A Dynamic Analysis of Cooperative Research in the Semiconductor Industry

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Abstract

In this paper I consider a dynamic oligopolistic model of research joint venture (RJV). In this model firms invest to improve product quality, and share the transition probability of quality improvement when they form an RJV. The model is applied to analyze the research cooperation in the semiconductor industry. I estimate firms' locations in the state space using product level data, and compute research expenditures in Markov Perfect Equilibrium. The result shows that firms save research cost by forming the RJV, and its benefit outweighs the foregone benefit of being a solo innovator in its absence. It also shows that consumers benefit from lower new product price in the RJV, and the benefit is likely to outweigh the foregone benefit of having new products more frequently without it. Lastly, I show that a more competitive product market is likely to reduce research expenditure when firms cooperate in research.

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1 Introduction

Firms competing in the product market often form a joint research venture (RJV) and cooperate in research and development (R&D). A prominent example is SEMATECH in the semiconductor industry where rival firms cooperate in developing generic manufacturing technology, mainly the photolithography technology. Other examples are found in the automotive industry, the biopharmaceutical industry, the food and beverage industry, the paper and pulp industry, etc. While the US government prohibits firms from colluding in the product market, it allows cooperation in R&D. The National Cooperative Research Act, enacted in 1984, provides government support to RJVs.

The theoretical literature argues that RJVs are welfare enhancing. A usual argument is that RJVs internalize spillover so that member firms increase their R&D spending, which in turn increases profit and consumer surplus through cost reduction (Katz, 1986; d'Aspremont and Jacquemin, 1988; Suzumura, 1992; Kamien, Muller, and Zang, 1992.) The spillover rate, roughly defined as the rate at which a firm benefits from its rival firm's R&D spending, should be sufficiently high to have this result. For example, d'Aspremont and Jacquemin (1988) need a condition that a firm's one dollar R&D spending reduces its rival firm's cost by at least 50 cents for an RJV to be welfare enhancing. Kamien, Muller, and Zang (1992) define RJV as a state where the spillover rate is at the maximum level.

In this paper I evaluate RJVs in different perspectives. I consider trade-offs that both firms and consumers face in RJVs as compared to a non-cooperative (competitive) research regime. Firms may benefit from RJVs by eliminating duplicative research efforts, but should give up a possibility to become a solo innovator. Consumers may benefit from RJVs with lower new product price as rent from innovation is shared by all member firms, but may wait longer for a new innovation to arrive.

I model an RJV using a structural dynamic oligopoly model developed by Ericson and Pakes (1995) and Pakes and McGuire (1994). In particular, I consider duopolists in a differentiated product market who invest to improve product quality, and define an RJV as firms' sharing a research success probability. This probability is a function of firms' research expenditure and governs a transition of a state variable that represents each firm's technological advance.[1] The non-cooperative research regime or the competitive

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[1] My definition of RJV is similar to Choi (1993). Marjit (1991) and Combs (1992) also define RJV in a similar manner but

research regime is identical to a quality improving game modeled by Pakes and McGuire (1994) . In both regimes firms compete *á la* Bertrand in the product market.[2]

I consider two types of RJVs: RJV competition and RJV cartel. In the RJV competition regime firms maximize the discounted sum of their own profits in setting research expenditure. In the RJV cartel regime they maximize the discounted sum of joint profit.[3] It turns out that the two regimes differ in how firms divide research expenditures. In RJV cartel firms spend equally as long as their research efficiency is the same, where the research efficiency represents their ability to transform research expenditure into the success probability. In RJV competition the relative size of expected gains matters such that a firm with a higher expected gain spends more even when the research efficiency is the same.

I apply this model to the semiconductor industry and analyze research cooperation through SEMATECH. The competitive research regime in comparison is a hypothetical regime where firms unilaterally develop the photolithography technology. I confine my analysis to the CPU sector where Intel and Advanced Micro Devices (AMD) are major players.[4]

Two state variables are chosen to describe an evolution of the industry. The one is the maximum CPU speed available in each period, and represents a path of the technological advance in the industry. In the RJV regimes the same maximum CPU speed is available to both firms, and a transition to a higher maximum speed is only possible with research success by SEMATECH.

The other state variable is product quality not related to the CPU speed. This state variable represents an evolution of firms' competitiveness apart from the CPU speed in the product market. For example, actual performance of the same speed CPU can be different depending on the design of transistor patterns. Thus, firms still sell differentiated products even when they fully share research outcomes through the RJV. I use each firm's mean value of "unobserved" quality to estimate this state variable.[5]

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treat the research success probability as an exogenous parameter.

[2] Although I focus on the product innovation (quality improvement) in this paper, the model can be easily modified to describe the process innovation (cost reduction). In the process innovation firms are heterogenous with respect to the production cost and compete a la Cournot in the product market.

[3] This distinction is similar to Kamien, et.al. (1992) who consider both the unilateral and the joint profit maximization within their RJV regime.

[4] Firms in other sectors of the industry such as DRAM and flash memory sectors also participate to SEMATECH and produce a wide range of semiconductors using this technology. However, the CPU sector is a leading technology sector that benefits most from the advancement of photolithography technology.

[5] I do not model how firms competitively improve unobservable characteristics. Instead I analyze how firms' cooperative research behaviors are affected by changes in unobservable characteristics.

Data on Intel and AMD CPUs from 1993 to 2000 are used to estimate consumer demand, employing a discrete choice model of differentiated product demand. Demand estimates link the state variables to per-period variable profit and consumer surplus. Then research expenditure and firms values are computed for every combination of the state variables by finding the Markov Perfect Equilibrium. The computation algorithm is based on the one in Pakes and McGuire (1994) and is modified to describe cooperative research.

Based on the computed research expenditure and firm values I compare firm profit and consumer surplus in three research regimes: RJV cartel, RJV competition, and competitive research. I assume that a consumer utility function does not change regardless of how firms conduct research. I also assume that the transition probability of the second state variable, i.e., the mean value of unobserved quality, is the same in all regimes. However, the transition probability of the maximum speed differs across the regimes as research expenditure is different.

My results show that research expenditure in the RJV regimes is about one fifth of what firms would spend in competitive research. Lower research expenditure is likely to result in higher net profits in RJVs as the cost saving outweighs the foregone benefit of being a solo innovator. The RJV regimes are also more likely to generate higher consumer surplus as the benefit of paying lower price for new products outweighs the benefit of having new products more frequently in competitive research.

My paper is the first to explicitly model investment decisions in the presence of RJV in a dynamic oligopoly framework. Almost all empirical studies on RJVs take the reduced-form regression approach. For example, Branstetter and Sakakibara (2002) test whether RJV outcomes are correlated with R&D spillovers with data on a large number of Japanese research consortia. They measure consortium outcomes with patenting registered by the participating firms during and after the consortium, and measure the level of potential R&D spillovers with the firm proximity index in technology space developed by Jaffe (1986). Then using the difference-in-difference approach, they show that consortium outcomes are positively associated with the level of potential R&D spillovers within the consortium.

Regarding research cooperation in the semiconductor industry, the most well known empirical study is Irwin and Klenow (1996*a*). They compare SEMATECH members' R&D spending with those of non-members, controlling other firm specific variables, and show that member companies are likely to spend less in R&D. This leads them to conclude that SEMATECH cuts duplication of R&D efforts.

In contrast to these studies, my study is based on a structural model that describes how firms make research decisions in different research regimes. Thus, I can compare firms' research behavior across research regimes without being concerned about endogeneity of membership decisions. Having a structural model, I can also compare welfare across the regimes and explain what drives welfare differences.

However, I do not attempt to estimate every parameter of the model. Instead, I fix parameters such as the research efficiency, the spillover rate, the marginal cost, etc at benchmark numbers, and assess the model sensitivity by varying these parameter values. The model can also become more enriched by including more state variables and market sectors.

Nevertheless, quantitative results are still meaningful as product market data are used to estimate firms' locations in the state space. Moreover, this allows me to link firms' research decisions to changes in the product market. For example, in the late 1990s the competition between Intel and AMD became more intense. Until the mid 1990s, AMD mainly served consumers at the low end of the market, but became Intel's stronger competitor thanks to the success of K6 processors.

I ask how their research cooperation would be affected by this change in the product market and answer it in section 6 by comparing firms' research expenditure for two different paths of the product market evolution. One path represents a market where one firm dominates the other in product quality, whereas the other path represents a market where two firms compete neck and neck. Results show that, when the product market becomes more competitive, the total research expenditure is likely to decrease in RJVs, while it is likely to increase in competitive research.

The rest of the paper is organized as follows. Section 2 describes a dynamic model of cooperative research. Section 3 provides a brief description on SEMATECH. Section 4 presents computational results, followed by welfare analysis in section 5. Section 6 examines how the market structure affects firms' research behaviors. Section 7 concludes.

2 Model

2.1 Setup and Timing

In each period two firms (say, Intel and AMD) decide how much to invest in order to develop a more advanced technology (a new generation of photolithography technology) for the next period. The more advanced technology improves product quality (a faster processing speed.) The outcome of the research investment is assumed to be stochastic. The more firms invest in research, the higher the probability of research success becomes, but success is not guaranteed. Firms share costs and outcomes of research by having a common probability of research success.

After making their research decisions but before research outcome is realized, firms make their own products (processors) with the current technology and compete *à la* Bertrand in the product market (the CPU market.) The technology they develop together is a generic manufacturing technology, so they can differentiate their products in multiple ways in the product development stage. For example, Intel and AMD inscribe different patterns of transistors on the silicon wafer, and the transistor pattern determines actual performance of the CPU.

At the end of each period research outcome is realized, and a technology for the next period is determined. If research is successful, the firms have a more advanced technology. If not, they use the current technology in the next period.

2.2 Probability of Research Success

I assume that the probability of research success $f(.)$ is a continuous function of research expenditure x with $f'(x) > 0$, $f^{"}(x) \leq 0$, $f(0) = 0$ and $\lim_{x\to\infty} f(x) = 1$. Although any probability functions that satisfy these properties can be used, I make the following parametric assumptions for analytical and computational convenience.

Assumption 1 *Given firm k's research expenditure, x_k, the probability of firm j's research success is*

$$f_j(x|a,\sigma) = \frac{a_j x_j + \sigma a_j a_k x_j x_k}{1 + a_j x_j + a_k x_k + \sigma a_j a_k x_j x_k}, \tag{1}$$

for $j = 1, 2$, $k = 1, 2$ and $j \neq k$. *x_j is firm j's research expenditure, which is constrained to take non-negative values, a_j is firm j's efficiency level, and σ denotes a degree of spillover with $\sigma \geq 1$.*

The efficiency level α_j represents a firm's ability to transfer dollar expenditures into the likelihood of research success. A more efficient firm attains a higher success probability with the same expenditure. The degree of spillover σ indicates how much one firm benefits from the other firm's research expenditure. With $\sigma > 1$, firm i's success probability increases as firm j increases its expenditure. As a result, the two firms' probabilities, *i.e.*, f_1 and f_2, are positively correlated. When there is no spillover, the probability function becomes

$$f_j\left(x|a, \sigma = 1\right) = \frac{a_j x_j}{1 + a_j x_j}, \ j = 1, 2, \tag{2}$$

and the two firms' probabilities are independent of each other.

Assumption 2 *When firms form a research joint venture (RJV), the success probability of cooperative research is*

$$f^J\left(x|a, \sigma\right) = \frac{a_1 x_1 + a_2 x_2 + \sigma a_1 a_2 x_1 x_2}{1 + a_1 x_1 + a_2 x_2 + \sigma a_1 a_2 x_1 x_2}. \tag{3}$$

In RJVs firms share the probability of research success, which is a function of participants' research expenditures. Sharing the success probability represents the role of SEMATECH as a sole provider of the generic technology. All member firms have access to a new photolithography technology and improve the processing speed at the same time.

Assumption 2 restricts the success probability of RJV such that the industry-wide probability of research success is the same whether firms compete or cooperate as long as the total research expenditure is the same. In other words, given research expenditures,

$$f^J\left(x_1, x_2\right) = f_1\left(x_1, x_2\right) + f_2\left(x_1, x_2\right) - f_b\left(x_1, x_2\right) \tag{4}$$

where f_b is the probability that both firms succeed at the same time in competitive research. However, note that x_i differs depending on whether firms form a RJV or not. This means that equation (4) may not hold in equilibrium and the industry wide probability of research success may be different across the regimes.

My definition of RJV is different from those in the previous literature in two significant ways. First, my definition does not depend on the spillover effect. The degree of spillover σ is the same in equations (1) and (3). This allows me to consider the effect of sharing research costs and outcomes apart from the spillover effect. Consider d'Aspremont and Jacquemin (1988) and Kamien, *et.al.* (1992). In both papers RJV increases research expenditure by internalizing spillovers. Separating the cost saving from the spillover is important as they have the opposite predictions on research expenditure.

Second, in my model the research intensity (research expenditure) determines the probability of research success and differs whether firms cooperate or not. Most literature on stochastic research adopts the fixed research intensity assumption (Marjit, 1991; Combs, 1992; Bloch and Markowitz, 1996; Miyagiwa, 2005.) Under this assumption, the probability of research success is exogenously given. For example, Combs (1992) assumes that each firm faces a menu of m research projects with the success probability equal to $1/m$. When two firms form an RJV, they can choose two projects without replacement so that the success probability of the RJV becomes $2/m$. This becomes equivalent to equation (4) when $f_b(x_1, x_2)$ is set to zero and x_i remains the same in all regimes.[6]

2.3 Value Function and State Variables

Given states in the current period, ω, the value function for firm j is defined as

$$V_j(\omega) = \sup_{x_j \geq 0} \left[\pi_j(\omega) - x_j + \beta \sum V_j(\omega') G(\omega' | \omega, \mathbf{x}) \right], \quad \text{for } j = 1, 2,$$

where π_j is a variable profit for firm j, β a discount rate, ω' a vector of the state variables in the next period, G is the probability distribution generating the transition probabilities of the states. I explain which variables are included in ω below.

With firms cooperating in research, the value function can be rewritten as

$$V_j(\omega) = \sup_{x_j \geq 0} \left[\pi_j(\omega) - x_j + \beta \left(f^J(\mathbf{x}|a, \sigma, \omega) EV_j^s + \left(1 - f^J(\mathbf{x}|a, \sigma, \omega)\right) EV_j^n \right) \right], \tag{5}$$

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[6] My model does not capture all aspects of cooperative research. For example, the model does not allow any synergy that may arise in cooperative research. Although the synergy effect can be described with higher research efficiency in RJVs, i.e., higher a_i in equation (3), I do not pursue to explore this. See section 7 for further discussions on limits of my model.

where EV_j^s is firm $j's$ expected value conditional on successful cooperative research and EV_j^n on unsuccessful cooperative research.

When firms unilaterally invest in competitive research, the value function becomes

$$V_j(\omega) = \sup_{x_j \geq 0} \left[\pi_j(\omega) - x_j + \beta \left(f_j(\mathbf{x}|a, \sigma, \omega) \widetilde{EV}_j^s + (1 - f_j(\mathbf{x}|a, \sigma, \omega)) \widetilde{EV}_j^n \right) \right],$$

where $f_j(x|a, \sigma, \omega)$ is a probability that firm j succeeds in research (equation (1)), $\widetilde{EV}_j^s$ is firm $j's$ expected value conditional on firm j's research being successful, and $\widetilde{EV}_j^n$ is firm $j's$ expected value conditional on firm $j's$ research being unsuccessful. One should note that firm j takes an expectation over firm $k's$ research outcomes in computing $\widetilde{EV}_j^s$ and $\widetilde{EV}_j^n$. Therefore, firm $k's$ research expenditure ($k \neq j$) also affects $\widetilde{EV}_j^s$ and $\widetilde{EV}_j^n$ in competitive research.

I use two state variables to describe an industry evolution. One is the maximum processing speed attainable with each generation of photolithography technology. It represents the path of technological advance accomplished by SEMATECH. A more advanced photolithography technology increases the processing speed by allowing more transistors to be inscribed. Section 3 provides more details on SEMATECH.

The other state variable is a detrended mean value of unobserved characteristics, and I use it to reflect firms' product market competitiveness that is not related to the process speed. This state variable captures differences in market share due to factors other than the processor speed. For example, actual performance of the same speed processors can be different depending on designs of transistor patterns. Or it can reflect share differences due to advertising or marketing campaigns. I treat all of them as the unobserved characteristics following the industrial organization literature (for example, Berry, Levinsohn, and Pakes, 1995.)

I assume that the second state variable evolves independently of the first, but the first evolves conditional on realizations of the second. It means that firms take actions affecting the unobserved characteristics independently of the maximum processing speed, but account for their realizations in the investment decision for the maximum speed. Consider the design of the transistor pattern as an example. Under this assumption firms improve the efficiency of the design regardless of the likelihood of improving the maximum speed, but take into account the likelihood of the design improvement in choosing research expenditure for improving the maximum speed. However, if marketing efforts for new products are significant part of the unobservables, this assumption is not innocuous as firms may change their marketing efforts expecting a new product arrival. Nevertheless, this assumption is necessary in computing the dynamic model and is standard in the literature (Ericson and Pakes, 1995; Pakes and McGuire, 1994.)

The transition probability of the first state variable is determined by firms' research expenditure through $f^J(.)$ in equation (3). The transition probability of the second is estimated nonparametrically by discretizing it and using its cell means.

I treat firms as if they were producing one product each. State variables representing non frontier products' processing speed and their unobservable characteristics should be included to model the multi-product feature. Although ignoring the multi-product feature is a limitation of the model, firms' investment decisions are unlikely to be affected by adding them since the value of research success is determined by quality of the most frontier product.

2.4 Investment Strategies

I consider two types of RJV. One type is RJV cartel (CJ) where firms share the single probability of research success and maximize the discounted sum of joint profits in deciding how much to invest.[7] The other type is RJV competition (NJ) where firms share the single probability of research success but maximize the discounted sum of individual profits in deciding how much to invest.

In RJV cartel firms solve

$$\max_{x_1,x_2}\left(V_1+V_2\right),$$

where V_j is defined in equation (5). Given that firms remain cooperative, research expenditures are determined by

$$\begin{aligned}
1 &= \beta a_1\left(1+\sigma a_2 x_2^{CJ}\right)\left(1-f^J\right)^2\left(\left(EV_1^s-EV_1^n\right)+\left(EV_2^s-EV_2^n\right)\right),\\
1 &= \beta a_2\left(1+\sigma a_1 x_1^{CJ}\right)\left(1-f^J\right)^2\left(\left(EV_1^s-EV_1^n\right)+\left(EV_2^s-EV_2^n\right)\right).
\end{aligned}$$

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[7] In RJV cartel perfect monitoring is assumed so that firms do not deviate from research collusion.

These conditions determine each firm's contribution to an RJV, and that is

$$x_2^{CJ} = x_1^{CJ} + \frac{1}{\sigma}\left(\frac{1}{a_1} - \frac{1}{a_2}\right). \tag{6}$$

It means that a firm whose research efficiency, a_i, is higher should invest more by $\frac{1}{\sigma}\left(\frac{1}{a_j} - \frac{1}{a_i}\right)$. Interestingly the contribution does not depend on firms' expected return of research outcomes. When member firms are equally efficient in their research, they spend equally even if their gains are different.

When there is no spillover ($\sigma = 1$), research expenditures can be analytically solved as

$$\begin{aligned} x_1^{CJ} &= \max\left\{\left(\frac{\beta\left(EV_1^s - EV_1^n + EV_2^s - EV_2^n\right)}{a_1 a_2}\right)^{\frac{1}{3}} - \frac{1}{a_1}, 0\right\} \\ x_2^{CJ} &= \max\left\{\left(\frac{\beta\left(EV_1^s - EV_1^n + EV_2^s - EV_2^n\right)}{a_1 a_2}\right)^{\frac{1}{3}} - \frac{1}{a_2}, 0\right\}. \end{aligned}$$

It shows that research expenditure is a function of the sum of the net expected returns.

In RJV competition research expenditure is determined by

$$\begin{aligned} 1 &= \beta a_1\left(1 + \sigma a_2 x_2^{NJ}\right)\left(1 - f^J\right)^2\left(EV_1^s - EV_1^n\right), \\ 1 &= \beta a_2\left(1 + \sigma a_1 x_1^{NJ}\right)\left(1 - f^J\right)^2\left(EV_2^s - EV_2^n\right), \end{aligned}$$

given that firms remain cooperative. The contribution rule in this regime is

$$x_2^{NJ} = \frac{1}{\sigma}\left(\frac{1}{a_1}\frac{\left(EV_2^s - EV_2^n\right)}{\left(EV_1^s - EV_1^n\right)} - \frac{1}{a_2}\right) + \frac{\left(EV_2^s - EV_2^n\right)}{\left(EV_1^s - EV_1^n\right)} x_1^{NJ}. \tag{7}$$

It shows that the contribution depends on firms' relative gains from research success, *i.e.*, $\frac{\left(EV_2^s - EV_2^n\right)}{\left(EV_1^s - EV_1^n\right)}$, such that a firm whose expected gain is higher contributes more to an RJV even when the efficiency level is the same.

As in RJV cartel, research expenditure can be analytically expressed when there is no spillover, and they are

$$
\begin{aligned}
x_1^{NJ} &= \begin{cases} \max\left\{ \left(\frac{\beta (EV_1^s - EV_1^n)^2}{a_1 a_2 \left(EV_2^s - EV_2^n\right)} \right)^{\frac{1}{3}} - \frac{1}{a_1}, 0 \right\}, & if \;\; (EV_1^s - EV_1^n) > 0, \\ 0, & \text{otherwise} \end{cases} \\
x_2^{NJ} &= \begin{cases} \max\left\{ \left(\frac{\beta (EV_2^s - EV_2^n)^2}{a_1 a_2 \left(EV_1^s - EV_1^n\right)} \right)^{\frac{1}{3}} - \frac{1}{a_2}, 0 \right\}, & if \;\; (EV_2^s - EV_2^n) > 0, \\ 0, & \text{otherwise.} \end{cases}
\end{aligned}
$$

It shows that, in contrast to RJV cartel, a firm's research expenditure is adversely affected by the other firm's expected gain.

When firms unilaterally invest without forming an RJV (N), firm $j's$ research expenditure, given firm $k's$ research expenditure, satisfies

$$1 = \beta a_j \left(1 + \sigma a_k x_k^N\right) \left(1 - f_j\left(.\right)\right)^2 \left(\widetilde{EV}_j^s - \widetilde{EV}_j^n\right),$$

where f_j is defined in equation (1). When there is no spillover, firm $j's$ research expenditure is simplified to

$$x_j^N = \max\left\{ \left(\frac{\beta\left(\widetilde{EV}_j^s - \widetilde{EV}_j^n\right)}{a_j} \right)^{\frac{1}{2}} - \frac{1}{a_j}, 0 \right\},$$

which is identical to the investment policy function in Pakes and McGuire (1994).

2.5 Product Market Competition

Consumer utility is defined as

$$
\begin{aligned}
u_{ij} &= \delta_j - \alpha p_j + \epsilon_{ij}, \quad \text{for } j = 1, 2, ..., J \\
u_{i0} &= 0
\end{aligned}
$$

where δ_j indexes product $j's$ quality, f_j its price with the coefficient α, and ϵ_{ij} is an idiosyncratic logit error term. In this demand model, a firm's profit always increases as it improves product quality with other things being constant. This condition is necessary to obtain Markov Perfect Equilibrium in the dynamic model. See Ericson and Pakes (1995) for details.

Firms compete *á la* Bertrand in the product market. So given the product quality of all products in the market $\boldsymbol{\delta}$ and the unit cost of production c_j, a firm sets a price p_j to maximize

$$\pi_j = (p_j - c_j)\, s_j M$$

where s_j denotes product $j's$ market share and equals $\exp(\delta_j) \,/\, \left(1 + \sum_{j=1}^{J} \exp(\delta_j)\right)$ and M denotes the market size.

I assume that product quality linearly depends on product characteristics. Thus,

$$\delta_j = \mathbf{x}_j \beta + \xi_j \tag{8}$$

where $\mathbf{x}_j$ includes product characteristics such as the processing speed, the capacity of the level two cache (L2 cache), and the time dummy variables. ξ_j represents the unobserved characteristics.

When firms succeed in developing a new technology, they are able to improve product characteristics. In the case of the CPU, when SEMATECH succeeds in advancing the photolithography technology, Intel and AMD increase the processing speed. The coefficient on the processing speed quantifies the consumer appreciation for a faster CPU and determines how much a firm's profit increases from successful research.

While firms cooperate in developing the generic technology, they also compete to develop better products. The whole process of product development may consist of many stages and involve technologies that are unilaterally developed by each firm. Instead of modeling this process, I use the unobserved characteristics to estimate product quality determined by unilateral product development. Overall product quality is first estimated by matching the model predicted market shares to actual market shares, and then the unobserved characteristics are recovered from the difference between overall product quality δ_j and quality explained by the observed characteristics $\mathbf{x}_j\widehat{\beta}$.

Lastly, I assume that firms are not allowed to appropriate other firms' research outcome when they do not cooperate. Under this assumption a firm can increase the maximum processing speed only from its own research success in the competitive research regime.[8] However, this assumption is not applied to RJVs where the maximum processing speed is always the same for both firms and their product market competitiveness is solely determined by the unobserved characteristics.

3 SEMATECH

In August 1987 SEMATECH was incorporated with thirteen U.S. charter members. U.S. producers had dominated the world semiconductor market in the 1970s, but were facing an increasing challenge from the Japanese counterparts in the late 1970s. By the mid-1980s, their market share dropped significantly, and the creation of a research joint venture was proposed by both the industry and the Department of Defence.

SEMATECH started with an initial budget of $250 million. Federal Government and member firms contributed $100 million each toward its $250 million 1988 budget. The remaining funds were provided by state and local funds from Austin, Texas, where SEMATECH was (and still is) located. The government reduced its funding gradually over time, and stopped it entirely in 1998 as the SEMATECH board determined federal funding was no longer needed. As of 2005 its $170 million annual budget was mainly funded by member dues. Other sources include matching funding from the states of Texas and New York for selected programs and royalties. Data on individual members' contributions to SEMATECH are not publicly available. However, it is known that, before the federal government stopped its funding, members were required to contribute 1% of their semiconductor sales revenue, with a minimum of $1 million and a maximum of $15 million (Irwin and Klenow, 1996*b*.)

This contribution rule suggests that SEMATECH has features of both RJV cartel and RJV competition. The contribution based on sales revenue is similar to the contribution rule in RJV competition, but putting the upper bound is similar to the contribution rule in RJV cartel. The bounds ensure that the contribution is not significantly different among members.

SEMATECH's members have changed over time. Initial thirteen members were all U.S. producers, and they are Advanced Micro Devices (AMD), AT&T, Digital Equipment Corp., Harris Corp., Hewlett Packard Co., IBM Corp., Intel Corp., LSI Logic Corp., Micron Technology Inc., Motorola Inc., National

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[8] An alternative assumption would be that a firm can adopt other firms' research outcomes by paying a licensing fee.

Semiconductor Corp., Rockwell International Corp., and Texas Instruments Inc. Some members like LSI Logit and Micron Technology left SEMATECH when they found they would not benefit from a joint investment. In 2000 SEMATECH abandoned its original intent to keep the consortium limited to U.S. companies and became International SEMATECH. As of 2005 the U.S. members are AMD, Freescale Semiconductor, Hewlett Packard, IBM, Intel, Spansion, and Texas Instruments, and the non-U.S. members are Infineon Technologies (Germany), NEC (Japan), Panasonic (Japan), Philips (Netherlands), Renesas Technology (Japan), Samsung (South Korea), and TSMC (Taiwan).

Out of fourteen members only Intel, AMD, and IBM produce the CPU for the personal computer. During the sample period (from 1993 to 2000) IBM exclusively supplied the CPU to Apple Computer and its market share was about 2%.[9] Because of data availability and its non-compatibility with other brand PCs I exclude it from the analysis. The other members mainly produce the memory chip and the microcontroller.[10]

SEMATECH's goal has changed over time as well. When it was first incorporated, SEMATECH decided to pursue the development of an end-to-end manufacturing process and built a large-scale fabrication facility in Austin for this purpose. However, it had difficulty developing a research agenda that would satisfy all members as they had different technological advantages and were reluctant to share them.

In 1991, SEMATECH switched its goal to developing and qualifying equipment for new photolithography technology.[11] The wavelength of ultraviolet light used in this technology determines the maximum number of transistors inscribed on the silicon wafer. With more transistors the semiconductor can store more information and/or execute more complicated instructions. This technology is generic rather than product-specific or firm-specific. Table 1 shows generations of the CPU associated with the advancement of photolithography technology.

4 Computational Results

My analysis consists of two stages. In the first stage, demand side parameters are estimated using the product level data, and the transition probabilities of the unobserved characteristics are estimated nonparametrically.

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[9] In June, 2005, Apple Computer announced that it would switch its computers to Intel's microprocessors as early as 2006.

[10] The microcontroller is used to control electronic devices like washing machines, microwave ovens, telephones etc.

[11] For the evolution of SEMATECH objectives, see Grindley, Mowery, and Silverman (1994).

In the second stage, research expenditure and firms' value are computed as a solution to the dynamic model. The computation algorithm is based on the algorithm in Pakes and McGuire (1995) with modifications. The main difference is that firms share a transition probability of research success in RJVs, and this probability is a function of both firms' research expenditures. I do not consider entry decisions. There was no new entrant in the CPU market during the sample period, which suggests that the entry cost is too high for any potential entrants.

4.1 Demand Estimates

The data set consists of quarterly data on price, units sold, and product characteristics of Intel and AMD products. Data on price and quantity were acquired from MicroDesign Resources (MDR), an independent research group that collects data on the CPU market. The sample period starts at the second quarter of 1993 and ends in the third quarter of 2000. Intel and AMD are two major producers during the sample period with the combined market share over 90%. I treat 386 and 486 class processors as the outside option because price data on these products are not available.

I consider the world CPU market in each quarter as different markets. So there are 30 markets with 320 observations in total. The total number of CPUs sold each quarter is used as the primary proxy for the size of the CPU market, and the market share of a product is defined as the number of units sold divided by the total number of CPU sold. The outside option is to buy CPUs produced by firms other than Intel and AMD like IBM CPUs used in Apple computers. The summary statistics is provided in table 2 and more details on the data can be found in Song (2007).

I estimate consumer demand using the logit demand model. Estimates are reported in table 3. I use $\log(Speed)$, $\log(Speed)$ squared, the dummy variable for having different capacities of the level-2 cache (No_Cache) as observable characteristics. By using the log of the processing speed, I restrict product quality to be a monotonically increasing function of the processing speed. I also include the time dummy variables. They capture two types of time-varying effects. One is quarterly changes in the mean value of the unobserved characteristics. The other is quarterly changes in the value of the outside option. However, only the sum of the two effects is identified unless more assumptions are made. I do not attempt to separate these two effects here as it is irrelevant to my analysis.[12]

To account for a possible correlation between the unobserved characteristics and price, I use the log of the processing speed interacted with the time dummy variables as instruments. They are used as proxies for the production cost. In this industry the processing speed increases over time, but the production cost does not change much. By interacting the processing speed with the time dummy variables I reflect the stability of the production cost over time. Note that the processing speed is an endogenous variable in the dynamic model, but firms' research decisions are conditional on the current period's unobserved characteristics and research outcomes are realized in the next period. The third and fourth columns of table 3 show that the price coefficient goes down as expected, and all other coefficients hardly change. Standard errors of all the coefficients go up with the instruments, but the coefficient on the log of the processing speed is still statistically significant.

Coefficients on product characteristics measure consumers' willingness to pay for improvement of the corresponding characteristics, and the coefficient on the processing speed in particular determines firms' profitability from research success. In the third column the consumer is willing to pay \$400 $\sim$ \$450 for a 100MHz increase in the processing speed when she has a 300 MHz processor, and \$200 $\sim$ \$230 when she has a 600 MHz processor. With the log of the processing speed squared added (the fourth column), the consumer is willing to pay \$410 $\sim$ \$480 when she has a 300 MHz processor, and \$220 $\sim$ \$270 when she has a 600 MHz processor.

I use the estimates in the third column (IV logit 1) in the dynamic model. Although the IV logit model does not identify parameters as well as the logit model, the estimate on the price coefficient is more reasonable. However, key results are not sensitive to which estimates are used. The estimates on the unobserved characteristics are also very similar across the specifications. Comparing the logit with the IV logit model, the mean difference is 0.033 with the standard deviation 0.021 for Intel and -0.003 with the standard deviation 0.014 for AMD.

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[12] The two time effects are separated in the pure characteristics demand model in Song (2007).

4.2 State Variables and Transition Probabilities

I choose five levels of the processing speed to reflect the advancement of the photolithography technology, and they are 66, 200, 333, 800, and 1000 MHz. They match the maximum processing speed in 1993, 1995, 1997, 1999, and 2000 respectively. Then I add 1500, 2100, and 2800 MHz to ensure that firms still have an incentive to invest when the maximum speed approaches 1,000 MHz.

The transition probability of the maximum speed is represented by the probability of research success. That is, for firm j,

$$q_j \left(Speed_{t+1} | Speed_t, \omega_t \right) = f^J \left(\mathbf{x}_t | a, \sigma, \omega_t \right)$$

in RJVs (see equation (3)) and

$$q_j \left(Speed_{t+1} | Speed_t, \omega_t \right) = f_j \left(\mathbf{x}_t | a, \sigma, \omega_t \right)$$

in competitive research (see equation (1)). The transition probabilities are determined by firms' research expenditures in Markov Perfect Equilibrium.

A detrended value of the unobserved characteristics captures product quality not related to the processing speed and is estimated by

$$\widehat{\xi} = \delta - \mathbf{x}\widehat{\beta}$$

where $\mathbf{x}$ contains the observed characteristics including the time dummy variables, and $\widehat{\beta}$ is the estimated coefficient. For Intel I select the three most expensive products of each period and take the average value of their unobserved characteristics to compute $\widehat{\xi}$. For AMD I select the most expensive product group as its data are more aggregated, and use its value of the unobserved characteristics. In table 4 the estimated values are discretized at five points for each firm and the first order stochastic process $\eta \left(\xi_{t+1} | \xi_t \right)$ is nonparametrically estimated using cell means.

Figure **??** shows trends of the unobserved quality of Intel and AMD frontier products that were constructed in the way explained above. The figure shows an important change in the CPU market in the late 1990's. Before the late 1990's the unobserved quality of Intel's frontier product increases steadily and is better than that of AMD's frontier product. However, in the late 1990s the unobserved quality of AMD's frontier product, which was very volatile previously, becomes steady and improves rapidly, while Intel's frontier product shows no sign of improvement. I explore the effect of this change on research expenditure in section 6.

The remaining model parameters are the investment efficiency a_j, the degree of spillover σ, the discount rate β, and the unit cost c_j. The investment efficiency and the degree of spillover are set to 1 and the discount rate is set to 0.98. The unit cost is set to the overall quality δ_j divided by 10. The sensitivity of research expenditure to different values is reported in the next section.

4.3 Research Expenditure

I first compute firms' static profits for every combination of the state variables. Research expenditure is computed as a solution of the dynamic model for each combination of the state variables, given static profits, transition probabilities of the unobserved characteristics, and other parameters of the model. I let the market size increase at a constant rate (10%) whenever the maximum speed improves to the next level. This is equivalent to adding new consumers in the market whenever there is a technological innovation. This partially offsets the diminishing return to research expenditure.

Table 5 shows research expenditure in each regime for various levels of the maximum processing speed. It is averaged across 25 pairs of the unobserved characteristics for each maximum speed. As equations (6) and (7) show, firms invest equally in RJV cartel as long as their research efficiencies are the same. In RJV competition research expenditure depends on how much firms gain from research success. For example, when the maximum processing speed is 333 MHz, Intel spends 29.96 million dollars and AMD spends 15.36 million dollars in RJV competition, while they equally spend 27.81 million dollars in RJV cartel. So Intel bears about 66% of research expenditure in RJV competition. The probability of research success is slightly higher in RJV cartel due to higher research expenditure but the difference is negligible.

A higher maximum speed reduces research expenditure due to the diminishing return. This is because the profit is a concave function of the maximum speed. An increase in the market size offsets the diminishing return, but a 10% increase does so only partially. As the maximum processing speed increases, research expenditure goes down by about 7% on average in both RJV regimes.

The table also shows that firms would invest much more aggressively in competitive research. Compared to RJV competition, Intel spends about four times more and AMD over five times more. Thus, firms significantly save research expenditure by forming an RJV. However, they have to give up an opportunity of becoming a solo innovator in RJVs as they fully share research outcomes.

Higher research expenditure in competitive research renders the research success probability higher at the industry level than in RJVs. Thus, a new technology is more frequently introduced in competitive research, and this benefits consumers. However, consumers are likely to pay higher price for new products because of an event that only one firm succeeds in research. On the other hand, new product price is likely to be lower in RJVs, but a new technology is introduced less frequently than in competitive research.

In the next section I simulate the industry with the three different regimes over 30 periods and repeat it for 1,000 iterations to compare firms' profits and consumer surplus across the regimes. Because of these trade-offs for both firms and consumers not only do I compare magnitudes of welfare but also the frequency that one regime generates higher welfare than another.

There are three parameters that affect research expenditure and they are the degree of spillover (σ), the research efficiency (a), and the discount rate (β). Both the degree of spillover and the research efficiency are neither observed by the econometrician nor identified by the data. A usual practice in this case is to vary their values and see how sensitively results change.[13]

The degree of spillover indicates how strongly the two firms' research outcomes are correlated when they unilaterally invest in research (see equations (1) and (2).) With research expenditure fixed, the probability of research success in RJVs increases with the degree of spillover. So given the benefit of research success firms reduces research expenditure with a higher degree of spillover. For example, when the degree of spillover increases from 1 to 1.5 at the maximum processing speed of 333 MHz, the average research expenditure decreases by 11.93% in RJV cartel and by 12% for Intel and 11.34% for AMD in RJV competition. The rate of reduction goes down as the degree of spillover increases. When the degree of spillover increases from 1.5 to 2, the average expenditure decreases by 8.73% in RJV cartel and by 8.77% for Intel and 8.39%

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[13] For example, in Besanko and Doraszelski (2004), they set a such that $f(\overline{x}|a) = \overline{\theta}$ where $\overline{x} = 20$ and $\overline{\theta} = 0.5$.

for AMD in RJV competition. And when it increases from 2 to 2.5, the average expenditure decreases by 6.89% in RJV cartel and by 6.91% for Intel and 6.67% for AMD in RJV competition.

The level of the research efficiency indicates a firm's ability to transform a dollar of research expenditure into the likelihood of research success. A higher research efficiency means that a firm can achieve the same probability of research success with less research expenditures. Moreover, since firms share the success probability, an increase in any firm's research efficiency reduces both firms' research expenditures. For example, when the research efficiency goes up from 1 to 1.5 for Intel at the maximum processing speed of 333 MHz, the average research expenditure decreases by 11.91% for Intel and 13.11% for AMD in RJV cartel and by 11.96% for Intel and 13.48% for AMD in RJV competition. When the research efficiency goes up from 1 to 1.5 for AMD at the same maximum processing speed, the average research expenditure decreases by 13.11% for Intel and 11.91% for AMD in RJV cartel and by 13.08% for Intel and 11.31% for AMD in RJV competition.

The discount rate is usually used to indicate an interest rate or a length of one period. A lower discount rate means a higher interest rate or a longer time period, so results in a lower present value of a future payoff from research success. This in turn leads firms to reduce research expenditures. When the discount rate goes down from 0.98 to 0.96 at the maximum processing speed of 333 MHz, for example, research expenditure decreases by 2.06% on average in RJV cartel and by 2.08% for Intel and 2.07% for AMD (also on average) in RJV competition. The rate of reduction in research expenditure barely changes as the discount rate goes down further. When it goes down from 0.96 to 0.94 at the same maximum processing speed, the average research expenditure decreases by 2.07% in RJV cartel and by 2.10% for Intel and 2.09% for AMD in RJV competition.

The research expenditure is also affected by an industry-wide negative demand shock, which makes quality of all products go down at the same time. When there is a negative shock, firms tend to invest more in cooperative research. For example, when the probability of having a negative shock goes up from 0.1 to 0.3 at the maximum processing speed of 333 MHz, the average research expenditure increases by 9.87% in RJV cartel and by 10.84% for Intel and 8.97% for AMD in RJV competition. Research expenditure increases more rapidly as the probability becomes higher. At the same maximum processing speed the average research expenditure increases by 17.19% in RJV cartel when the probability goes up from 0.5 to 0.7, while it increases by 29.7% when the probability goes up from 0.7 to 0.9.

The increasing research expenditure means that the expected gain from research success increases. The expected gain is a function of the difference between firm values at two adjacent maximum speed levels. As the probability of having a shock goes up, the firm value tends to decrease at all maximum speed levels, but it decreases more at lower levels. As a result, the expected gain increases, and so does the expenditure.

As I explain in section 7 my dynamic model is a limited description of SEMATECH, so I do not expect the computed research expenditure to be a close estimate of what it actually spends for the photolithography technology. Nevertheless, I compare the computed expenditure to the total contribution of all member firms to SEMATECH. Unfortunately, data on individual member firms' contribution to SEMATECH are not publicly available. The annual budget of SEMATECH is $170 millions and member firms are responsible for $100 millions. The number of members has been around $10 \sim 12$, which means that each member pays around $8 \sim 10$ million dollars if they pay equally. The computed research expenditures are comparable but higher than the actual average contribution. Considering the fact that I only account for the expected return in one sector of the industry, it is much higher than the actual. However, one should note that each maximum speed level I choose represents technologies introduced about every two year. Thus, it is more reasonable to interpret the computed research expenditure as the expenditure needed to introduce the next generation technology rather than the contribution to a yearly budget.

5 Welfare Analysis

Given the computed research expenditure, I simulate the CPU market over 30 periods for the three different research regimes, and compare firms' variable and net profits and consumer surplus. The starting point is a state where both firms produce a 200 MHz CPU and values of the unobserved characteristics are -0.8131 and -2.2353 respectively.

I iterate the simulation for 1,000 times to account for four types of random outcomes. The first type is whether firms succeed in research or not, and these probabilities are determined by how much firms invest in research. The second type is whether there is an industry-wide negative demand shock, and I set this probability at 0.7. The third and fourth types are how the two firms' unobserved characteristics evolve over time, and their probabilities are estimated nonparametrically and reported in table 4. For the model parameters I use the default values. I cover almost all patterns of the industry evolution by simulating the industry for 30 periods and repeating it 1,000 times. The probability that the maximum processing speed reaches 2.8 GHz is about 0.5 after 20 periods for all research regimes, and is higher than 0.90 at the 30^{th} period.

In table 6 I compare a pair of regimes in variable and net profits and consumer surplus. Two regimes in comparison share the same realizations of the random outcomes other than research success in each iteration, and the frequency that one regime generates higher, equal, and lower values of variables at the end of the 30^{th} period is reported. So the difference is solely driven by different paths of the technological evolution across the regimes.

The first two columns compare RJV competition (NJ) with competitive research (N). The comparison shows that both regimes generate the same variable profit for both firms in 650 out of 1,000 iterations. This means that the probability that both regimes follow the same path of technological evolution is 65 percent. This happens when no single firm solely succeeds in research in competitive research for 30 periods. And when this happens, consumer surplus is also the same in the two regimes because both the frequency of new product introduction and new product prices are the same in both regimes.

However, firms incur much higher research expenditures in competitive research. As shown in the previous section, research expenditure is $3 \sim 5$ times higher in competitive research than in the RJV regimes. This is reflected in firms' net profits. Both Intel and AMD make higher net profits in RJV competition in 831 iterations. They can still make higher net profits in competitive research due to the event of solo innovation. However, the probability that this happens is 16.9 percent for Intel and 12.1 percent for AMD.

When the two regimes do not follow the same path of technological evolution, consumers are most likely to be better off in RJV competition. Competitive research is more likely to introduce new products than RJV competition. However, when only one firm succeeds in competitive research, this firm charges a higher price for a new product than when both firms succeed at the same time. While consumers benefit from more frequent introductions of higher quality products, they pay higher prices for the same quality products than in RJVs. The net effect is that the benefit of paying lower price for new products in RJV competition outweighs the benefit of having new products more frequently in competitive research. The latter benefit can still be larger than the former but the probability that this happens is only 3 percent.

The comparison between RJV cartel (CJ) and competitive research (N) (in the next two columns of the table) is qualitatively the same. The probability that firms earn higher net profits in RJV cartel is slightly higher but not much different, and the probability that consumers are better off in RJV cartel is also slightly higher but not much different.

The last two columns of the table compares RJV cartel and RJV competition. These two regimes almost always generate the same variable profits and consumer surplus. This result is expected since firms always share research outcomes in both regimes and the research success probability is not much different. A slightly higher success probability in RJV cartel occasionally makes consumer surplus and variable profit higher and this happens at a 1.2 percent chance.

However, Intel's net profit is always higher in RJV cartel, while AMD's is almost always higher in RJV competition. This is because Intel tends to spend less in RJV cartel, while AMD tends to spend less in RJV competition, for the same innovation outcome. This suggests that Intel, a dominant firm, prefers RJV cartel, while AMD prefers RJV competition. It also raises a question of what type of RJV two firms would agree to have. An answer may depend on who has a more bargaining power and how they negotiate. In any case firms are unlikely to compete in research as both types of RJV dominate competitive research.[14]

Next I compare magnitudes of welfare differences. Table 7 shows the average discounted values of net profits and consumer surplus over 30 periods for 1,000 iterations in the three regimes. The standard deviation reported in the brackets indicates that each iteration can results in significantly different market evolutions. For example, Intel makes on average 37.36 billion dollar net profits over 30 periods in RJV competition, but makes less than 28 billion dollars for 100 iterations and makes more than 45 billion dollars for 100 iterations.

One should combine the numbers in the table with the results in table 6 to make a meaningful

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[14] It is interesting that SEMATECH has features of both types of RJV as discussed in section 3. The member contribution is based on sales revenue but has the lower and upper bounds. AMD is likely to benefit from the former feature, and Intel is likely to benefit from the latter.

comparison across the regimes. For example, Intel's discounted sum of net profit in RJV cartel is 37.42 billion dollars, 60 million dollars higher than in RJV competition. Considering its variation over time, this difference may look negligible. However, table 6 shows that Intel always makes higher net profit in RJV cartel. So this difference is significant and can be interpreted as the average gain to Intel when the firms switch their RJV objective from maximizing their own profits to maximize joint profit.

In comparing RJV competition with competitive research (similarly RJV cartel with competitive research) table 7 shows that Intel makes higher net profit in RJV competition and the average difference is about 150 million dollars. However, table 6 shows that Intel makes higher net profit in RJV competition in 842 iterations and makes lower net profit in the remaining 158 iterations. A further comparison shows that in those 842 iterations the difference is about 500 million dollars (1.3 percent higher net profit) and in the remaining 158 iterations Intel's net profit is lower by 1.7 billion dollars (4.6 percent lower net profit). This implies that the profit as a solo innovator is quite substantial, but firms still prefer RJVs because they do not expect it to happen frequently.

6 Product Market Competition and Research Expenditure

In this section I ask how research expenditure is affected by changes in the product market conditions. In particular, I look at how cooperative research expenditure changes as the product market becomes more competitive.

The unobserved characteristics ξ reflect firms' product market competitiveness in RJVs. When firms' unobserved characteristics become more similar, their product quality becomes less different as shown in equation (8) . So firms set prices more competitively in Bertrand-Nash equilibrium. Figure **??** shows that in the late 1990s the unobserved characteristics of AMD products steadily improved, while those of Intel products did not. As a result, a quality gap between the two rival firms became narrower and the product market became more competitive. This change is reflected in their market shares. From the third quarter of 1997 to the fourth quarter of 1998, Intel lost about 14% of market share as AMD's frontier products, K6 and K6-2 processors, were successful at the high end of the market.

In order to examine the effect of this change on RJV, I divide the sample period into two eras. The first era is from the beginning of the sample period to the second quarter of 1997, and it is an era of Intel dominance in the CPU market. The second era is from the third quarter of 1997 to the end of the sample period, and it is an era of neck and neck competition between the two rivals. Then I separately estimate the transition probability of the unobserved characteristics $\eta\left(\xi_{t+1}|\xi_t\right)$ for each era, and examine how changes in $\eta\left(\xi_{t+1}|\xi_t\right)$ affect cooperative research expenditure. Table 8 shows the estimated $\eta\left(\xi_{t+1}|\xi_t\right)$ for each era.[15]

Table 9 shows the average discounted sum of research expenditure over 30 periods with different $\eta\left(\xi_{t+1}|\xi_t\right)$. The average research expenditure decreases in both RJV regimes when the product market becomes more competitive. In RJV cartel, both firms' average research expenditures decrease by 46.11%. In RJV competition Intel's average expenditure decreases by 52.67%, and AMD's decreases by 32.05%. This implies that a more competitive product market makes RJV cartel's total expected profit lower. It is also true in RJV competition, but AMD now bears a larger portion of research expenditure. It went up from 24.3% to 31.55%. This means that in RJV competition Intel is hurt relatively more than AMD when the product market becomes more competitive. However, in competitive research AMD invests more aggressively. Its average research expenditure increases by 16.72%, while Intel's decreases by 11.76%. AMD now has a chance of catching up with Intel, and a more competitive product market makes it more plausible.

The probability of research success goes down in RJVs as a result of reduced research expenditure. In RJV cartel the probability of research success is always lower when the product market becomes more competitive. In RJV competition the probability is lower for 998 times out of 1,000 iterations. This suggests that a more competitive product market is likely to slow down a pace of innovation in RJVs. However, in competitive research the industry-wide probability of research success, *i.e.*, the probability that at least one firm succeeds in research, is higher for 992 times when the market becomes more competitive.

These results shed light on causes of an accelerated technological change in the semiconductor industry, identified by a shift from a three-year to a two-year product cycle beginning in 1995.[16] Jorgenson (2001) associates it with an increased productivity growth in the U.S. economy, but points out that there is not a fully satisfactory economic model that explains this change.[17] My results do not support a hypothesis

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[15] I also divided the period at the first and the third quarter of 1997, but results rarely changed.

[16] See the International Technology Roadmap for Semiconductors (2001 Edition and 2002 Updates).

[17] Azicorbe and Kortum (forthcoming) use a vintage model to explain the link between technological improvements and price declines of individual products. However, technological improvement is given exogenously in their model.

that more intense competition in the product market caused SEMATECH to accelerate the technological change. Instead, they predict that the technological change will slow down if SEMATECH members foresee a more competitive product market.

Then why did SEMATECH switch from a three-year cycle to a two-year cycle? My results support two explanations. One is an expectation of the market growth and the other is an expectation of a negative demand shock. As shown in section 4 research expenditure increases in RJV when the market size grows or when the probability of having a negative shock goes up. A larger market size means the total number of potential consumers increases. The negative demand shock means that more consumers are switching to an option of no purchase although they remain as potential consumers. Research expenditure increases in both events and they are not necessarily mutually exclusive. Nevertheless, considering the fact that the information technology boom started in the early 1990s, the first explanation is more convincing.

7 Conclusions and Discussions

In this paper I first construct a dynamic model of RJVs in which firms competing in the product market cooperate to improve product quality. Research success is a stochastic event and the probability of research success is a function of firms' research expenditures. I model cooperative research by making firms share a probability function of research success.

Using this dynamic model and the demand estimates from the CPU sector I analyze research cooperation led by SEMATECH in the semiconductor industry. The results show that research expenditure in RJVs is one fifth of what they would spend in competitive research. Lower research expenditure results in higher net profits in RJVs. Consumer surplus is also likely to be higher. This is because, while consumers benefit from more frequent introductions of higher quality products in competitive research, they occasionally pay higher prices for the same quality products than they do in RJVs. The net effect is that consumers are hurt more by higher price in competitive research than by less frequent introductions of new products in RJVs.

I also show that firms make different research decisions for the same change in the product market, depending on whether they cooperate or compete in research. When the product market becomes more competitive like in the late 1990s in the CPU market, the overall research expenditure decreases in RJVs, while it slightly increases in competitive research. The difference comes from a laggard firm who reduces its research expenditure in RJVs but increases it in competitive research. This result suggests that a more competitive product market is likely to slow a pace of innovation in RJVs.

One should note that I only analyze one aspect of research cooperation in this paper. There are at least two other important aspects that are excluded from my analysis. One is research cooperation for the process innovation and the other is the interaction among multiple RJVs in the same industry. Both aspects are present in the semiconductor industry. SEMATECH plays a leading role in the process innovation by setting up a standard wafer size and moving up to a larger size. The wafer is a basic unit of production, on which identical semiconductors are made. As identical chips are produced from a given size of the wafer, a larger size means lower unit cost. From the mid 1990s, it has led an international conversion from eight-inch diameter to twelve-inch diameter wafers.

As my model is based on the dynamic oligopoly model in Pakes and McGuire (1994) , the model can be easily modified to incorporate the process innovation. Adding the process innovation may make the model more realistic, but it complicates the analysis without changing the main results. Both types of innovation benefit firms by increasing their expected profits, but the product innovation is a “drastic" innovation that has a larger impact.

The interaction among multiple RJVs is a more interesting aspect of RJVs I miss here but is beyond the scope of this paper. It is still important in the semiconductor industry as SEMATECH was formed as a counterpart to other RJVs in Japan and Europe and started to seek areas of possible cooperation with them as early as 1989. The memory chip sector is an interesting industry to study for this aspect as the U.S. firms belong to SEMATECH and the Japanese belong to SELETE, a Japanese RJV.

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Table 1: Chronicles of microprocessor and photolithography technology

Year	Type	# of transistors (in thousands)	Technology† (micron)	Photolithography system
1971	4004	2.3	10	contact aligners
1972	8008	3.5	10	
1974	8080	6	6	proximity aligners
1979	8088	29	3	projection aligners
1982	286	134	1.5	first G-line steppers
1985	386DX	275	1	advanced G-line steppers
1989	486DX	1200	1	
1993	Pentium	3100	0.8	first I-line steppers
1995	Pentium Pro	5500	0.35	advanced I-line steppers
1997	Pentium II	7500	0.25	
1999	Pentium III	28000	0.18	first deep-UV steppers
2000	Pentium IV	42000	0.18	

Source: http://www.intel.com/intel/intelis/museum/exhibit/hist_micro/hof/tspecs.htm

†The number indicates the wavelength of ultraviolet light used in the photolithography technology. A smaller wavelength allows more transistors to be inscribed on the processor.

Table 2: Summary Statistics: CPUs from 1993Q2 to 2000Q3

	Speed (in MHz)			Price (in dollar)			Share[‡]		
Year	Min	Mean	Max	Min	Mean[†]	Max	Min	Mean	Max
1993	60	63	66	818	888	965	0.0036	0.0063	0.0095
1994	60	79.7	100	418	764.2	995	0.0013	0.0253	0.0557
1995	60	102	200	158	490.6	1324	0.0016	0.0529	0.1604
1996	75	143.2	200	106	334.5	1018	0.0011	0.0709	0.1701
1997	90	189.6	333	85	325.1	1981	0.0004	0.0639	0.2022
1998	166	290.4	450	86	335.2	773	0.0048	0.0861	0.1832
1999	300	467.1	800	64	275.6	851	0.0037	0.0725	0.1456
2000	433	615.6	1000	69	285.5	990	0.0005	0.0495	0.1002

[†] The mean price is the average price weighted by quantity.

[‡] Share is defined as quantity sold divided by the total number of products sold in the market.

Table 3: Estimates of consumer demand in the CPU market.

Characteristics	Logit 1	Logit 2	IV Logit 1	IV Logit 2
Constant	-1.83**(0.75)	-2.13**(0.81)	-1.74 (1.36)	-2.08 (1.50)
log(Speed)	1.49**(0.43)	1.31**(0.46)	1.46*(0.87)	1.45*(0.87)
$(\log(\text{Speed}))^2$		0.18 (0.18)		0.11 (0.20)
No_Cache$^{\diamond}$	-0.20 (0.21)	-0.17 (0.21)	-0.23 (0.24)	-0.22 (0.24)
Price				
α	-1.09**(0.46)	-1.19**(0.47)	-1.20 (1.06)	-1.37 (1.10)
μ				
σ				
N	321	321	321	321

Standard errors are reported in parenthesis.
In every specification, dummy variables for quarters are included.
$^{\diamond}$*No_Cache* is a dummy variable for processors with lower capacity of the level 2 cache.
*significant at the 10% level.
**significant at the 5% level.

Table 4: Quality unrelated to the maximum processing speed

Parameter	Explanation	Value
ξ_{Intel}	Unob. characteristics for Intel	$\{-1.5174, -0.8131, -0.3070, 0.1886, 0.8565\}$
$\eta_{Intel}\left(\xi_{t+1}\vert\xi_t\right)$	Transition matrix of ξ_{Intel}	$\begin{pmatrix} 0 & 0 & 0 & 0 & 0.14 \\ 1.00 & 0.33 & 0.25 & 0 & 0 \\ 0 & 0.33 & 0.25 & 0.20 & 0 \\ 0 & 0.33 & 0.50 & 0.50 & 0.14 \\ 0 & 0 & 0 & 0.30 & 0.72 \end{pmatrix}$
ξ_{AMD}	Unob. characteristics for AMD	$\{-3.8972, -2.2353, -1.5623, -0.3575, 0.67\}$
$\eta_{AMD}\left(\xi_{t+1}\vert\xi_t\right)$	Transition matrix of ξ_{AMD}	$\begin{pmatrix} 0 & 0 & 0.11 & 0.25 & 0 \\ 0.67 & 0.25 & 0 & 0 & 0.33 \\ 0.33 & 0.75 & 0.45 & 0 & 0.33 \\ 0 & 0 & 0.33 & 0.25 & 0 \\ 0 & 0 & 0.11 & 0.50 & 0.33 \end{pmatrix}$

See the text for details.

Table 5: Research expenditure in Markov Perfect Equilibrium (in million dollars)

	RJV cartel		RJV competition		Competitive research	
Maximum Speed	Intel	AMD	Intel	AMD	Intel	AMD
66 MHz	31.00	31.00	33.53	17.07	129.98	95.01
	(0.12)	(0.12)	(1.14)	(0.63)	(1.21)	(1.25)
200 MHz	29.67	29.67	31.98	16.39	125.21	91.74
	(0.11)	(0.11)	(1.26)	(0.70)	(2.02)	(2.15)
333 MHz	27.81	27.81	29.96	15.36	113.83	83.87
	(0.12)	(0.12)	(1.39)	(0.78)	(2.23)	(2.46)
800 MHz	25.73	25.73	27.69	14.22	100.82	73.91
	(0.14)	(0.14)	(1.60)	(0.90)	(2.37)	(2.66)
1,000 MHz	23.31	23.31	25.07	12.89	86.77	63.73
	(0.17)	(0.17)	(1.91)	(1.10)	(2.68)	(3.05)

The degree of spillover is set to 1 and the standard deviations are in parenthesis.

Table 6: Comparison of research regimes

	NJ vs. N		CJ vs. N		CJ vs. NJ	
Intel's Var. Profits	$\Pr(NJ = N)^*$	0.650	$\Pr(CJ = N)^*$	0.657	$\Pr(CJ = NJ)^*$	0.988
	$\Pr(NJ > N)^\dagger$	0.139	$\Pr(CJ > N)^\dagger$	0.139	$\Pr(CJ > NJ)^\dagger$	0.012
	$\Pr(NJ < N)$	0.211	$\Pr(CJ < N)$	0.204	$\Pr(CJ < NJ)$	0
AMD's VAr. Profits	$\Pr(NJ = N)$	0.650	$\Pr(CJ = N)$	0.657	$\Pr(CJ = NJ)$	0.988
	$\Pr(NJ > N)$	0.192	$\Pr(CJ > N)$	0.192	$\Pr(CJ > NJ)$	0.012
	$\Pr(NJ < N)$	0.158	$\Pr(CJ < N)$	0.151	$\Pr(CJ < NJ)$	0
Intel's Net Profits	$\Pr(NJ = N)$	0	$\Pr(CJ = N)$	0	$\Pr(CJ = NJ)$	0
	$\Pr(NJ > N)$	0.831	$\Pr(CJ > N)$	0.842	$\Pr(CJ > NJ)$	1
	$\Pr(NJ < N)$	0.169	$\Pr(CJ < N)$	0.158	$\Pr(CJ < NJ)$	0
AMD's Net Profits	$\Pr(NJ = N)$	0	$\Pr(CJ = N)$	0	$\Pr(CJ = NJ)$	0
	$\Pr(NJ > N)$	0.879	$\Pr(CJ > N)$	0.882	$\Pr(CJ > NJ)$	0.012
	$\Pr(NJ < N)$	0.121	$\Pr(CJ < N)$	0.118	$\Pr(CJ < NJ)$	0.988
Consumer Surplus	$\Pr(NJ = N)$	0.650	$\Pr(CJ = N)$	0.657	$\Pr(CJ = NJ)$	0.988
	$\Pr(NJ > N)$	0.320	$\Pr(CJ > N)$	0.323	$\Pr(CJ > NJ)$	0.012
	$\Pr(NJ < N)$	0.03	$\Pr(CJ < N)$	0.020	$\Pr(CJ < NJ)$	0

NJ denotes RJV competition, CJ RJV cartel, and N competitive research.
The simulation is repeated for 1,000 times for each comparison.
*The frequency that two regimes generate the same discounted sum of variable profit for Intel.
†The frequency that one regime generates a higher discounted sum of variable profit for Intel than the other regime.

Table 7: Average discounted sum of variable and net profits and consumer surplus (in billion dollars)

	RJV cartel	RJV competition	Competitive research
Intel's Net Profits	37.423	37.364	37.207
	(6.574)	(6.588)	(6.688)
AMD's Net Profits	19.101	19.128	18.917
	(3.429)	(3.436)	(3.526)
Consumer Surplus	116.706	116.591	116.181
	(23.601)	(23.677)	(23.818)

The simulation is repeated for 1,000 times. The average values are reported and the standard deviations are in parenthesis.

Table 8: Transition matrix of unobservable characteristics before and after 1997Q2.

Parameter	Explanation	Value
$\eta_{Intel\_before}\left(\xi_{t+1}\vert\xi_t\right)$	Intel before 1997Q2	$\begin{pmatrix} 0 & 0 & 0 & 0 & 0.25 \\ 1 & 0.33 & 0.33 & 0 & 0 \\ 0 & 0.33 & 0.33 & 0.50 & 0 \\ 0 & 0.33 & 0.33 & 0 & 0 \\ 0 & 0 & 0 & 0.50 & 0.75 \end{pmatrix}$
$\eta_{Intel\_after}\left(\xi_{t+1}\vert\xi_t\right)$	Intel after 1997Q2	$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.125 & 0 \\ 0 & 0 & 1 & 0.625 & 0.33 \\ 0 & 0 & 0 & 0.25 & 0.67 \end{pmatrix}$
$\eta_{AMD\_before}\left(\xi_{t+1}\vert\xi_t\right)$	AMD before 1997Q2	$\begin{pmatrix} 0 & 0 & 0.33 & 1 & 0 \\ 0.67 & 0.33 & 0 & 0 & 0 \\ 0.33 & 0.67 & 0.33 & 0 & 0 \\ 0 & 0 & 0.33 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$
$\eta_{AMD\_after}\left(\xi_{t+1}\vert\xi_t\right)$	AMD after 1997Q2	$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.33 \\ 0 & 1 & 0.50 & 0 & 0.33 \\ 0 & 0 & 0.33 & 0.33 & 0 \\ 0 & 0 & 0.17 & 0.67 & 0.33 \end{pmatrix}$

Table 9: Discounted sum of research expenditure before and after 1997Q2 (in billion dollars)

	RJV cartel		RJV competition		Competitive research	
	before	after	before	after	before	after
Intel	1.80	0.97	2.43	1.15	4.93	4.35
	(0.25)	(0.07)	(0.31)	(0.10)	(0.69)	(0.60)
AMD	1.80	0.97	0.78	0.53	2.99	3.49
	(0.25)	(0.07)	(0.13)	(0.07)	(0.39)	(0.45)

The simulation is repeated for 1,000 times. The average values are reported and the standard deviations are in parenthesis.

Figure 1: Unobservable characteristics of frontier products