findings in other contexts. Our theory is based on the differences in the speed with which firms introduce new product innovations. We note that time to market is an important but not the *only* determinant of firm performance. It is possible that whereas integrated firms are able to introduce new generations earlier and differentiate based on product performance, nonintegrated firms may use other means to compete. For example, a nonintegrated firm, Micron Technology, has been known in the industry to use fewer mask layers so as to economize on the production process. However, in the face of increasing complexity of DRAM manufacturing, Micron has recently formed a joint venture with a specialized mask supplier and hence moved closer toward an integrated mode. Another possible explanation for the coexistence of integrated and nonintegrated firms in industries characterized by technology transitions is provided by Helfat and Campo-Rembado (2010). Their formal analysis considers the superiority of integrated firms during technology transitions when the industry shifts to a new technology life cycle and the superiority of nonintegrated firms during the technology's maturity. They show that integrated firms may rationally choose to remain integrated during the technology's maturity so as to maintain their capability to manage future technology transitions.

Our use of patent data to measure firms' component knowledge assumes a propensity to disclose such knowledge. It is possible that certain DRAM firms may choose to keep this knowledge a trade secret. However, there is strong evidence that semiconductor firms aggressively patent to use their knowledge as bargaining chips for cross-licensing agreements (Hall and Ziedonis 2001), such that our context at least partially controls for this concern. Unobserved heterogeneity underlying firms' vertical integration choices is clearly an important caveat with respect to our analysis. Although we have performed a number of robustness checks to ensure that our findings are not driven by unobserved firm-level effects, we cannot completely mitigate this concern. Finally, we are unable to identify differences in the ways in which firms govern their relationships with component suppliers. In future work, it would be interesting to explore how firms' abilities to manage different types of technological change are affected by the interaction between their organizational designs, governance mechanisms, and investments in component knowledge. It would also be interesting to contrast performance differences across technology life cycles, as in this study, from performance differences within technology life cycles (e.g., Adner and Kapoor 2010).

Despite these limitations, our findings suggest that differences in the nature of technological change and differences in firms' ability to derive benefits from their knowledge of external components may shape the extent to which firms pursuing vertical integration or outsourcing strategies can effectively compete and coexist within a given industry. We hope that our results will encourage researchers to expand their examination of firm boundaries beyond the make-or-buy decision to also consider firms' knowledge profiles and governance capabilities, as well as to consider how organizational designs and capabilities interact with changes in technology to shape performance outcomes.

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Appendix. Robustness Checks

Table A.1 Firm-Effects Panel Regression Results for Firms' Time to Market

	(9) Random effects, all firms	(10) Fixed effects, all firms	(11) Fixed effects, all firms	(12) Fixed effects, all firms	(13) Fixed effects		(14) Fixed effects		(15) Fixed effects	
					In-house mask	Outsource mask	In-house mask	Outsource mask	In-house mask	Outsource mask
Outsource mask (H1)	0.382** (0.177)	0.314 (0.285)	0.182 (0.282)	0.117 (0.283)						
Mask knowledge (H2)	−0.024*** (0.009)	−0.023** (0.011)	−0.018** (0.009)	−0.016* (0.009)	−0.018 (0.017)	−0.036*** (0.012)	−0.015 (0.017)	−0.023* (0.013)	−0.015 (0.017)	−0.020* (0.011)
Resist knowledge (H2)			−0.041 (0.029)	−0.039 (0.028)			−0.018 (0.019)	−0.063** (0.028)	−0.018 (0.019)	−0.062** (0.025)
Outsource mask × *Architectural innovation* (H3)				0.457** (0.221)						
Architectural innovation				0.033 (0.145)					0.008 (0.150)	0.448*** (0.147)
Firm size	−0.289*** (0.066)	−0.326*** (0.112)	−0.344*** (0.110)	−0.327*** (0.108)	−0.541*** (0.152)	−0.249 (0.161)	−0.541*** (0.152)	−0.217 (0.153)	−0.541*** (0.153)	−0.133 (0.141)
Non-DRAM sales (%)	0.373 (0.241)	0.070 (0.388)	0.089 (0.379)	0.100 (0.372)	0.466 (0.762)	−0.040 (0.403)	0.587 (0.773)	−0.032 (0.382)	0.584 (0.780)	0.017 (0.345)
DRAM feature size	−0.308*** (0.092)	−0.362** (0.166)	−0.472*** (0.168)	−0.434** (0.166)	−0.494** (0.227)	−0.762** (0.320)	−0.544** (0.233)	−0.700** (0.304)	−0.544** (0.235)	−0.456 (0.285)
Constant	3.200*** (0.480)	3.623*** (0.901)	3.854*** (0.885)	3.667*** (0.872)	4.854*** (1.447)	3.327*** (0.935)	4.816*** (1.448)	3.212*** (0.887)	4.815*** (1.458)	2.625*** (0.822)
Observations	161	161	161	161	97	64	97	64	97	64
R^2	0.37	0.35	0.36	0.39	0.25	0.26	0.26	0.33	0.26	0.44

Note. The dependent variable is ln(*time to market*).
*Significant at 10%; **significant at 5%; ***significant at 1%.

Table A.2 Difference-in-Differences Estimation

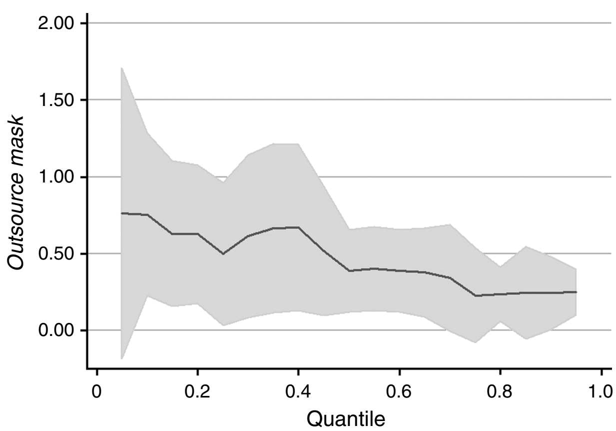
Treatment: Nonintegration → Vertical Integration	Hyundai		Intel	
Treated	−0.781 (0.482)	0.169 (0.455)	−0.237 (0.347)	0.195 (0.424)
Post-treatment	−0.384 (0.277)	−0.215* (0.129)	0.072 (0.209)	0.078 (0.241)
Treated × *Post-treatment*	−1.226* (0.696)	−1.144* (0.625)	0.296 (0.484)	0.362 (0.494)
Other controls	No	Yes	No	Yes
Observations	14	14	11	11
Log likelihood	−11.50	0.55	−4.47	−3.04
Time at risk	105	105	115	115

Table A.2 (cont'd)

	Treatment: Vertical integration → Nonintegration								
	Mitsubishi		Oki		Sharp		Infineon	Texas Instruments	
Treated	−0.440	−1.370***	−1.234	−2.191***	−1.347**	−1.278**	−0.119	0.426	0.764
	(0.578)	(0.473)	(0.773)	(0.520)	(0.581)	(0.564)	(0.860)	(0.768)	(0.771)
Post-treatment	0.398	−0.453*	0.086	0.802**	−0.559**	−0.384	0.717	−0.197	0.133
	(0.376)	(0.242)	(0.345)	(0.345)	(0.227)	(0.352)	(0.707)	(0.323)	(0.369)
Treated × Post-treatment	0.008	0.228	2.111*	1.041	2.263***	2.156***	−1.005	−0.209	−0.604
	(0.839)	(0.418)	(1.088)	(0.708)	(0.819)	(0.810)	(1.211)	(1.088)	(1.062)
Other controls	No	Yes	No	Yes	No	Yes	No	No	Yes
Observations	11	11	20	20	26	26	7	23	23
Log likelihood	−10.40	−2.79	−24.23	−16.31	−26.27	−24.83	−8.94	−28.30	−26.96
Time at risk	33	33	68	68	141	141	34	78	78

Note. Standard errors are in parentheses.
*Significant at 10%; **significant at 5%; ***significant at 1% (two-tailed *t*-test).

Figure A.1 Instrumental Variable Quantile Regression Estimate



Notes. The dependent variable is ln(*time to market*). The vertical axis shows the coefficient estimate for *outsource mask*. The horizontal axis shows the quantile of ln(*time to market*). The shaded region is a 90% confidence interval for the coefficient estimate for *outsource mask*. The horizontal line at 0 represents the null hypothesis of no effect of *outsource mask* on firms' time to market.

many industry professionals who shared their insights. All errors remain the authors'.

Endnotes

[1]In this study, we consider product innovations that require at least a moderate amount of interaction between component development and product development tasks. Hence, we do not consider product innovations that are a result of autonomous changes in components with little or no interaction between the component development and the product development tasks. For example, an innovation in the personal computer (PC) that is enabled by changes in a microprocessor component requires relatively little interaction between the PC firm and the microprocessor supplier (Intel or AMD). Such product innovations are also less likely to be an important source of differentiation among competing PC firms.

[2]It is possible that firms could vertically integrate and try to sell excess capacity to rivals to gain economies of scale and scope. However, as Williamson (1975, p. 16–19; 1985, p. 92) notes, given the strategic hazards associated with supplying to rivals, this is unlikely to be a key driver of a firm's decision to vertically integrate.

[3]The memory density of a DRAM chip is defined based on the number of "bits" of binary data the chip can store. For example, the 1M DRAM chip can store 1×10^6 bits of data. Each bit on the chip is stored in a memory cell, a simple electric circuit of transistor and capacitor. The 1M generation was succeeded by the 4M generation, which increased memory density and could store 4×10^6 bits of data on the chip. The increase in the density of the DRAM is achieved by increasing the number of cells in the chip. However, the increase in the number of cells per chip is economically viable only if the size of the cell is reduced. This reduction is enabled by improvements in the design of the integrated circuits, the materials from which the chip is composed, and the component technologies that underlie the semiconductor lithography process.

[4]Feature size has been used in a number of other studies of semiconductor manufacturing. Some studies (e.g., Leiblein et al. 2002, Macher 2006, Salomon and Martin 2008) have focused on *relative* feature size to characterize a firm's position along the technology frontier. Relative feature size is less appropriate in our study because DRAM firms, unlike semiconductor firms in other product markets, are always at the technology frontier with their new product generations (Moore 1995). For this reason, in our study we focus on *absolute* feature size (e.g., Eisenhardt and Schoonhoven 1996, Hatch and Mowery 1998) to characterize a product generation's levels of development and production challenges.

[5]For example, Allen (2000, p. 1048) estimates that, on average, as feature size has decreased from 16 to 0.50 μm, the capital cost of a semiconductor fabrication plant has risen from \$3 million to \$875 million. Similarly, Weber and Berglund (2005) estimate that as feature size decreased from 0.18 to 0.13 μm, capital investments in mask production increased from \$40 million to more than \$150 million.

[6]We thank an anonymous reviewer for suggesting the use of the difference-in-differences approach to identify the effect of vertical integration on the firms' time to market.

[7]To assess the sensitivity of our main results from the event history models, we performed an alternative analysis by excluding the switchers from our data. The estimates were robust to this alternative analysis.

[8]An incumbent firm, GCA, acquired a lens maker, Tropel, in 1982 but continued to rely on an external supplier for most of its technical and commercial needs (Henderson 1988, p. 227).

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