

6. FOCUS STUDIES

The Role of Knowledge Spillovers in Buyer-Supplier Co-Development

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Abstract

This paper presents a model of cooperative technology development undertaken by a buyer and a supplier of capital equipment in the semiconductor industry. In order to meet the demanding technical requirements of their production processes, chip producers, the "buyers," often spearhead technology development projects with their equipment suppliers to advance the processing capabilities of their capital stock.

The model developed in this paper captures the tradeoffs a buyer faces when initiating an equipment improvement project. On one hand, the buyer wants the piece of equipment, or "tool," to be tailored to its particular processing needs. On the other hand, the buyer wants the modification to be incorporated into multiple generations of the tool, and equipment suppliers will more readily incorporate hardware changes that have general applicability across its customer base. The model shows that buyers will pursue equipment modifications that have some applicability to other chip producers' processing needs and may have to offer inducements to the supplier to ensure participation. In this modeling framework, knowledge spillovers across buyers occur not because one buyer uses another's modification without compensation but instead are embodied in capital equipment purchased from a common supplier. This paper finds that the growth of and access to the supplier's stock of knowledge discourages vertical integration in the semiconductor industry.

A case study from the industry highlights the features of the model by detailing the decisions a buyer faces when initiating co-development with an equipment supplier. This case study describes how the buyer initiated the project, the degree of general applicability of the resultant modification, and the types of inducements the buyer had to offer the supplier to secure its participation.

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I. Introduction

Knowledge accumulation and diffusion in the semiconductor industry occurs through an intricate system of innovation. This paper examines cross-company knowledge flows and focuses on vertical relationships. Buyer-supplier co-development projects are common in the semiconductor industry. In order to meet the demanding technical requirements of their production processes, chip producers, the "buyers," often spearhead technology development projects with their equipment suppliers to advance the processing capabilities of their capital stock.

Following a review of the literature addressing user-led technology development in Section II, Section III presents a model of buyer-supplier cooperative development. This model captures the tradeoffs a buyer faces when initiating an equipment improvement project. On one hand, the buyer wants the piece of equipment, or "tool," to be tailored to its particular processing needs. On the other hand, the buyer wants modifications to be incorporated into multiple generations of the tool, and equipment suppliers will more readily incorporate hardware changes that have general applicability across its customer base. The model shows that buyers will pursue equipment modifications that have *some* applicability to other chip producers' processing needs and may have to offer inducements to the supplier to ensure participation. Knowledge spillovers across chip producers occur through knowledge accumulation at the equipment supplier resulting from buyer-supplier co-development. The supplier's knowledge accumulation function presented in Section III reflects a relationship found in many industries: equipment suppliers have historically relied on co-development projects with their customers to increase their knowledge stock rather than undertake R&D in isolation. This reliance has been great in the semiconductor industry, since semiconductor equipment suppliers traditionally specialized in a particular equipment area and therefore depended on their customers to help them understand how modifications to their equipment would affect subsequent process steps.¹

Section IV analyzes a case study of co-development and compares the project's results with the predictions from the model of Section III. This case study describes how a buyer initiated a co-development project with one of its suppliers, the degree of general applicability of the modification, and the types of inducements the buyer had to offer the supplier. Section V concludes by discussing the implications of buyer-supplier co-development for industry structure and the dynamic effects of knowledge accumulation by the supplier.

II. The User as the Technology Driver

Over the last thirty years, a number of semiconductor producers (*e.g.*, IBM, AT&T, and Texas Instruments) have shifted from making their own production equipment to purchasing it from independent suppliers. Although chip makers and their equipment suppliers have become increasingly independent in terms of ownership, they frequently undertake co-development projects.² As Stigler (1951) observes, this pattern of "vertical

disintegration" is common as an industry matures (p. 190): Economies of scale in producing capital equipment and the related gains from specialization encourage the formation of independent suppliers once demand reaches a certain threshold. Although this "disintegration threshold" of demand was reached in the semiconductor industry over two decades ago, equipment suppliers still rely on their customers for technical knowledge. As discussed below, user-led technology development is common in many industries, including the semiconductor industry, and plays a commanding role in fueling technological change.

The machine tool industry has provided fertile ground for studies of buyer-initiated technology development. Rosenberg (1963) presents historical evidence that the machine tool industry grew as a result of the "convergence" of technical needs spanning a number of industries: The tooling needs of the firearms industry overlapped with those of the sewing-machine industry and similarly the needs of the bicycle industry overlapped with those of the automobile industry. The overlap in demand fueled the burgeoning machine tool industry in the United States during the late 1800s, which in turn fueled the growth of manufacturing-intensive industries and economic growth. Demand was great enough to sustain independent machine tool companies, and technology developed by the users often diffused back to the machine tool companies. For example, gearing and lubrication systems developed for automobiles were adapted to the machine tools that made automobile components.

In a study of the rise of machine tools in Japan, Lee (1996) provides empirical evidence that user investment in capital goods is positively related to the innovative performance of the machine tool industry measured by patenting activity. Lee uses investment data from Japanese automakers from 1963-1988, and finds a positive relationship with the share of U.S. patent applications by Japanese machine tool companies relative to other foreign companies (Lee, 1996, p.498). By examining total machine tool patents held in the U.S. by Japanese firms from 1963-1986, Lee demonstrates the pervasive role of user firms in *directly* advancing machine tool technology: Users held 39% of the patents.

Echoing the findings from the machine tool studies, von Hippel (1977) shows that users dominate innovative activities for significant process innovations in both semiconductor manufacturing and the manufacture of electronic subassemblies. Von Hippel employs Meyers and Marquis's (1969) classification of innovation. It contains six stages: 1) Recognition; 2) Idea Formulation; 3) Problem Solving; 4) Solution; 5) Utilization and Diffusion—Pre-commercial; 6) Utilization and Diffusion—Commercial. Von Hippel characterizes "user-dominant" innovation when the user is responsible for the first five stages and "manufacturer-dominant" innovation when the user is responsible only for the first stage. Von Hippel notes that he chose the semiconductor industry for his study, because the equipment manufacturers in the industry rarely produce chips. That is, the equipment manufacturers are not user-inventors. This allows him to separate user-driven and supplier-driven innovation.

Von Hippel finds clear evidence of user-dominant innovation in the early days of the two industries in his study:

1. In his sample, suppliers were not responsible for the initial innovation and were responsible for no more than half of the major and minor improvements in the two industries. Of the fourteen major process machinery innovations studied in the semiconductor industry, users were responsible for over 70% of them (von Hippel, 1977, p.67);
2. He found similar levels of user dominated innovation in the two industries, although he had not anticipated this similarity given the industries' different levels of technical sophistication;
3. During the period of the semiconductor sample, 1954-1971, innovators classified as "Supplier" or "Other" participated increasingly in follow-on innovations, but were minor players in initial innovation.³

To explain user-dominated technical change, von Hippel asserts that suppliers prefer to avoid uncertainty by waiting until the demand for an improvement is proven and the market expands. Von Hippel wished to test the hypothesis that the size of market potential for a particular modification would be positively correlated with the likelihood that the innovation would be supplier dominated. However, his attempts were thwarted, since "the confidentiality of sales data was apparently prized more highly than life itself by manufacturers" (von Hippel, 1977, p.68).

Drawing on von Hippel, Teece (1992) notes that users often initiate innovation, and their suppliers succeed by honing their "product engineering skills" rather than their R&D abilities (p.11). User-initiated innovation "requires two kinds of technology transfer: first from user to manufacturer, and then from manufacturer to the developer-user and other users" (Teece, 1992, p.11). This pattern of innovation exists in the semiconductor industry, and many equipment modifications have been initiated by users. As Teece highlights, the manufacturers must ferret out the needs of their customers and meet their customers' specifications.⁴

The existing literature has established the wide-spread phenomenon of user-led innovation, particularly in industries such as the semiconductor industry where the technical sophistication of the user historically eclipsed that of their equipment suppliers. The studies discussed above present evidence that buyer-initiated co-development both accelerates and directs knowledge accumulation within certain industries. However, few studies have detailed the interactions between buyers and suppliers while they undertake co-development. One notable exception is Shuen (1994), which examines co-development projects between a semiconductor producer and two of its component packaging suppliers. In one of the projects, Shuen finds that the chip producer was willing to transfer knowledge to the packaging supplier to develop a new technology in order to secure a time-to-market advantage, even when recognizing that competitors would have access to the knowledge via the supplier (Shuen, 1994, p.32). The buyer attempted to curb knowledge spillovers by filing patents jointly with the supplier, co-opting the supplier's resources by conducting subsequent co-development projects, and filling the supplier's

processing capacity to prevent other chip producers from utilizing the new technology. In some instances, Shuen finds that the buyers have to "sweeten the deal" to induce suppliers to cooperate by incurring a high proportion of the initial development costs (Shuen, 1994, p.36). These features of cooperative development—suppliers serving as the conduit of knowledge spillovers and the occasional need for inducements—are incorporated into the model found in the following section. The case study in Section IV fleshes out these features in a project undertaken in the "front-end" of semiconductor manufacturing.⁵

III. Modeling Buyer-Supplier Co-Development

This section models the tradeoffs that a buyer faces when engaging in cooperative development with an equipment supplier. The buyer is assumed to be a chip producer that identifies a processing need only attainable by modifying a particular piece of equipment. The required modification is radical enough that the hardware must be reconfigured, but the equipment supplier cannot modify the hardware without guidance from the buyer. The two parties enter into a cooperative agreement, bringing their complementary expertise to the relationship: The buyer's knowledge of the chemistry and physics backing its processing needs is merged with the supplier's knowledge of machine-tooling and calibration to produce the modification. It is assumed that suppliers will incorporate modifications into future generations of their equipment if the modifications are broadly applicable to the industry, resulting in intertemporal knowledge spillovers.

Section A presents the base case, where a supplier can accommodate all requests for co-development projects, and the buyers are not product market rivals. The base case reflects how a buyer must balance its desire for customized equipment against the gains from having broadly applicable modifications built into the supplier's equipment. When a supplier cannot fulfill all requests for modifications, buyers compete for the supplier's resources by offering inducements as modeled in Section B. Section C introduces product market competition across the buyers, which diminishes a buyer's gain from intertemporal knowledge spillovers and encourages modifications that are more customized.

III.A Customized vs. Generally Applicable Modifications

The model developed in this section reflects the payoffs to buyers when they enter into co-development projects with a common equipment supplier. The payoffs from co-development are internalized by the buyers through improved capital equipment that they use to produce their chips. For simplicity, it is assumed that there are two buyers, B_i where $i=1,2$, and one equipment supplier, S , and the buyers enjoy a monopoly in their respective product markets.⁶ It is also assumed that the supplier has enough resources to staff equipment improvement projects with both buyers. In addition to determining the optimal mix of labor and capital to produce its chips, a buyer must select the level of customization for its equipment modification projects. In the model below, when a buyer elects modifications with general applicability across the industry it benefits in two ways. First, its capital equipment becomes more productive over time due to knowledge accumulation at the supplier, and second, it benefits from economies of scale when renting

the equipment because of its broad base of demand. However, there is a downside to pursuing generally applicable modifications: In a particular production period, the buyer forgoes the gains to customization which would reduce the effective rental rate of capital. One could think of customization as a way to reduce processing time for a buyer-specific process, thus permitting the buyer to cut the number of hours it has to rent equipment to complete its production run.

As noted above, although buyers benefit from having their equipment customized to their particular process flows, they also benefit from the knowledge embodied in their machines over time. If the modification embodying the knowledge has general application throughout the industry, *i.e.*, is useful to both buyers, it is assumed that the equipment supplier will incorporate the resultant knowledge from the co-development project into its machines the following period.^{7,8} In practice, the "improvements" incorporated into the next generation of equipment include hardware modifications, as well as the supplier's ability to "support" the tool with spare parts, training classes, proficient troubleshooting, etc. The buyers must weigh the short-run loss of not having customized equipment in the current period against the gains from both economies of scale and improved equipment and support next period. In the model below, the buyer balances these forces by pursuing modification projects that are not fully customized.

Profit maximization requires the buyers to select how general they wish to make their modifications, reflected by their choice over the degree of generality, γ , (where $0 \leq \gamma \leq 1$) in addition to selecting levels of engineering hours, E , in light of the wage rate w and capital, K , in light of the effective rental rate $r(\gamma)$. It is assumed that the rental rate of capital, $r(\gamma)$, varies inversely with γ , reflecting economies of scale. It is also assumed that the supplier's stock of knowledge at time t , A_t^S , is positively related to γ , and heightens the productivity of K . These are the two positive effects on a buyer when it pursues generally applicable modifications and chooses a high γ . However, when considering the *effective* rental rate of capital, $\gamma r(\gamma)$, γ has a direct effect that hurts the buyer in a particular time period. With the price and level of its output represented by p and $F(\bullet)$, respectively, Buyer i faces the following net revenue function at each time period:

$$p_t^{Bi} = pF(E_t, K_t, A_t^S) - wE_t - \frac{1}{\gamma_t^{Bi}} r(\gamma_t^{Bi}) K_t,$$

where $\frac{\partial F(\bullet)}{\partial A_t^S} > 0$, while $\frac{\partial^2 F(\bullet)}{\partial A_t^S{}^2} < 0$. Buyer i maximizes its stream of profits over the lifetime of this particular process technology, T , with respect to γ_t and subject to the supplier's knowledge accumulation function:

$$\max_{\mathbf{g}} \sum_{t=0}^{T-1} p_t^{Bi} + L(A_T^S)$$

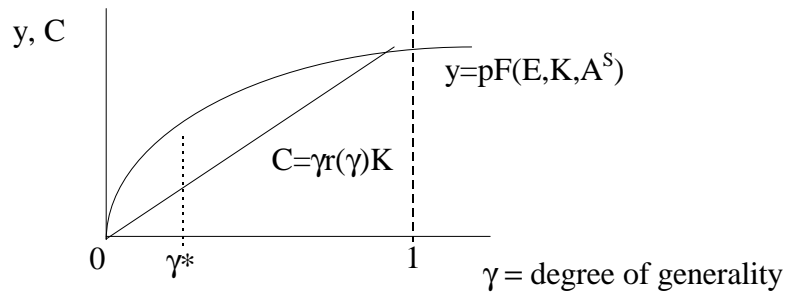
subject to

$A_{t+1}^S - A_t^S = g(A_t^S, \mathbf{g}^{Bi})$, where $i=1, 2$,
and $A_0^S = a$, where a is given.

The function $L(\bullet)$ determines the net value associated with the supplier's knowledge stock at the terminal period, A_T^S . Knowledge accumulation at the supplier is assumed to increase in γ , $\frac{\partial L(\bullet)}{\partial \mathbf{g}^{Bi}} > 0$, and knowledge spillovers across buyers are transmitted through the supplier's knowledge accumulation function. If a buyer chooses to work on generally applicable co-development projects, a high γ , its net period returns increase indirectly due to γ ($\frac{\partial F(\bullet)}{\partial A_t^S} \frac{\partial A_t^S}{\partial \mathbf{g}^{Bi}} > 0$ and $\mathbf{g}^{Bi} \frac{\partial r(\mathbf{g}^{Bi})}{\partial \mathbf{g}^{Bi}} < 0$) but decrease due to γ 's direct effect on the effective rental rate of capital ($r(\mathbf{g}^{Bi}) \frac{\partial \mathbf{g}^{Bi}}{\partial \mathbf{g}^{Bi}} = r(\mathbf{g}^{Bi}) > 0$). Although the buyers will benefit from an improved equipment set over time as the supplier incorporates general modifications and improves the support for its general equipment "platform," they incur greater costs of capital in any point in time by not having customized equipment. Dropping the time subscripts, Figure 1 depicts these tradeoffs, where C represents the capital costs and y represents revenues. At $\gamma=0$, revenues are assumed to increase more rapidly in γ than the capital costs,

$$\left. \frac{\partial F(\bullet)}{\partial A_t^S} \frac{\partial A_t^S}{\partial \mathbf{g}^{Bi}} \right]_{\mathbf{g}=0} > [r(\mathbf{g}^{Bi})K + \mathbf{g}^{Bi} \frac{\partial r(\mathbf{g}^{Bi})}{\partial \mathbf{g}^{Bi}} K]_{\mathbf{g}=0}.$$

Figure 1. The Costs and Benefits of Co-Development Projects



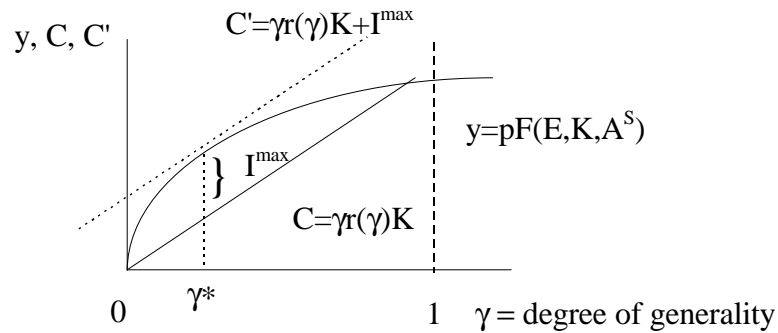
As the figure demonstrates, a buyer facing such tradeoffs would not choose to customize the equipment ($\gamma=0$), but opt for some degree of general applicability, γ^* , where $0 < \gamma^* \leq 1$. Since the firms do not insist on customized equipment, knowledge spillovers between buyers are positive and flow through the equipment supplier. Due to the implicit assumption discussed earlier that buyers would shy away from undertaking co-development with suppliers owned by other buyers, it is access to these spillovers that dissuade the buyers from acquiring their suppliers.⁹

III.B Competing for Supplier's Resources

In the previous section, the supplier could accommodate all requests for equipment modification projects. In reality, the supplier must ration its resources across its customers. As shown below, its customers can offer inducements to attract the supplier's resources for co-development. To entice the supplier to cooperate, buyers often offer inducements such as additional engineering resources or additional equipment purchases.

The level of inducements, I , that a buyer can offer depends on its production technology and its per period capital costs. Building on the example from the previous section, the buyer would be willing to offer inducements each time period equal to its net benefits from the modification, $I \leq pF(E, K, A^S) - \gamma^*r(\gamma^*)K$. Figure 2 depicts the maximum level of inducement, I^{\max} , that the buyer would be willing to offer the supplier, and the associated new capital costs, C' .

Figure 2. The Costs and Benefits of Co-Development Projects Net of Inducements



At the optimal degree of generality, γ^* , the buyer can offer its maximum inducement, I^{\max} . Whether I^{\max} is high enough to outbid other buyers for the supplier's resources, depends on the other buyers' production function and cost of capital, as well as the supplier's willingness to engage in co-development. If a buyer cannot outbid others for the supplier's resources, it loses this period by forgoing a reduction in its effective rental rate of capital through the direct effect of γ , but will benefit the following period from the improved equipment set.¹⁰

III.C The Influence of Product Market Rivalry

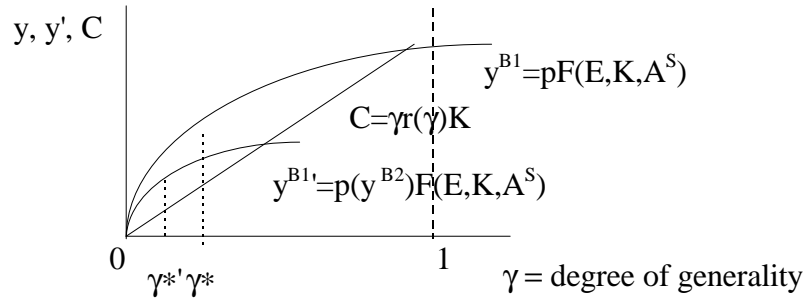
In the prior two sections, it is assumed that the buyers are not product market rivals. This section introduces product market rivalry across the buyers in a setting where, back to one of the assumptions of Section A, all co-development projects can be accommodated by the supplier. The introduction of competition places a downward pressure on the optimal level of generality, γ^* , since the buyers wish to limit the knowledge spillovers to each other via A^S . Instead, buyers prefer more customized modifications, $\gamma^{*'} < \gamma^*$, thus reducing knowledge accumulation at the supplier.^{11,12}

Product market competition erodes the real returns to a buyer. With competition, Buyer 1's profit function (suppressing the time subscripts) becomes

$$p^{B1} = p(y^{B2})F(E, K, A^S) - wE - g^{B1}r(g^{B1})K,$$

and Buyer 2's real output exerts a downward pressure on Buyer 1's real returns, $\frac{\partial p(y^{B2})}{\partial y^{B2}} < 0$. As depicted in Figure 3, the optimal degree of generality falls to γ^* with competition.

Figure 3. The Costs and Benefits of Co-Development Projects with Competition



In the presence of competition, the results of the model change in three primary ways relative to the findings of Sections A and B: first, the buyers will demand more customized co-development projects; second, this increase in customization decreases knowledge accumulation at the supplier and decreases the knowledge spillovers embodied in subsequent generations of equipment; finally, since the knowledge spillovers via the supplier are reduced, the appeal of buying equipment from independent suppliers diminishes, and vertical integration may result. However, in the semiconductor industry, "re-integration" has not followed intensified product market competition for example in DRAMs. The reason may be that chip producers benefit greatly from off-loading risks of cyclical demand onto independent suppliers.

IV. A Case Study of Buyer-Initiated Co-Development

The case study presented below highlights the decisions a buyer faces when initiating co-development with an equipment supplier.¹³ The setting for this case study could be considered a mix between the conditions found in Sections B and C above. As discussed in Section B, the buyer (pseudonym: ChipCo) was in competition for the supplier's resources and had to offer inducements to entice the supplier (pseudonym: EquipCo) to cooperate. As found in Section C, a high degree of competition in the buyer's product market led it to pursue a customized modification. ChipCo sought a dramatic departure from the current processing capabilities of EquipCo's machine. A new production process developed by ChipCo required a more precise etching capability than previously available in order to fit more transistors into a given area. The procedure had been discussed in the technical literature but had not been commercialized. It required a

new etch "recipe" to be run on EquipCo's machine complemented by a minor hardware modification to the machine.

The co-development project progressed through three primary stages: 1) conception, 2) development, and 3) optimization.¹⁴ The following table presents estimates of the lengths of each stage. In his estimate of the length of the optimization stage, the lead engineer at ChipCo included the elapsed time required to complete a few follow-on equipment "tweaks," whereas the lead engineers at EquipCo considered the project optimized after the completion of the original hardware change required by the new etch recipe. During the course of the project, ChipCo developed an intimate understanding of the new etch procedure and realized that a few additional hardware changes would increase the repeatability of the etch results. These changes were difficult to predict at the outset of the project, and EquipCo did not feel obligated to undertake them since the new etch met the primary goals agreed upon at the outset of the project.

Table 1. Duration of the Project's Stages

Stage	According to Buyer	According to Supplier
1) Conception	3.0 months	1.5 months
2) Development	3.0 months	2.5 months
3) Optimization	9.0 months	2.0 months

Consistent with von Hippel's classification of user- dominant innovation, ChipCo led the project through all of these major stages by directing goal setting activities, determining which experiments to run, and conducting the majority of the experiments. The two parties interacted most frequently during the development stage with the lead engineer at ChipCo talking with his counterparts at EquipCo roughly 60 times. Interaction during the conception stage was limited to negotiating the co-development agreement and the number of machines that ChipCo would purchase. During the optimization stage, they only interacted a handful of times when they discussed the manufacturability of the machine and the follow-on hardware changes that ChipCo expected EquipCo to complete.

This modification required the revision of over 50 variables at the etch processing step. In semiconductor manufacturing, etching operations remove unwanted layers of deposited compounds such as photo-resist or oxide, to permit the deposit of other compounds such as metal alloys to create a chip's circuitry. The primary goal of this project was to heighten selectivity to one compound while leaving a neighboring compound intact. Although ChipCo sought improved selectivity for a higher precision etch, it was unwilling to sacrifice performance in terms of uniformity of the etch across the silicon wafer, rate of the etch, and uptime of the machine. To achieve the new etch, ChipCo altered the "recipe" of the etch, namely the temperature and gas pressure inside the etching chamber, the temperature of the wafer being processed, and the "quality" of the wafers entering the etch chamber. EquipCo had to alter the hardware to accommodate the new recipe. Of the more than 50 variables identified by ChipCo as important to the success of the new etch procedure, approximately 65% were considered crucial. By the

end of the primary phase of the co-development project, ChipCo estimated they had succeeded in "locking-in" 10% of the crucial variables and expressed optimism that with follow-on help from EquipCo (or from another outside contractor), they would lock-in the remainder in a short period of time.¹⁵

The buyer and supplier that entered into this co-development project differed in their expectations of its applicability across the industry. Throughout the project, ChipCo required that the modification met the specific needs of its new production process, but it also asserted that other chip producers would demand the new capability. Consistent with this belief, ChipCo incurred the cost of filing a patent after preliminary experiments with the new etch recipe even before the hardware change was fully underway.¹⁶ In contrast, EquipCo contended that it was a customized recipe and hardware modification, and none of its other customers would desire it. To some degree, these claims were used as posturing tactics in order to bargain for favorable conditions governing the project, and in fact, two years after the project, no other chip producer had licensed the technology supporting the supplier's initial stance.¹⁷ Since EquipCo believed the project would have very limited general applicability (a low γ), and there was excess demand for its resources, EquipCo required that ChipCo offer inducements. ChipCo acquiesced by agreeing to purchase an additional machine and commit a higher relative fraction of engineering hours, since it desperately needed the modification for its new production process, and it anticipated licensing revenues from patents from the project that would help off-set the costs of inducements.

The primary inducement offered by the buyer was a commitment of engineering resources. Since ChipCo anticipated brisk demand for the modification, it was contented with taking the lead on the project so that it could secure the patents over the resultant technology. Over the life of the project, ChipCo committed more engineering resources than the supplier (see Table 2). "Core Team" represents the number of people who spent the majority ($\geq 50\%$) of their work time on the project, averaged over the three stages of the project. "Periphery" represents those who spent the minority ($< 50\%$) of their time working on the project, again averaged over the three stages.

Table 2. Resources Committed to the Co-Development Project

	Buyer		Supplier	
	Core Team	Periphery	Core Team	Periphery
Engineers	2	7	1.5	2
Technicians	0	1	0	1.5
Operators	0	0	0	0
Other	0	2	0.5	0

Overall, both ChipCo and EquipCo considered the project to be a success. They achieved the primary processing goals defined at the outset of the project, except that the rate of the etch was slower than desired by ChipCo. As a general rule and in line with the model in Section III.A, the lead engineer at ChipCo ascribes to following the "mainstream" so as to "benefit from the larger pool of learning going on," but in this case

he knew that his company's new process technology required a radical improvement to existing etch capabilities. ChipCo anticipated the useful life of the modification would run five years and see them through two additional new process introductions. Consistent with the findings of Section III.B, the buyer had to offer the supplier inducements to secure some of its scarce resources by agreeing to buy an additional machine and by committing more engineering resources to the project.

The influence of competition in the buyer's product market was also relevant to this co-development project, since it prompted ChipCo to develop a cutting-edge process flow requiring this etch equipment modification. The findings of Section III.C suggest that competition increases the customization of modifications, since a buyer wishes to curtail knowledge spillovers via the supplier to its rival. The buyer in this case study actually believed the modification would have general applicability in the industry but wanted to control knowledge spillovers to its rivals by conducting preliminary experiments and submitting patent applications even before approaching the supplier. Given the lack of follow-on demand for the modification, however, it could be considered a customized modification consistent with EquipCo's initial claims. The lack of demand also indicates the difficulty in anticipating the payoffs from modification projects in a technology-intensive industry and suggests that expectations should be introduced into the modeling framework found in the previous section.

V. The Implications of Vertical Knowledge Sharing

This chapter presents a model of cooperative technology development undertaken by a buyer and supplier of capital equipment in the semiconductor industry. The terms of the agreements governing co-development projects are assumed to reflect how customized the modification is to the buyer's processing needs and the demands on the supplier's resources. A higher level of competition faced by a buyer in its product market increases its desire to seek customized modifications. In this modeling framework, knowledge spillovers across buyers occur not because one buyer uses another's modification without compensation but instead are embodied in the capital equipment and the skills needed to "support" the equipment developed at a common supplier. It is the growth of and access to this pool of general knowledge at the supplier that discourages vertical integration in the industry. On the surface, it seems somewhat paradoxical that in a technology-intensive industry such as the semiconductor industry, producers benefit from buying equipment that incorporates generally applicable modifications. Depending upon the costs, chip producers are willing to buy "off-the-shelf" equipment to benefit from economies of scale and engage in generally applicable modifications that will be incorporated into future machines.

Historically, chip producers have ceded the lower value-added hardware market to independent suppliers and consequently freed their engineering resources to concentrate on higher value-added process technologies. Because of their limited stock of knowledge, suppliers had to follow the lead of their customers when developing new equipment technology. However, an interesting trend in the industry is emerging whereby

experienced equipment suppliers are migrating towards developing process technology. This trend may hamper buyer-supplier co-development projects involving experienced suppliers. If suppliers amass process-related knowledge as well as hardware-related knowledge during co-development projects, chip producers may fear that this would lower the entry barrier for new semiconductor producers, since the new entrants could buy not only machines but also process technology from their equipment suppliers. If this fear discourages buyers from undertaking co-development, the spillover of hardware-related knowledge via the supplier will be curtailed and suppliers will have to rely solely on their in-house R&D.

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¹ A number of leading suppliers, including Applied Materials and Lam Research, are diversifying their product lines to decrease their dependence on their customers.

² This chapter makes an implicit assumption that chip producers prefer to engage in co-development projects with independent equipment suppliers rather than suppliers owned by other chip producers, such as the equipment arm of Hitachi. This preference reflects the willingness to share hardware knowledge but the desire to keep close control over process-related knowledge and was voiced by a number of U.S. development engineers met by the author during field work.

³ "Other" included "independent inventors" and "suppliers of new materials" (von Hippel, 1977, p.67 fn13).

⁴ In the semiconductor industry, determining whether a new tool meets a customer's specifications can only be done once the tool is installed in the customer's fabrication facility, and it processes a sizable number of wafers. Equipment suppliers often lament of being "starved" of silicon in their development labs.

⁵ Shuen's study presents a case from the "back-end" of the manufacturing flow, where finished chips are packaged in plastic or ceramic prior to insertion into a computer motherboard for example. During the "front-end" of manufacturing when the layers of circuitry on the chips are made, a buyer may be even more concerned with the supplier's potential role as a conduit of knowledge, making the negotiation of a co-development agreement potentially more challenging.

⁶ In all of the primary semiconductor equipment areas, there actually are at least two viable suppliers which helps discourage a supplier from "holding up" a buyer during a co-development project, since the buyer can credibly threaten to switch to another supplier.

⁷ This is a strong assumption, since equipment suppliers *do* learn during projects involving fully customized modifications. For simplicity, it is assumed that the incorporation of general knowledge swamps the incorporation of knowledge from full-custom projects.

⁸ Langlois (1992) attributes the creation of "cluster-tools" in the semiconductor industry to the accumulation of general knowledge at the equipment suppliers directed by technical standards agreed upon by the industry.

⁹ In the early days of the semiconductor industry, it made sense for buyers to own their suppliers, since the potential level of knowledge spillovers was small. As the number of buyers grew over time, potential spillovers also grew which encouraged dis-integration.

¹⁰ This assumes that firms which do undertake co-development choose $g > 0$.

¹¹ Mishina (1991) employs a game theoretic framework to show that knowledge spillovers via equipment suppliers are *more* likely with competition than when one buyer possesses superior technology capabilities.

¹² As discussed in the case study in Section IV, buyers facing intense rivalry not only will pursue more customized modifications, but often will secure patents over the modifications to control their diffusion. Still other buyers facing severe competition will shy away from co-development altogether and modify equipment only after it is installed in their manufacturing operations.

¹³ Both the buyer and supplier in this case study are U.S. companies. This case study was documented through a written questionnaire completed by the "champion" of the project at the buyer and the two key players at the supplier. These three individuals were also interviewed either in person or over the phone.

¹⁴ These stages spanned the first five stages of Meyers and Marquis's classification discussed in Section II above. The conception stage covered Meyers and Marquis's Recognition and Idea Formulation stages; the development stage combined their Problem Solving and Solution stages; and the optimization stage mirrored their Utilization and Diffusion—Pre-commercial stage.

¹⁵ In the buyer's terminology, a particular variable that is "locked-in" will not cause the processing accuracy of the equipment to "drift" from its optimal level.

¹⁶ For simplicity the modeling framework of the previous section suppresses the possibility of the buyer earning licensing revenue from modifications that it initiates and assumes that the buyer only earns revenues from product sales. Presumably the possibility of earning licensing revenue would counteract the desire for a more customized modification in the face of competition as depicted in Figure 3.

¹⁷ The lack of demand for the modification may have been because it was customized to ChipCo's production process, but another explanation is that other chip makers could not wait for the completion of this project and had to develop their own new etch procedures. During the time of its project with ChipCo, EquipCo was working with at least one other major chip producer on a very similar modification.