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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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Abstract

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.

Keywords

firm boundaries, vertical integration, time to market, architectural innovation

Disciplines

Business Administration, Management, and Operations

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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ABSTRACT

Product innovation often hinges on technological changes in underlying components. We examine how firms' success in managing such component-enabled innovation is impacted by their knowledge and production strategies with respect to key components. We further consider how this relationship depends on whether the innovation is incremental or architectural. Using data on all firms in the DRAM industry across 12 technology generations from 1974 to 2005, we find that vertical integration into component production improves firms' success in managing technological change. Although non-integrated firms have lower performance, their disadvantage is muted by the extent of their component knowledge. We find that the relative advantage of extending production vs. knowledge boundaries is determined by two factors. The first is the nature of the innovation: integrated firms have a greater advantage over non-integrated firms when the change is architectural than when it is incremental. The second is the degree of integration: non-integrated firms derive greater benefit from their knowledge of external components than do integrated firms. Our results clarify the conditions under which extending knowledge boundaries can be a substitute for extending production boundaries in managing technological change.

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INTRODUCTION

Technological change is a primary engine of economic progress. Governing the pace of progress, however, lie challenges that firms face in introducing and competing with their new innovations. Scholars have uncovered important mechanisms by which new innovations affect the performance advantage of firms. These examinations have clarified the role of firms' existing competencies (Tushman and Anderson, 1986), cognitive frames and information filters (Henderson and Clark, 1990), complementary assets (Tripsas, 1997) and resource allocation processes (Christensen, 1997) in affecting firm outcomes. Although prior studies have explored a broad range of mechanisms and innovation typologies, they have tended to concentrate on how different types of technological change interact with firms' *internal* resources and product development routines to affect performance. In so doing, they have tended to overlook the role of firms' *external* dependencies. New innovations are often enabled by changes in components (Rosenberg, 1976; Hughes, 1983). From the point of view of an innovating firm, managing technological change requires close coordination between the necessary component developments and the integration of these components into the final product. Firms vary in the extent to which they rely on external suppliers for components. The differences in firms' production choices derive from differences in firms' capabilities, economies of scale and scope, and the transaction costs associated with the development of components (e.g., Monteverde and Teece, 1982; Walker and Weber, 1984; Argyres, 1996; Novak and Eppinger, 2001; Leiblein and Miller, 2003).

Beyond production boundaries, scholars have recently recognized that firms' vertical scope choices encompass not only production decisions, but also decisions with respect to the integration of knowledge; i.e., firms may invest in knowledge of activities even if the production function is outsourced (Fine and Whitney, 1996; Patel and Pavitt, 1997; Brusoni et al., 2001). While both streams recognize the performance implications of firm boundary choices, they have, to this point, remained largely separate from one another. Thus, studies that examine the performance implications of firms' make-or-buy choices (e.g., Poppo and Zenger, 1998; Leiblein et al., 2002) do so without considering the extent of firms' knowledge of outsourced activities; while studies that examine the benefits of knowledge of outsourced activities (e.g., Brusoni et al., 2001; Takeishi, 2002) do so without considering the performance tradeoffs with respect to internal production. Production and knowledge boundaries, however, coexist within firms, raising key questions regarding the extent to which they complement and substitute for one another.

The relative effectiveness of firm boundary choices in managing technological change is likely to be shaped by the nature of the change. While the innovation literature has paid attention to the interaction between different types of technological change and firms' internal resources and product development routines, the literature has largely neglected the interaction between different types of technological change and firm boundaries. Notable exceptions are Teece (1996) and Wolter and Veloso (2008), who theorized about the link between firms' production boundaries and their ability to manage technological change, and Afuah (2001) who examined the relationship between vertical integration and firm performance in the context of the computer workstation industry when both suppliers of microprocessors and workstation manufacturers were faced with an architectural change.

In this paper, we explore the joint effects of both production and knowledge boundaries, and examine how different types of component enabled technology transitions interact with vertical scope to impact firm performance. In so doing, we assess how technological and strategic factors shape the extent to which a firm's investment in component knowledge can substitute for investment in component production. We explore our arguments in the context of the dynamic random access memory (DRAM) industry from 1974-2005. During this period, the industry transitioned through 12 distinct technology generations. We create a unique dataset that characterizes each of these technology transitions. We follow Henderson and Clark (1990: 11-12) to distinguish between incremental innovations in which improvements occur through refinements in existing components but the underlying core design concepts and the links between the components remain the same, and architectural innovations in which the links among improved components are themselves reconfigured.[1] The data set also includes data on the vertical integration choices, knowledge of components and market performance of every firm that participated in each one of these technology generations.

We consider how a firm's decision to vertically integrate is determined not only by coordination challenges but also by its capabilities and production economies. We first argue that when requirements for coordination and co-specialization between upstream and downstream activities are high, vertically integrated firms are likely to gain advantage from extending their production boundaries to encompass

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[1] The innovation literature is replete with innovation typologies, and has at times been criticized for lacking a systematic approach for characterizing technological change (c.f., Dahlin and Behrens, 2005). However, by following the typology developed in a single source (Henderson and Clark, 1990) and by applying it to the same technological context that was used to develop the typology (semiconductor lithography), we are confident in the consistency of our categorization.

component production. We then posit that, in the absence of production activities, non-integrated firms can improve their performance by investing in the knowledge of components i.e., by extending their knowledge boundaries.[2] Finally, we predict that the magnitude of the performance difference between vertically integrated firms and non-integrated firms depends on the nature of technological change: non-integrated firms will be more disadvantaged when technological change is architectural than when it is incremental.

We find that, after controlling for the endogeneity of firm's make-or-buy choice, vertically integrating into component production improves a firm's ability to manage transitions across technology generations. Although non-integrated firms have lower performance, this deficit is reduced by the development of component knowledge. Moreover, the relative advantage of extending production vs. knowledge boundaries is determined by two factors. The first is the nature of technological change: integrated firms have a greater advantage over non-integrated firms when innovation is architectural than when it is incremental. The second is the choice of vertical integration: non-integrated firms derive greater benefit from their knowledge of external components than do integrated firms.

Prior research on innovation has examined how different types of technological change impact the internal challenges that firms face in managing technology transitions (e.g., Henderson and Clark, 1990). Firms, however, often depend on external suppliers for their innovation, and coordination of technological changes across firm boundaries may play no less a role in shaping firms' performance. Our examination of such coordination challenges across 12 different technology generations sheds important light on how firms' production and knowledge strategies within the vertical chain jointly affect their ability to commercialize different types of innovations. Our results also extend the emerging literature that integrates transaction cost economics with competence based perspectives (e.g., Leiblein and Miller, 2003; Hoetker, 2005; Mayer and Salomon, 2006). We show that while knowledge of external activities may improve firms' governance capabilities, its effect may be muted for partially integrated firms that have a lower reliance on external suppliers. Hence, we highlight an important asymmetry in the relationship between firms' technological capabilities and its governance capabilities. Finally, we contribute to the emerging literature of innovation ecosystems by explicitly recognizing that the success of

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[2] Our conceptualization is consistent with prior research that has examined firms' knowledge in the context of activities in the vertical chain (e.g., Fine, 1998; Brusoni et al., 2001; Takeishi, 2002). However, we note that firms' knowledge boundaries may encompass broader domains than those considered here.

firms' innovation efforts depends on other innovations in the firms' environments (e.g., Afuah and Bahram, 1995; Adner and Kapoor, 2006; Adner, 2006; Gawer and Henderson, 2007), and by showing how firm strategies interact with technological changes in the environment to influence performance outcomes.

In the next section, we provide a brief review of the literature on firm's vertical scope and its implication for performance. We then provide a detailed description of the DRAM industry. Our description focuses on the key technological components, the nature of technological change and how firms organize their production and knowledge boundaries in this industry. After describing the context, we specify hypotheses relating firms' production and knowledge boundaries to performance outcomes. We then detail our methodology and discuss our results.

VERTICAL SCOPE AND PERFORMANCE

Scholars have long been interested in understanding the drivers and performance implications of firms' vertical scope. This literature has extensively investigated the factors that determine firms' production boundaries i.e., make-or-buy choices (e.g., Monteverde and Teece, 1982; Masten, 1984; Walker and Weber, 1984; Argyres, 1996) and more recently, have started to explore how firms' make-or-buy choices shape performance outcomes (Poppo and Zenger, 1998; Leiblein et al., 2002; Nickerson and Silverman, 2003). Implicit in these analyses is the observation that most industries are characterized by significant variations in firms' make-or buy choices for a given activity.

Several theories have been put forward and tested to explain why firms in an industry may choose to either vertically integrate or to rely on external suppliers for a given activity. Predominant among these is transaction cost economics (TCE), which characterizes transactions between upstream suppliers and downstream buyers according to asset specificity, uncertainty, and frequency. Taking the transaction as its unit of analysis, TCE views the make or buy decision as the solution that minimizes transaction costs between the parties (e.g., Williamson, 1985). Many studies have found strong empirical support for TCE explanations of firm boundary choice, especially with regards to the asset specificity of the transaction (cf. David and Han, 2004).

Beyond TCE explanations, prior research has revealed a host of other factors that may affect the extent of firms' vertical integration in a given industry. First, firms have been shown to economize not only on transaction costs but also on production costs (Walker and Weber, 1984). Such production cost differences could be a result of differences in economies of scale and scope as well as differences in firms' production capabilities (Argyres, 1996). Second, firms may choose to rely on suppliers when there is a greater risk of technological obsolescence and a need to repeatedly incur large scale capital investments (Balakrishnan and Wernerfelt, 1986). Third, firms may vary in their capabilities to manage suppliers. These capabilities may encompass a combination of both formal governance capabilities (Mayer and Salomon; 2006; Argyres and Mayer, 2007) and relational governance capabilities (Dyer, 1997; Dyer and Singh, 1998). Hence, vertical scope decisions may be determined both by the coordination challenges between upstream and downstream activities as well as by the economics of production and firm level capabilities. Empirical studies that link firms' make-or-buy choices to performance outcomes (e.g., Poppo and Zenger, 1998; Leiblein et al. 2002) have found support for the economic consequences of the need to match high coordination requirements with vertical integration.

While the strategic choice of firms' production boundaries has been dominant in studies examining firms' vertical scope, scholars have recently started to examine a new dimension of firms' vertical scope – knowledge boundaries. A number of studies have revealed that firms may invest in knowledge of activities in the vertical chain even if the activities are fully sourced through the market (Patel and Pavitt, 1997; Fine, 1998; Brusoni et al., 2001; Ahmadjian and Lincoln, 2001; Takeishi, 2002). Such knowledge has been shown to impact firms' formal governance capabilities through crafting of superior contracts and more effective monitoring mechanisms (Mowery, 1983; Mayer and Salomon, 2007; Argyres and Mayer, 2007; Tiwana and Keil, 2007); as well as their relational governance capabilities through superior communication between firms and their suppliers (MacDuffie and Helper, 1997; Takeishi, 2002). In the absence of vertical integration, investment in knowledge of upstream activities may confer firms with an absorptive capacity (Cohen and Levinthal, 1990) that may facilitate improved governance in the vertical chain. For example, Ahmadjian and Lincoln (2001) provided evidence of how Toyota's investment in knowledge of electronics improved its governance of activities with its key 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 (pp. 689).

For an innovating firm, coordinating between the development of upstream components and their integration into the final product architecture is an important part of managing technology transitions. These coordination challenges, however, vary depending on the nature of the specific technological change: there is a qualitative difference between incremental transitions that only impact components and architectural transitions that impact the links among components (Henderson and Clark, 1990). We explore how different types of technology transitions interact with vertical scope to impact firm performance in the context of the DRAM industry.

INNOVATION IN THE DRAM INDUSTRY

The global DRAM industry is an ideal setting in which to explore how firm boundaries shape performance outcomes during different types of technology transitions. 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 (the period of this study), a total of 36 firms competed in the industry across 12 technology transitions. Second, each of these transitions preserved firms' technological capabilities and hence, the industry provides a natural control for some of the alternative capability based explanations that may be difficult to observe. Third, throughout the industry's history, the key component technologies have been characterized by high degrees of coordination and transaction specific investments during the commercialization of new innovations. Despite these coordination challenges, firms in the industry have shown significant differences in their vertical scope. Finally, DRAMs are homogenous goods (Irwin and Klenow, 1994), such that each firm introduces the new innovation with essentially the same product characteristics. Hence, comparing differences in firm performance for a given product innovation is less likely to suffer from biases from unobserved differences in product quality and attributes (e.g., Martin and Salomon, 2003).

Component Technologies and Technological Change in the DRAM Industry

Since its emergence in the late 1960s, the DRAM industry has been viewed as a main engine of growth for the entire semiconductor value chain. Due to advances in computing applications, DRAM firms face a continuous need to introduce new generations that increase the memory density of the DRAM chip. The memory density of a DRAM chip is defined based on the number of “bits” of binary data that the chip can store. For example, the 1 Megabit (1M) DRAM chip can store 1 x 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 x 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 can only be economically viable if the size of the cell is reduced. This reduction is constrained by the design of the integrated circuits, the materials from which the chip is composed, and the process used to manufacture the circuits.

The core capabilities of the DRAM firms encompass product design, process technology and manufacturing engineering (Burgelman, 1994). The process technology and the manufacturing engineering groups can be considered as part of the DRAM firm’s manufacturing capability. The successful commercialization of a new DRAM generation requires co-development of product design and process technology to achieve the required DRAM density. Once the new product is developed and commercialized, the focus moves to manufacturing engineering to scale up the process to achieve large volumes with high yields. Of the many processes required to manufacture a DRAM, the lithography process, illustrated in Figure 1, plays the most critical role in reducing the cell size and allowing for the introduction of new DRAM generations (Moore, 1995; Martin and Salomon, 2003).

There are three key component technologies that are integrated in the lithography process - the mask, the alignment equipment and the resist.[3] 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. Since the DRAM chip is made up of several stacked layers with each layer 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 an energy sensitive chemical resist. The resist undergoes a chemical reaction wherever the mask has allowed 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

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[3] Note that components can be either 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).

process. Another chemical process is then initiated in which the exposed parts of the wafer are etched. Finally, the remaining resist is removed, creating a final circuit that replicates the initial DRAM design. A typical DRAM chip goes through this process a number of times to sequentially build the integrated circuits with different mask designs. For example, the recent 128M DRAM chip went through as many as 120 lithography process steps.

(Insert Figure 1 about here)

The DRAM firm's commercialization of new generation depends in large part on progress in the alignment equipment, the resist and the mask component technologies. While all three component technologies have been progressing at fast rates, their progress has not been uniform, leading to the rise of technological bottlenecks (Kapoor and Adner, 2007). 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."

Hence, DRAM firms are faced with significant challenges in coordinating the technological changes in the lithography components in order to commercialize the new generation.

Component Technologies and Asset Specificity

The commercialization of a new DRAM generation requires close collaboration between personnel in the product design, process technology and manufacturing engineering groups within the DRAM firm. This close collaboration has been referred to as "unstructured technical dialog" which creates human asset specificity between the design and manufacturing activities (Monteverde, 1995). Since the mask represents the blueprint of the firm's product design and is used to develop and scale up the manufacturing process, it is the bridge through which this unstructured technical dialog takes place. The mask activity is normally located in very close geographic proximity to the semiconductor manufacturing. This is due to 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. The required coordination between mask making activity and DRAM production is therefore also characterized by temporal specificity (Masten et al., 1991). 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 commercialization process 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 as well as its stability during the chemical processes of developing and etching. A DRAM manufacturer invests significant amount of effort and resources extending over many months in finalizing a resist for the new DRAM process. Once a particular resist is finalized in a firm's process "recipe", any changes are time consuming and extremely costly. In addition, DRAM firms invest in dedicated equipment for downstream processes in their manufacturing lines which may be specific to a given resist chemistry.

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

Component Technologies and Firm Boundaries

All three lithography component technologies exhibit a high degree of asset specificity for a DRAM firm during the commercialization of new generation. For this reason, vertical integration of these components may provide superior coordination of activities underlying the technological change. 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 that we studied, some DRAM firms integrated the production of mask, no firm integrated the production of resist, and only one firm (Hitachi) integrated into the alignment equipment.

The development and production of resist requires large R&D and production investments, and a deep knowledge of chemical compounds and processing. Therefore, only large specialized chemical suppliers such as Kodak, Hoechst and Shipley have manufactured resist for semiconductor manufacturing. These specialized chemical firms also enjoy large economies of scope through participation in other chemical markets. Similarly, the development and production of alignment equipment also require enormous R&D expenditures, and advanced knowledge of optics and mechanics. Hence, firms such as Perkin Elmer, Nikon and Canon with superior optics and mechanics capabilities, and participation in multiple photo-imaging markets have supplied alignment equipment to DRAM firms.

Of the DRAM firms that did not integrate the production of key components, we found that some firms invested in the knowledge of such components. As discussed later, our examination of patents filed by DRAM firms showed that these firms invested in the knowledge of components even when they outsourced their production. This finding is consistent with prior examination of knowledge boundaries (Patel and Pavitt, 1997; Brusoni et al., 2001; Takeishi, 2002).

DRAM Innovation and the Nature of Technological Change

The capability of the lithography process is defined based on the minimum feature size - the smallest circuit dimension that can be patterned on the semiconductor. Figure 2 plots the introduction of different DRAM generations and the minimum feature size in microns ($\mu m = 10^{-6} m$) that was achieved through improvements in the lithography process. Since the emergence of the DRAM industry with the introduction of 1K DRAM, there have been a total of 12 new generations from 1974 to 2005. Each generation was enabled by the DRAM firm’s reduction of the minimum feature size, which in turn was largely attributable to progress in the alignment equipment, the resist and the mask.

(Insert Figure 2 about here)

While the new DRAM generations were commercialized through improvements in the alignment equipment, the resist, and the mask, there were important differences in the nature of the technological changes across these generations. Table 1 lists the different DRAM generations, the minimum feature size and the key changes in the lithography technology that enabled the commercialization of the new product. 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 between the components, others entailed changes both to the individual components as well as the critical interactions between the components. Following Henderson and Clark (1990), we characterize the former as incremental transitions and the latter as architectural transitions. For example, in the 64K DRAM innovation, there was a change in the lithography technology from the proximity printing method to the projection printing method. Projection printing entailed gradually scanning the energy field across the wafer, and 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 aligner equipment, but also in the relationship between the aligner and the mask. In contrast, the commercialization of 1M DRAM was achieved through incremental changes in components within the same technology architecture as the previous generation of product.

(Insert Table 1 about here)

While all the successful DRAM generations have been either incremental or architectural, there have also been attempts to introduce radical innovations. Attempts to replace the conventional integrated circuit technology based on the metal-oxide-semiconductor (MOS) technology include the development of various magnetic memory products such as the bubble memory and the magnetoresistive random access memory (MRAM), both of which required very different processing technologies and materials. The fact that none of the radical innovations have ever entered the mainstream of DRAM markets provides a natural control for alternative competence based explanations (e.g. Tushman and Anderson, 1986), but limits our analysis to explore only the effects of these two innovation types.

Hypotheses

Firms in the DRAM industry are continuously competing to introduce new product innovations. As evident from the discussion above, the development and commercialization of new innovations require close coordination and transaction specific investments between firms and suppliers. In such contexts, vertical integration into components should provide superior coordination of technological changes in the vertical chain and result in greater performance.

Hypothesis 1: A firm's vertical integration of a component characterized by high asset specificity will have a positive effect on its performance in a new product technology.

Vertical integration decisions, however, are determined not only by transaction costs but also by firms' production costs and capabilities. Hence, even in the presence of high coordination needs and high transaction costs, firms may not be able to vertically integrate. In the absence of vertical integration, we expect that a firm's knowledge of external components should enhance its formal and relational governance and improve its ability to manage technological change.

Hypothesis 2: In the absence of vertical integration, a firm's knowledge of the external component will improve its performance in a new product technology.

Finally, successful technology transitions in the DRAM industry have been either incremental or architectural. Vertically integrated firms may be able to better coordinate technological changes that underlie an architectural innovation. This prediction is consistent with TCE. The changes in interactions between components during an architectural innovation are likely to increase the uncertainty associated with the coordination of various tasks. An increase in uncertainty coupled with greater asset specificity should exacerbate the transaction cost and hence, further increase the advantage of hierarchy over markets as a preferred organization mode to minimizing contractual hazards (Williamson, 1985).

Hypothesis 3: A vertically integrated firm will have a greater advantage over a non-integrated firm when the technological change is architectural than when it is incremental.

Data

We used both primary and secondary data for this study. The primary data was collected through a series of interviews with over twenty industry experts over a period of 18 months. The secondary data was collected from semiconductor industry analysis firms, industry publications and the US Patent and Trademark Office (USPTO). Appendix I provides the details of the sources of secondary data that we used in the study to carry out the quantitative analysis. Our sample includes every firm that ever sold a DRAM on the open market.[4] We identified a total of 36 firms in the DRAM industry that competed in 12 distinct DRAM generations ranging from 4 Kilobit (4K) to 1 Gigabit (1G) memory density from 1974 to 2005. In this study, we only consider 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 the firm's timing of commercialization of the new DRAM generation. 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 firm's timing of new innovation as a key measure of its performance (e.g., Schoonhoven et al., 1990; Brown and Eisenhardt, 1995; Gatignon et al., 2002). The sharp price erosion and intensive rivalry in the DRAM industry creates a significant early mover advantage within a given DRAM generation (Methe, 1992; Enz, 2003). These advantages are largely a result of learning by doing (Hatch and Mowery, 1998; Irwin and Klenow, 1994). As a result, DRAM firms are continuously striving to be first to introduce the new generation with improved lithography technology. The measure is also appropriate for testing the firm's ability to coordinate technological changes in its vertical chain so as to minimize delays in the commercialization of new innovations.

We measure the firm's *Time to Market* as one plus the difference in the number of quarters (3-month periods) between the first shipment by the firm and the first shipment in the industry for a given DRAM generation. Hence, the first firm takes the value of 1 and a firm that commercializes the generation

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[4] We do not have data on the small number of firms that produced DRAMs exclusively for their own in-house use.

three quarters after the first firm takes a value of 4. We used the logarithmic transformation of the dependent variable in our analyses.[5]

Because no firm in the industry has ever 'skipped' a technology generation, strategic non-participation is not an issue in our context (i.e., non participation in a new generation implies exit from the industry). Since we examine all firms that have participated in the industry, we do not face any left censoring issues. We are also confident that right censoring is not a problem in our data given the dynamics of the industry. In the DRAM industry, product life cycles are short and entry into older generation of products is not economically viable once a new product has taken root; that is, firms begin their production in the newly introduced generation, not the older ones.

The only generation for which we have potentially incomplete observations is the 1G generation that emerged in 2003, into which a number of incumbents had yet to enter by 2005. We performed robustness test by excluding the 1G generation. We performed an additional test to ensure that our reported results are not sensitive to the chosen measures. It is possible that the first shipment may represent delivery of samples that may not be fully qualified by the customers. Hence, the quarter in which the first shipment is recorded for the new DRAM innovation may inappropriately characterize an early "sampler" as a full-fledged market pioneer. In order to check for this bias, we also tested two alternative commercialization thresholds in which the time to market was measured as the first quarter in which the firm shipped 100,000 and 250,000 units of the new DRAM generation. The results are consistent with the ones reported here.

Independent Variables

Among the three component technologies – the mask, the resist and the alignment equipment – we focus on the firm's make-or-buy decision for the mask technology and the firm's investment in knowledge for both the mask and the resist. As discussed earlier, none of the DRAM firms internalized the production of the resist due to the high cost of development and production and hence, we do not consider the governance choice for the resist. We also exclude the alignment equipment from the boundaries' analysis as there was only a single instance in which a DRAM firm (Hitachi) also manufactured alignment

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[5] As a test of robustness, we also used a linear specification and the results are consistent with those reported here, but with a lower R-squared.

equipment, and it did so in a standalone business unit. Further, because alignment equipment knowledge draws on a multitude of scientific domains (e.g., optics, mechanics, software) that overlap with many of the firms' other businesses it was not possible to measure specific knowledge investments in alignment equipment using the patent data.

The industry has treated the mask and the resist as key component technologies for semiconductor manufacturing, as demonstrated by numerous annual dedicated conferences such as Photomask Japan, the Annual BACUS Symposium, the European Conference on Mask Technology, and Advances in Resist Technology and Processing in which new technological developments are presented and discussed. The variable *Outsource Mask* takes a value of 1 if the DRAM firm outsourced the production of mask technology and takes the value of 0 if the firm is vertically integrated into the mask technology in the year prior to its commercialization of the new DRAM innovation.

We measured the firm's knowledge in the mask and resist technology using patent data. We asked industry experts who have been associated with the mask and resist R&D to provide us with the most prominent technology subclasses associated with the two components.[6] We identified the patent subclass 430/5 as the key technology subclass for the mask technology, and patent subclasses 430/270.1, 430/191a, 430/192a, 430/326, 430/325, 430/281.1, 430/190, 430/311 as key technology subclasses for the resist technology. We also confirmed the validity of the subclasses as proxy for 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 filed by a DRAM firm in the 3 years preceding the firm's commercialization of its new DRAM generation. Similar patent based measures have been used in prior studies to examine firm's knowledge in a given technology (e.g., Patel and Pavitt, 1997; Cattani, 2005).

As a test of robustness we also included a 5-year window for the patent based measures of component knowledge. Also, because the primary subclass may under-represent the knowledge underlying the patent granted to the firm, we included component knowledge measures using patents

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[6] These experts included industry veterans such as Marc Levenson, who worked for IBM during the 1980's and is the inventor of perhaps the most important innovation in the mask technology – the phase shift mask, that allowed for feature sizes to be smaller than 0.25μm.

where the mask or the resist subclass is not restricted to only the primary subclass. The results using these alternative measures were consistent with the ones reported in the paper.

Finally, we characterize the nature of technology transition for each of the generations. The classification of these generations as entailing incremental or architectural transitions 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. For each technology transition we identified the significant changes in the individual components of lithography technology that enabled the new DRAM generation – changes in aligner design, mask production process, and resist chemistry. Such changes were present in every technology transitions (see column 2 of Table 1). We also identified the significant changes in the relationship and linkages among the aligner, mask and resist. Such changes were present in some generations but not others (see column 3 of Table 1).

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

With Table 1 complete and validated, we then coded the different DRAM generations according to whether a technological generation entailed changes in the critical relationships among key components (coded architectural) or not (coded incremental). This characterization is fully consistent with the description of architectural innovation in Henderson and Clark (1990) and on the construct items developed by Gatignon et al. (2002). We defined the variable *Architectural Innovation* as taking a value of 1 if the DRAM innovation is architectural and 0 if it is incremental.

Control Variables

We controlled for *Firm Size* as measured by the log of firm's annual sales (in millions of dollars) in the year prior to its commercialization of the 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 the microprocessor markets suggests that firm's market scope may influence its resource allocation towards the development of new innovations. We controlled for this effect using the variable *Non-DRAM Sales*, measured as the percentage of firm's sales in non-DRAM markets in the previous year. Finally, we accounted for variations in the complexity of the DRAM generation (e.g., Macher, 2006). The variable *DRAM Feature Size,* the smallest circuit dimension printed in a given year, and is a widely used measure of the sophistication of the product and the process technology required to create these miniaturized DRAM products.

As a robustness check, we also controlled for Japanese firms and the results are consistent with the ones reported in the paper. Earlier studies, primarily from the automotive industry, have shown that Japanese firms rely more heavily on relational governance that increases trust and decreases opportunism (e.g., Womack, Jones and Roos, 1990; Dyer, 1997). However, as noted by Williamson (1985) and more recently by Ahamdjian and Lincoln (2001), Japanese auto firms use a combination of formal and relational contracts to manage governance in the vertical chain. While Japanese firms may face reduced opportunism, governance of supplier activities is certainly a key determinant of their success and this governance capability has been shown to increase with their knowledge of supplier activities (e.g., Takeishi, 2002).

To ensure that our results are not biased by temporal effects, we created dummy controls for each of the four decades in our study. Although we would have preferred to use finer grained temporal controls, we are constrained by the degrees of freedom in our data. The results with time controls are consistent with the ones reported here.

Statistical Method and Analysis

Firms self-select into their governance mode. Unobserved factors can influence both firms' governance forms as well as their performance. This can create a selection bias such that normative implications drawn from the estimation may be incorrect. We follow the Heckman procedure (1979) to address this self-selection problem. This procedure includes a first-stage probit model to specify a selection equation and then calculates the inverse Mill's ratio (λ) that is used as a control variable in the second stage performance model (c.f., Shaver, 1998). The first stage selection equation is given by:

$$Prob\ (Y_i = 1|X_i) = \Phi(\delta' X_i)$$

where Y_i is governance choice variable that takes the value of one if a firm outsources the production of mask and zero if it vertically integrates into the mask. The set of independent variables includes measures for firm's production economies and knowledge in mask, the extent of new technology investment required in the mask to commercialize the new DRAM generation, and the contractual hazards associated with the existing mask supply. Firm characteristics include production scale measured through firm size, production scope measured through non-DRAM sales and mask knowledge. We also consider the extent of new technology investment that firms may incur in mask for the new DRAM generation. The need for new investment may prevent firms from vertical integration (Balakrishnan and Wernerfelt, 1986). The DRAM feature size is a useful proxy to measure the degree of new investment as smaller feature size significantly increases firm's investments in the mask making facility (Trybula and Grenon, 2003). Finally, we use the number of mask suppliers as an instrument in the first-stage estimation. Prior research has identified small numbers bargaining hazards due to the number of suppliers as being an important source of contractual hazards that firms may consider in choosing their governance mode (Pisano, 1990; Leiblein et al., 2002). We account for this hazard by measuring the number of mask suppliers in the given year of observation. The validity of this instrument hinges on the assumption that the number of suppliers is not correlated with a firm's time to market. Our discussions with industry participants, personnel from both mask suppliers and DRAM firms, provided a number of reasons that justify the use of the instrument. First, the number of external mask suppliers does not affect the market entry timing of integrated firms who fully rely on their internal supplier to develop the new technology. Second, non-integrated firms typically work with one mask supplier during the technology development stage and may use multiple suppliers only when the technology has matured. Hence, the concerns of bargaining power may only affect non-integrated firms performance (profitability) after the technology has reached maturity. Finally, the number of suppliers may affect the extent of R&D investments in mask technology and may affect the pace of progress of the industry as a whole but not necessarily affect the relative performance differences across individual firms.

After the first stage estimation for firm's governance choice and the calculation of the inverse Mill's ratio (λ), the second stage performance model is estimated using ordinary least squares (OLS).

Since firms participate in multiple DRAM generations, we account for the possibility that residuals for a given firm may be correlated across innovations by using STATA's "cluster" option.[7]

RESULTS

First-Stage Governance Choice Results

Table 2 presents results from the first stage governance choice models for mask (Buy=1, Make=0). In Model 1, we include the direct effects of firm attributes - firm size, non-DRAM sales and mask knowledge. In Model 2, we test the effect of new technology investment by also including DRAM feature size, and in Model 3, the full model, we test the effects of small numbers bargaining hazards by adding the number of mask suppliers. The decision to internalize the production of mask technology is based on firms' consideration of both production and transaction costs (Williamson, 1985: 93). The coefficient for firm size is negative and significant suggesting that large firms are more likely to vertically integrate into mask. Vertical integration is a costly strategy in terms of initial capital outlays, costly ongoing investment in required upgrades, and risks associated with guaranteeing sufficient mask quantities to operate past the minimum efficient scale. As expected, the coefficient for non-DRAM sales is negative indicating that firms that are also active in other non-DRAM markets have a greater propensity to vertically integrate. Firms are more likely to undertake large investments in mask production if they can leverage this strategic asset for DRAMs as well as for other markets. However, this effect is significant for only models 1 and 2. The effect of mask knowledge is positive and weakly significant for models 1 and 3 suggesting that firms with greater mask knowledge are more likely to use external governance. This result is consistent with findings in Mayer and Salomon (2006) in the context of information technology outsourcing. The coefficient for DRAM feature size is negative and significant suggesting that as the degree of investment in mask production increases, firms tend to rely on external suppliers for their

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[7] As a test of robustness, we performed two additional estimations. First, we used the Cox semiparametric proportional hazards model that allowed for the inclusion of right censored observations for the most recent 1G DRAM generation. Second, we used a firm fixed effects model to account for the unobserved differences across firms. The results from both of these alternative specifications were fully consistent with the ones reported in the paper and are available from the authors upon request.

masks.[8] Finally, the positive and significant coefficient for number of suppliers is consistent with the expectation that firms internalize the production of mask when small numbers bargaining hazards are likely (Pisano, 1990; Leiblein et al., 2002). We use the results from model 3 to calculate the inverse Mill's ratio for the second-stage performance model.

(Insert Table 2 about here)

Second-Stage Performance Results

Industry incumbents pioneered all new technology generations in our study sample, regardless of whether the innovation was incremental or architectural. Moreover, in 10 out of 12 generations (the exceptions are 4K and 128M), the pioneering incumbents were vertically integrated with respect to the mask technology. Therefore, vertical integration of mask seems to facilitate early commercialization of the DRAM generation. The descriptive statistics and correlations for variables used in the second stage model are reported in Table 3.

(Insert Table 3 about here)

Table 4 provides results from the firm's performance model. Model 1 includes the controls and the firm's knowledge and governance choice for mask. In Model 2, we account for the potential self selection bias in the choice of governance mode by including the inverse Mill's ratio. In Model 3, we relax the assumption that the coefficients for firms that are vertically integrated are the same as the firms that outsource the mask technology. Controlling for self selection, we split our sample between vertically integrated and non-integrated firms and estimate their effects separately. In Model 4 we include the effect of firm's resist knowledge and in Model 5 we include the covariate for architectural innovation.

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[8] We note that smaller feature size is likely to have two distinct effects. First, it can increase asset specificity because more complex components require a greater degree of coordination between a firm and its suppliers. Second, smaller feature size corresponds to increasing mask production costs. Whereas increasing asset specificity should lead firms towards vertical integration (i.e., Williamson, 1985), increasing production costs should lead firms towards outsourcing (i.e., Walker and Weber, 1984). The results in Table 2 suggest that in our context, with regards to increases in complexity as measured by DRAM feature size, production cost effects dominate asset specificity effects.

A comparison of the results of Model 2 with those of Model 1 indicates that the coefficients are broadly similar in signs and magnitude except with generally larger standard errors. The statistically significant coefficient for the inverse Mill's ratio justifies the use of the Heckman procedure in our performance estimation. After accounting for governance selection, the estimated effect for firm size is insignificant. The effect of non-DRAM sales is positive and significant for both the integrated and non-integrated firms suggesting that greater participation in non-DRAM markets could compromise the speed of the firm's new DRAM technology development as resources get shared across multiple product lines. As expected, the effect of DRAM feature size is negative. However, it is significant only for non-integrated firms. Greater complexity of the DRAM (smaller feature size) is correlated with greater delays in the non-integrated firms' commercialization of the new DRAM generation. The difference between the coefficients for integrated and non-integrated firms was insignificant (p=0.956).

The coefficient for outsource mask is positive and significant suggesting that firms that do not integrate into mask production tend to commercialize new generations later than their vertically integrated rivals, even after controlling for the unobserved characteristics that may influence both the firm's governance choice and performance. Hence, these results support Hypothesis 1.

(Insert Table 4 about here)

In Model 3, the coefficient for mask knowledge is negative and significant for firms that outsource the mask. Hence, non-integrated firms were able to benefit from their component knowledge (Hypothesis 2). The result implies that a firm's knowledge of external component plays an important role in its ability to coordinate technological changes in the vertical chain. The difference in the mask knowledge coefficient for the firms that vertically integrate into mask and those that do not was statistically insignificant (p=0.644).While both integrated and non-integrated firms benefit from their knowledge of masks, the estimated coefficient for resist knowledge is negative and significant only for firms that do not integrate into mask. Our hypothesis predicted that in the absence of vertical integration, firms' resist knowledge will improve its performance during technology transitions. Hence, the effect of resist knowledge on the firm's time to market provides mixed support for Hypothesis 2, i.e., while we found the prediction to hold for firms that did not integrate into any of the components, it did not hold for those firms that integrated into mask. Moreover, the difference in the resist knowledge coefficient between the two subsamples is significant (p=0.039) suggesting that non-integrated firms benefit more from their knowledge of resist than do firms that integrate into mask. We discuss this interesting finding in the next section.

In Model 5, the coefficient for architectural innovation is negative but insignificant for integrated firms. The effect is positive and significant for non-integrated firms. Hence, non-integrated firms tend to commercialize the new DRAM generation later when the change is architectural than when it is incremental. In contrast, vertically integrated firms seem unaffected by the nature of the transition. We also find that the difference between the two coefficients is significant (p=0.025). The findings from Model 5 support Hypothesis 3 that vertically integrated firms have a greater advantage over non-integrated firms during an architectural change than during an incremental change.

In order to better interpret the above findings, Figure 3 plots the expected time to market for an average firm as a function of the firm's mask and resist knowledge for the different governance choices and the transition types. We generate the figure by multiplying the coefficient estimates with the average firm attributes for the respective integrated and non-integrated sub-samples. At the mean levels of mask and resist knowledge, a firm that integrated into mask commercializes the new generation 2.5 quarters earlier than the non-integrated firm when the technological change is incremental, and 5 quarters earlier when the technological change architectural. A one standard deviation increase in the firm's mask and resist knowledge reduces the non-integrated firm's lag to 1 quarter in the case of an incremental change and 2.7 quarters in the case of an architectural change. In assessing the economic significance of these commercialization lags, consider that the average quarterly market size during the first two years of the 64M DRAM was US$497m. In addition to extracting greater share of this revenue, early commercialization may also provide a firm with a significant competitive advantage through learning by doing which carry over into later time periods (Irwin and Klenow, 1994).

(Insert Figure 3 about here)

DISCUSSION AND CONCLUSIONS

This study examines how firms' vertical scope, measured through both production and knowledge boundaries, affects their performance across different types of technology transitions. While prior research on innovation has focused on the internal challenges faced by firms, we explicitly add consideration of the external challenges in coordinating technological changes in the vertical chain. We suggest that in the context of interdependent component technologies being integrated by the innovating firm, governance of activities in the vertical chain is a key determinant of the firm's ability to commercialize new innovations.

We find support for prior research on production boundaries that firms' decision to integrate activities in the vertical chain is jointly determined by their capabilities, production and transaction costs. After taking into account the determinants of firms' make-or-buy choices, we find that firms that integrate into components with high asset specificity are able to commercialize new innovations earlier than their non-integrated rivals. We also find that while high production costs may deter firms from internalizing the production of components, firms' knowledge of such components can serve as an imperfect substitute to improving their commercialization of new innovations. This finding was validated in our conversations with industry participants who emphasized the importance of knowledge of the key lithography components in managing suppliers. For example, a technical manager with a large DRAM manufacturer remarked:

> "If we were to just get the resist from the market without having any expertise, it will be a disaster for developing the new technology……this knowledge is not just useful, but essential, and an important source of competitive advantage."

The knowledge of upstream components is likely to facilitate the firm's governance of activities in the vertical chain during their development and integration into the firm's product. We discussed this result with a manager in a non-integrated firm and he commented:

> "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….in most companies, 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 from the study was that firms' knowledge of external components with high asset specificity seems to play a more significant role for lean firms – those that do not vertically integrate into either of the components, but does not affect the performance of firms that vertically integrate into the mask. 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 asked this question of our industry experts and the following quote captures the essence of the 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."

This finding certainly warrants future research in understanding how the scope of firm's vertical integration in a multi-component technology interacts with its knowledge of components to influence governance capabilities and competitive advantage. It is possible that non-integrated firms may build superior capabilities to manage suppliers and enjoy greater benefits from their knowledge of external components. The increasing diversity of component technologies and their rapid rate of change are making it increasingly difficult for all critical components to be produced within a single firm (e.g., Fine, 1998). While this may result in greater use of modular product architectures (Baldwin and Clark, 1999; Schilling, 2000) and greater outsourcing (Schilling and Steensma, 2001), firms' effectiveness in integrating these diverse technological inputs may depend not only on their extended knowledge boundaries to encompass key components (e.g. Brusoni and Prencipe, 2001), but also on the extent to which firms are able to deploy such knowledge in their governance.

The final result of the study shows that within the existing vertical chain of activities, incremental changes in component technologies result in changes in the interactions between components, and such architectural changes seem to create significant delays in the commercialization efforts of non-integrated firms. Hence, vertically integrated firms seem better suited for architectural innovations. This finding suggests an important boundary condition for firms pursuing non-integrated "lean" strategies that they may be significantly disadvantaged if new innovations are architectural. This result may also help to clarify some inconsistencies in prior literature on technological change. While Henderson and Clark (1990) provided convincing evidence from the semiconductor lithography alignment equipment industry that architectural innovation was a major reason for incumbent's failure during technology transitions, subsequent research in other contexts has provided mixed findings. For example, Christensen and Rosenbloom (1995) showed 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 the architectural innovation.

We suggest a closer examination of the interaction between firms' production boundaries and the nature of technological change as a possible approach to resolving this inconsistency in empirical findings. 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). While many incumbent firms who relied on external lens suppliers to commercialize the new innovation exited the industry, the one firm that produced its own lens (Canon), despite facing significant challenges due to architectural innovations continued to be an important industry participant during and after the transitions.[9] Similarly, in the disk drive industry, the two technology generations 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 inch to 2.5 inch drives. In both of these 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 into the production of key components seem to successfully manage architectural transitions. This observation is in line with Teece's (1996) proposition that integrated firms fare better in commercializing innovations that require "coordinated adjustment" throughout the technological architecture:

> 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,

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[9] Another 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: 227).

> and where disputes can be monitored and resolved in a timely way. This is precisely what multi-product integrated firms achieve. (p. 219)

More recently, Wolter and Veloso (2008) have conjectured two opposing effects of architectural innovation on the performance of vertically integrated firms. They suggest that while vertically integrated firms may achieve superior coordination of technological changes underlying the architectural innovation, they may also be disadvantaged by the cognitive challenges that are embedded in a firm's communication channels, information filters and problem solving strategies. We note that just as the interactions within a firm are characterized by communication channels, information filters and problem solving strategies, so too are the interactions between the firm and its suppliers (e.g., Dyer and Nobeoka, 2000; Takeishi, 2002) which may also require greater adaptation during an architectural innovation. Hence, the relative shift in performance difference between vertically integrated and non-integrated firms during an architectural innovation is more likely to stem from the difference in coordination across these organization forms rather than the difference in the respective cognitive challenges.

While we have taken care in this empirical examination, there are several 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 use of patent data to measure firm's component knowledge assumes the firm's propensity to disclose such knowledge. It is possible that certain DRAM firms may choose to keep this knowledge as a trade secret. However, there is strong evidence that semiconductor firms aggressively patent to use their knowledge as bargaining chips (Hall and Ziedonis, 2001), such that our context at least partially controls for this concern. Although our measure of innovation performance as firm's time to market for a new DRAM generation is particularly suitable to our context, it may not fully correspond with profitability. Hence, it would be of interest to explore our hypothesized effects using additional measures of performance. Finally, we are unable to identify differences in the ways in which firms manage their relationships with external suppliers. In future work it would be interesting to explore how firms' abilities to manage different types of technological change are impacted by the interaction between their supplier capabilities (Dyer, 1997) and their investments in component knowledge (Fine, 1998; Takeishi, 2002; Brusoni et. al., 2001). It would also be interesting to explore how performance is impacted by the interaction of production choices with design choices (Ulrich and Ellison, 2005; Baldwin, 2008).

This study examines how firms' production and knowledge strategies within the vertical chain affect their ability to manage technological change. We show that heterogeneity in firms' vertical scope plays a critical role in the successful commercialization of new innovations. This study also extends the emerging literature that integrates transaction cost economics with competence based perspectives (Argyres, 1996; Leiblein and Miller, 2003; Mayer and Salomon, 2006). We show that while firms' knowledge of external activities may facilitate the governance of supplier activities, its effect may be muted for firms that are integrated into a subset of activities and have a lower reliance on external suppliers. We hope that our results encourage researchers to expand their examination of firm boundaries beyond the make-or-buy decision to also consider firms' knowledge profiles and governance capabilities, and to consider how these organizational factors interact with changes in technology to shape performance outcomes.

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Figure 1: Schema of the Semiconductor Lithography Technology

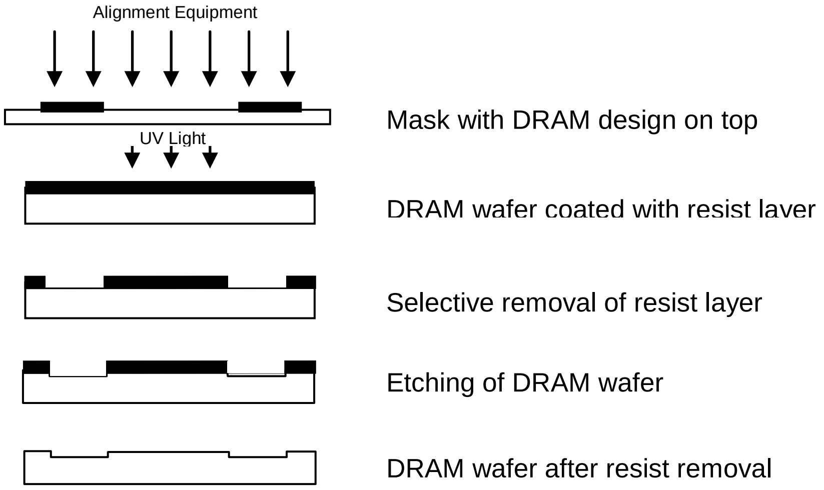

Figure 2: Introduction of New DRAM Generations, the Minimum Feature Size and Market Growth.

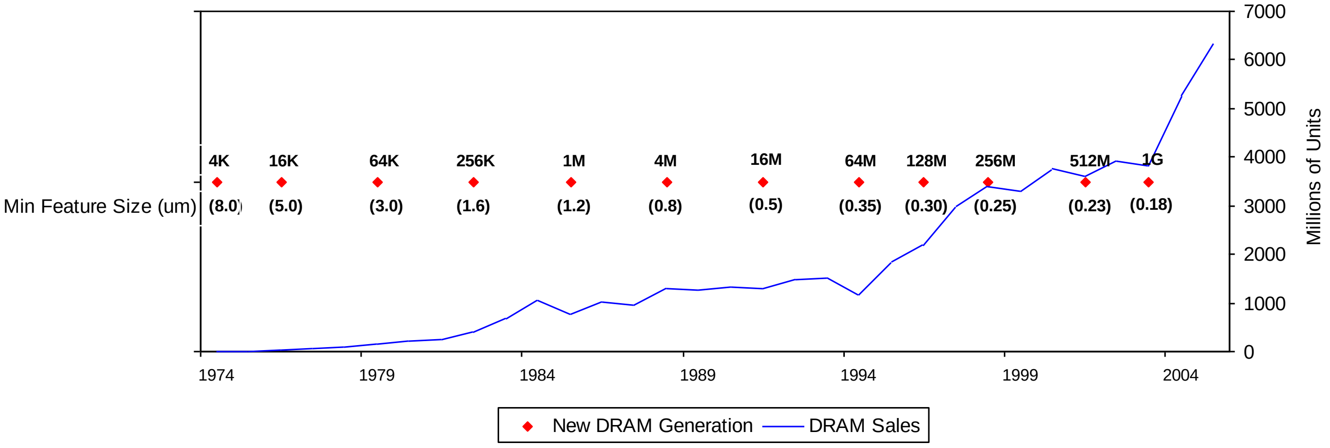

Figure 3: Firm's time to market as a function of its governance strategy for mask, its knowledge of mask and resist, and the nature of technological change.

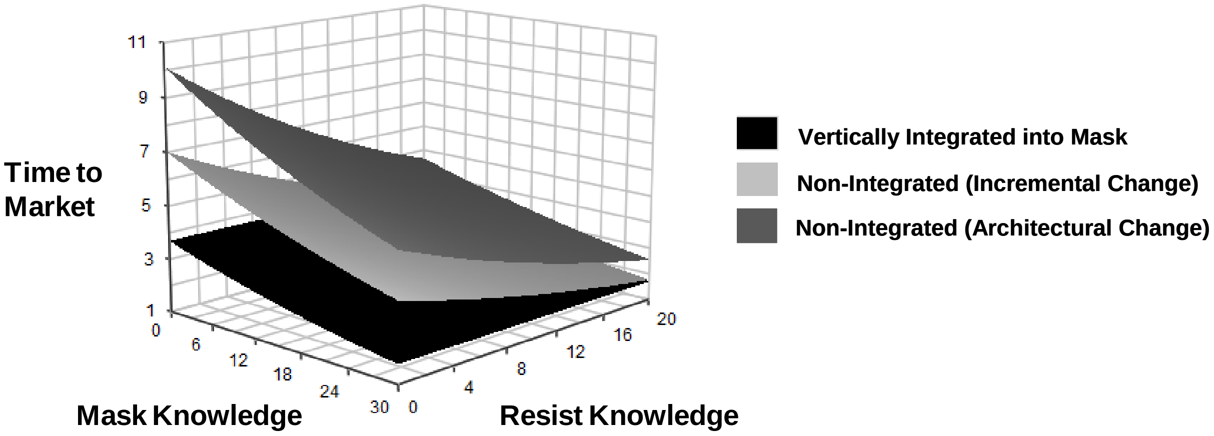

Table 1
Changes in Lithography Technology for Each DRAM Generation and the Nature of Technological Change

DRAM Generation (Year)	**Minimum Feature size (μm)**	**Description of Changes in Lithography Technology that Enabled the New DRAM Generation[a]**	**Major Changes in Critical Relationships Between Components**	**Type of Innovation**
1K (1970)	>8	N.A.		N.A.
4K (1974)	8.0	Mask is now separated from the wafer with a tiny gap to improve the process yield.		Incremental
16K (1976)	5.0	Improvements in mask making process and resist chemistry to print smaller circuits.		Incremental
64K (1979)	3.0	UV light is passed through reflective lens system of the alignment equipment and through the mask on to the wafer.	Interaction between mask and alignment tool. Manufacturing performance is now driven by mask as compared to the alignment equipment.	Architectural
256K (1982)	1.6	UV light is projected through refractive lens system on only a part of the wafer at any one 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 tool and the resist.	Architectural
1M (1985)	1.2	Improvement in resist chemistry to achieve smaller feature size.		Incremental
4M (1988)	0.8	An increase in the size of the lens in the alignment equipment and improvement in resist material.		Incremental
16M (1991)	0.5	Reduction in the wavelength of UV light from 435nm to 365nm accompanied by changes in the resist material to absorb lower wavelength light.	Relationship between the alignment equipment and the resist due to change in wavelength from 438 to 365 nanometers (nm).	Architectural
64M (1995)	0.35	Increase in the size of the lens of the alignment equipment; improvement in mask making process and resist material.		Incremental
128M (1998)	0.30	Increase in the size of the lens and improvement in mask and resist components.		Incremental
256M (2000)	0.25	Reduction in the wavelength of UV light from 365nm to 248nm accompanied by changes in the resist and mask material to absorb lower wavelength light.	Absorption of the low wavelength light by the mask and the resist becomes a key bottleneck to reducing the feature size. New mask techniques such as phase shift mask (PSM) and optical proximity correction (OPC) are employed to get smaller features.	Architectural
512M (2001)	0.23	Increase in numerical aperture of the lens; improvement in mask making process and resist material.		Incremental
1G (2003)	0.18	Increase in numerical aperture of the lens, improvement in mask and resist materials.		Incremental

[a] For details of changes in lithography technology, please refer to Kapoor and Adner (2007)

Table 2: Probit Estimates for First-stage Governance Choice Model for Mask (Buy=1, Make=0)

	(1)	(2)	(3)
Firm Size	-0.522***	-0.923***	-0.997***
	(0.100)	(0.162)	(0.174)
Non-DRAM sales	-2.280***	-1.165**	-0.843
	(0.372)	(0.511)	(0.550)
Mask Knowledge	0.032*	0.020	0.033*
	(0.017)	(0.015)	(0.017)
DRAM Feature Size		-0.783***	-0.964***
		(0.194)	(0.214)
Number of Suppliers			0.244***
			(0.076)
Constant	4.541***	6.362***	5.504***
	(0.710)	(0.924)	(0.974)
Log-likelihood	-71.60	-62.81	-58.32
Incremental χ^2		17.58***	8.98***
Observations	166	166	166

Robust standard errors in parenthesis. * significant at 10%; ** significant at 5%; *** significant at 1%.

Table 3: Descriptive Statistics and Correlations for Second-Stage Regression

	Time to Market	Mask Knowledge	Resist Knowledge	Architectural Innovation	Firm Size	Firm Scope	DRAM Feature
Entire Sample (N=166)							
Mean	1.58	4.84	3.66	0.40	6.73	0.64	-0.29
S.D.	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	
Make Mask (N=99)							
Mean	1.28	4.24	4.68	0.41	7.20	0.78	-0.07
S.D.	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
Buy Mask (N=67)							
Mean	2.03	5.73	2.15	0.37	6.04	0.42	-0.61
S.D.	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

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

Table 4: Second-Stage OLS Regression Results for the Firm's Log (Time to Market) [a]

	(1)	(2)	(3)		(4)		(5)	
	All Firms	All Firms	In-house Mask	Outsource Mask	In-house Mask	Outsource Mask	In-House Mask	Outsource Mask
Outsource Mask (H1)	0.404**	1.568***						
	(0.188)	(0.472)						
Mask Knowledge (H2)	-0.026***	-0.031***	-0.026*	-0.036***	-0.026**	-0.024***	-0.026**	-0.020***
	(0.009)	(0.008)	(0.012)	(0.007)	(0.012)	(0.007)	(0.012)	(0.006)
Resist Knowledge (H2)					0.004	-0.039**	0.004	-0.039***
					(0.017)	(0.014)	(0.017)	(0.012)
Architectural Innovation (H3)							-0.016	0.367***
							(0.132)	(0.090)
Firm Size	-0.297***	-0.055	-0.224	0.092	-0.231	0.055	-0.230	0.023
	(0.080)	(0.127)	(0.254)	(0.115)	(0.247)	(0.108)	(0.250)	(0.087)
Non-DRAM Sales (%)	0.367	0.822***	1.646**	0.626**	1.676**	0.578**	1.677**	0.510*
	(0.228)	(0.279)	(0.683)	(0.257)	(0.708)	(0.269)	(0.711)	(0.249)
DRAM Feature Size	-0.310***	-0.116	-0.210	-0.126	-0.204	-0.176*	-0.203	-0.188*
	(0.101)	(0.117)	(0.237)	(0.100)	(0.243)	(0.096)	(0.245)	(0.102)
Inverse Mill's Ratio (λ)		-0.753**	-0.702	-0.844**	-0.669	-0.707**	-0.672	-0.589*
		(0.309)	(0.602)	(0.307)	(0.559)	(0.328)	(0.568)	(0.298)
Constant	3.220***	0.910	1.472	1.741***	1.494	1.908***	1.493	1.905***
	(0.511)	(1.083)	(2.323)	(0.612)	(2.310)	(0.574)	(2.329)	(0.477)
R-squared	0.37	0.40	0.32	0.47	0.32	0.51	0.32	0.57
Observations	166	166	99	67	99	67	99	67

[a] Lower value of dependent variable implies superior performance i.e., earlier time to market.
Standard errors in parentheses, clustered by firm.
* significant at 10%; ** significant at 5%; *** significant at 1% (two-tailed t-test).

Appendix I: Description of the Secondary Data Used for the Study

Secondary Data Sources	**Data**
Gartner Dataquest	Quarterly DRAM shipment by firm, Quarterly DRAM price.
VLSI Research	DRAM firm annual sales.
US Patent and Trademark Office	Patents granted to DRAM firms.
Rose Reports	DRAM firm's participation in mask production.
Reynolds Consulting	DRAM firm's participation in mask production.
Grenon Consulting	DRAM firm's participation in mask production.
IC Knowledge	DRAM feature size
SPIE Conference Proceedings (Technical Articles)	Changes in component technologies of alignment equipment, resist and mask for DRAM generation. Changes in relationships between different components.
Industry Articles by Analysts	Changes in component technologies of alignment equipment, resist and mask for each DRAM generation.

[a] We had to use multiple sources for the firm's make-or-buy decision for the mask technology as 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 is consistent. We found no discrepancy between the three sources. This is expected as internal mask production was a "commonly" known fact in the industry.