

# Does AMD spur Intel to innovate more?\*

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## Abstract

We propose and estimate a model of dynamic oligopoly with durable goods and endogenous innovation to better understand the relationship between market structure and the evolution of quality. Firms make dynamic pricing and investment decisions while taking into account the dynamic behavior of consumers who anticipate the product improvements and declining prices. The distribution of currently owned products is a state variable that affects current demand and evolves endogenously as consumers make replacement purchases. Our work extends the dynamic oligopoly framework of Ericson and Pakes (1995) to incorporate durable goods and to yield an endogenous long-run rate of innovation. We estimate the model for the PC microprocessor industry and perform counterfactual simulations to measure the benefits of competition. Consumer surplus is 4.2 percent higher (\$12 billion per year) with AMD than if Intel were a monopolist. Innovation, however, would be 4.2 percent higher without AMD present. Counterfactuals reveal that consumer surplus can actually increase as the market moves toward monopoly, which suggests policymakers should consider the dynamic trade-off of lower current consumer surplus from higher prices for higher future surplus from more innovation. Comparative statics reveal the effect on equilibrium outcomes of consumer preferences, depreciation, market growth, product substitutability, and innovation spillovers. For example, competition increases innovation if consumers highly value quality and have low price sensitivity or if the market growth rate is high. We also show that under either market structure, consumers of durable goods are the primary beneficiaries of innovation opportunities.

**Keywords:** competition and innovation, dynamic oligopoly, durable goods, estimation of dynamic games, microprocessors

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# 1 Introduction

Economists have long sought to understand the relationship between market structure and innovation to inform policy governing antitrust, patent regulation, and economic growth. However, after more than 70 years of research, the conclusions of both the theoretical and empirical literatures are decidedly mixed. The original theoretical hypothesis, proposed by Schumpeter (1942), posits a positive relationship between market concentration and innovation. Fellner (1951) and Arrow (1962) argue for a linear negative relationship, and Scherer (1967) proposes a model yielding an inverted-U relationship. The empirical literature has found varying degrees of support for each of these hypotheses, leading Cohen and Levin (1989) to state, “The empirical results bearing on the Schumpeterian hypotheses are inconclusive.” They argue the lack of an empirical consensus is primarily due to data measurement errors and the difficulty of controlling for various industry-specific factors. Despite the absence of conclusive theoretical or empirical evidence, the Federal Trade Commission increasingly cites the potential effect of competition on innovation as a concern (Gilbert 2006).

In this paper, we pursue a complementary approach to the reduced-form empirical studies in Cohen and Levin’s review and continued by others, such as Blundell, Griffith and Van Reenen (1999) and Aghion et al. (2005). Rather than attempt to characterize the relationship between market structure and innovation across industries, we focus on understanding this relationship in a particular industry. This path of inquiry is motivated by the attention paid to industry-specific characteristics in antitrust investigations (e.g., Microsoft vs. Netscape and Intel vs. AMD). We construct and estimate a structural model of dynamic oligopoly with endogenous innovation and use it to assess the effect of competition on innovation, profits, and consumer surplus in the personal computer (PC) microprocessor industry. Like most manufactured goods, microprocessors are durable. We explicitly account for the effect of durability on equilibrium pricing and innovation policies and, consequently, on competition’s effect on innovation.

We study the microprocessor industry for three primary reasons. First, the industry is of extreme importance to the economy: Jorgenson, Ho, and Samuels (2010) report that the computer-equipment manufacturing industry generated 25 percent of U.S. productivity growth from 1960 to 2007. Second, recent antitrust lawsuits claim Intel’s anti-competitive practices, such as rewarding PC manufacturers who exclusively use Intel microprocessors, have restricted AMD’s access to consumers. Intel settled these claims in 2009 with a \$1.25 billion payment to AMD, but Intel is still under investigation by government authorities in the United States, Europe, and Asia.<sup>1</sup> Finally, most studies rely on indirect measures of innovation, such as patents, whereas innovations in microprocessors are directly measured via improved performance on benchmark tasks.

Our model reflects several industry features and stylized facts. First and foremost, the market is essentially a duopoly, with AMD and Intel selling 95 percent of the PC central-processing units

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<sup>1</sup>S. Lohr and J. Kanter, “AMD-Intel Settlement Won’t End Their Woes,” *New York Times*, November 13, 2009.

(CPUs).<sup>2</sup> Accordingly, we cannot treat firms as being small relative to the industry, as in Hopenhayn (1992) and Klette and Kortum (2004), and instead model their strategic interaction through Markov-perfect Nash equilibrium. Second, AMD and Intel invest substantially in R&D—respectively, 20 and 11 percent of revenues on average over the 1993 to 2004 span of our data. Innovation is rapid, with new products being released nearly every quarter and CPU performance doubling roughly every seven quarters.<sup>3</sup> Quarterly innovations, however, vary: the standard deviation in quarterly performance gains is slightly higher than the average gain. Finally, AMD and Intel extensively cross-license each other’s technologies, which leads to an industry structure in which neither firm gets too far ahead and technological leadership changes hands. To capture these supply-side features, we model innovation in an AMD-Intel duopoly as stochastic gains on a quality ladder in which success is more likely with higher investments and for laggards who benefit from innovation spillovers.

Consumer behavior also guides our model. As microprocessors are durable, replacement drives demand: 82 percent of PC purchases in 2004 were replacements (Computer Industry Almanac, 2005). A short-term increase in innovation widens the quality gap between currently owned products and new offerings. This boost in demand increases both prices and sales. After the upgrade boom, prices and sales fall as replacement demand drops. Firms must continue to innovate to rebuild replacement demand, because microprocessors do not physically depreciate. We explicitly model this upgrade cycle and the timing of consumers’ purchases given beliefs about future prices and innovation.

Product durability implies firms face competition from past sales and must innovate to sustain profits in the long run.<sup>4</sup> Such competition leads even monopolists to innovate to induce upgrade purchases. Monopolists selling nondurable goods, however, can earn monopoly rents in the long run with no innovation because demand is replenished each period.<sup>5</sup> Product durability introduces competition with past sales which can have first-order effects on the incentives to innovate, particularly in a monopoly for which past sales are the *only* source of competition. The degree of competition with past sales depends on the rate at which new consumers enter the market and on the product’s depreciation rate. We therefore investigate the effect of these two factors on innovation by monopolists and duopolists.

To identify the effect of competition on innovation, we estimate consumer preferences and firms’ innovation efficiencies, from which we can derive the benefits and costs of innovation and solve for

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<sup>2</sup>Cyrix Corporation (acquired in 1997 by National Semiconductor), Transmeta Corporation, and VIA Technologies were fringe players trying to break into the market during the 1990s and early 2000s, but none succeeded. The AIM Alliance of Apple Computer, IBM, and Motorola supplied the PowerPC microprocessor for Apple, which garnered a 2 percent share of sales in 2003.

<sup>3</sup>Intel co-founder Gordon Moore predicted in 1965 that the number of transistors per integrated circuit would double every two years for at least 10 more years. The trend’s persistence for nearly 50 years has led to it being known as “Moore’s law.” Doubling the transistor count of a CPU roughly doubles its performance.

<sup>4</sup>Carlton and Gertner (1989) show that competition from past sales of durable goods limits the welfare loss of mergers that increase market power.

<sup>5</sup>Although a nondurable-goods monopolist might innovate if consumers are willing to pay more for higher quality, eventually consumers will reach their maximum willingness to pay (perhaps their income), and the nondurable-goods monopolist will cease innovation.

equilibrium under various competitive scenarios. This approach accords with Dorfman and Steiner (1954), Needham (1975), and Lee (2005), who find consumer preferences and firm competencies are key determinants of R&D. We estimate preferences and innovation efficiencies using a minimum distance estimator to match simulated moments from our model’s equilibrium to observed aggregate moments, such as average prices and innovation rates, constructed from quarterly CPU prices, qualities, market shares, and innovation.<sup>6</sup> We then compare outcomes across counterfactual simulations with AMD either removed or strengthened to be an equal competitor to Intel.<sup>7</sup> Importantly, our model can generate either a positive or a negative relationship between competition and innovation, depending on parameter values. Thus we allow the data to guide our conclusions.

We find innovation would be 4.2 percent higher if Intel were a monopoly. Consumer surplus, however, is 4.2 percent (\$12 billion per year) higher with AMD because prices are lower than if Intel were a monopolist. To evaluate the effect of Intel’s alleged anti-competitive practices, we perform counterfactual simulations in which we vary the share of the market from which AMD is foreclosed. As the foreclosure share rises, prices and industry innovation both increase, lending support to the Schumpeterian hypothesis. Moreover, consumer surplus peaks when AMD is excluded from 40 percent of the market, as the higher innovation more than fully offsets the effect of higher prices on surplus. This finding supports the FTC’s recent consideration of the dynamic trade-off between lower current consumer surplus from higher prices and higher future surplus from more innovation.

To further understand the relationship of competition and innovation, we perform comparative statics by varying (i) consumer preferences for quality and price, (ii) depreciation rates (i.e., product durability), (iii) market growth rates, (iv) product substitutability, and (v) the degree of innovation spillovers that enable firms to innovate more efficiently when catching up to the frontier.

We find that equilibrium innovation rates increase monotonically as preferences for quality increase and as price sensitivity declines, for both duopoly and monopoly. As explained in section 4, duopoly innovation is more sensitive to preferences. Industry innovation is therefore higher in the duopoly than in the monopoly when quality preferences are high and price sensitivity is low.

Higher depreciation rates have similar effects on equilibrium outcomes in the monopoly and duopoly: innovation and consumer surplus decline and margins and profits increase. In contrast, the effect of market growth on innovation depends on industry structure. Innovation in the monopoly declines as the durable-goods monopolist faces less competition from itself. In the duopoly, each firm’s innovation is driven more by competition with the other firm than by a desire to induce upgrades (i.e., competition with past sales). Moreover, the increased flow of new consumers with faster market growth boosts demand, which increases the incentive to steal business from one’s

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<sup>6</sup>Several studies estimate demand for durable goods, taking product quality as exogenous (Melnikov 2001, Song and Chintagunta 2003, Nair 2007, Gordon 2009, Gowrisankaran and Rysman 2009, and Carranza 2010). Our econometric model differs from these in its use of supply-side equilibrium restrictions to help identify the structural parameters.

<sup>7</sup>Our model can be extended to yield an endogenous number of firms. Counterfactuals in the number of firms would then correspond to exogenous shifts in entry and exit costs.

competitor by improving quality. Industry innovation in the duopoly therefore increases as market growth quickens, and is higher than monopoly innovation if market growth is rapid.

Innovation spillovers reduce incentives for leaders to innovate but also ensure laggards do not fall so far behind that they give up trying to remain competitive, as they do with no spillovers. Hence duopoly innovation increases as spillovers decrease, as long as the laggard never concedes leadership. With no spillovers or large spillovers, monopoly innovation is higher than duopoly innovation, but with moderate spillovers duopoly innovation is higher.

As a whole, these comparative statics demonstrate that competition's effect on innovation depends on industry characteristics that likely vary across industries and perhaps across time within an industry. Such variation might be one reason cross-industry studies have difficulty identifying robust relationships.

Our work relates to the literatures on endogenous growth theory, dynamic oligopoly, and durable goods theory. A series of papers in endogenous growth theory (Aghion and Howitt 1992, Aghion et al. 2001, and Aghion et al. 2005) examines the relationship between competition and innovation. In addition to identifying the inverted-U relationship between the Lerner index and patent-production in UK industries, Aghion et al. (2005) develop a model of technological innovation that generates this relationship. We demonstrate that the durability of goods and nonzero investment by frontier firms in our model generate implications that differ from those in Aghion et al. (2005).

Vives (1990, 2008) also investigates the effect of competition on innovation by firms selling non-durable goods. He finds firms innovate less when facing more competitors and innovate more when competition increases via greater product substitutability. We find, with durable goods, that the effect of more competitors on innovation depends on consumer preferences and the strength of innovation spillovers.

Our work is a natural extension of the early industry simulation models of Nelson and Winter (1982) and Grabowski and Vernon (1987) and to the dynamic oligopoly model of Ericson and Pakes (1995, hereafter EP). The EP framework has been applied to a variety of industries, as summarized by Doraszelski and Pakes (2007), but none of the studies considers durable goods with forward-looking consumers and endogenous innovation. Given the prominence of durable goods in our economy (e.g., airplanes, automobiles, consumer electronics, etc.) and the importance of innovation for economic growth, filling this gap is a worthy goal.

We therefore incorporate durable goods into the EP framework as applied to differentiated products by Pakes and McGuire (1994). In our model, firms make dynamic pricing and investment decisions while taking into account the dynamic behavior of consumers. In turn, consumers account for the fact that firms' strategies lead to higher-quality products and lower prices when considering whether to buy now or later. Since consumers' choices depend on the products they currently own, the distribution of currently owned products affects aggregate demand. We explicitly model the endogenous evolution of this distribution and its effect on equilibrium behavior. Prices, innovation,

profits, and consumer surplus are all substantially higher when firms correctly account for the dynamic nature of demand arising from durability. One implication of this result is that marginal costs of durable goods derived from static first-order conditions will be too high: the prices are high to preserve future demand, not only because costs are high. We also find that ignoring the dynamic nature of demand for durable goods leads to a reversal of the effect of competition on innovation.

In the EP framework, the industry’s long-run innovation rate equals the exogenous rate at which the outside good’s quality improves. Since an industry’s innovation rate, rather than its pricing behavior, might be the primary determinant of discounted consumer surplus, providing an endogenous long-run innovation rate that varies across market structures and regulatory controls seems important for policy work. Our model with durable goods yields an endogenous long-run innovation rate because the quality of the no-purchase option depends on consumers’ past purchases.

The theoretical literature on durable goods, reviewed by Waldman (2003), focuses on monopoly and perfect competition, whereas we consider the more empirically relevant market structure of oligopoly. This literature also focuses on endogenous product durability (i.e., the rate of depreciation), whereas we focus on endogenous obsolescence due to innovation. Though similar, durability and obsolescence have an important difference: durability entails commitment since the good is produced with a given durability, whereas obsolescence depends on future innovations.

In the following section, we present our model of firm and consumer behavior. In section 3, we estimate the model using the microprocessor data and discuss implications specific to that industry. In section 4, we perform a series of comparative statics to further illustrate the model’s properties and its implications for other industries. Section 5 concludes.

## 2 Model

In this section, we present a dynamic model of differentiated-products oligopoly for a durable good. Although we interpret some model details in the context of microprocessors, the model applies to any durable good. We abstract away from the role of computer manufacturers because consumers can choose either firm’s microprocessors regardless of their choice of other computer components (e.g., disk drive, memory, video card, monitor, etc.).

Time, indexed by  $t$ , is discrete with an infinite horizon.<sup>8</sup> Each firm  $j \in \{1, \dots, J\}$  sells a single product and invests to improve its quality. If successful, quality improves next period by a fixed proportion; otherwise it is unchanged.<sup>9</sup> We therefore denote log-quality  $q_{jt} \in \{0, \delta, 2\delta, \dots\}$ .

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<sup>8</sup>We assume a firm’s ability to commit to prices is exogenously specified by the period length: firms commit to fixed prices within, but not across periods. Thus, we do not address the time-inconsistency problem of wanting to commit today to a high price, but then wanting to lower it later after some consumers buy at the high price (Coase 1972, Stokey 1981, Bulow 1982, and Bond and Samuelson 1984). Assessing the effect of period length on industry outcomes would be interesting, though difficult to implement since it involves changing the scale of several parameters simultaneously and tweaking the innovation process to maintain *ceteris paribus*.

<sup>9</sup>Borkovsky (2008) studies the timing of new releases, and Holmes, Levine, and Schmitz (2008) explore the effect of

A key feature of demand for durable goods is that the value of the no-purchase option is endogenous because it depends on past choices. Consumers decide each period whether to buy a new product or to continue using the one they already own. This feature generates a dynamic trade-off for pricing: selling more in the current period reduces demand in future periods because recent buyers are unlikely to buy again in the near future. The distribution of currently owned products, denoted  $\Delta_t$ , therefore affects current demand.

Firms and consumers are forward-looking and take into account the optimal dynamic behavior of other agents when choosing their respective actions. All agents observe the vector of firms' qualities  $q_t = (q_{1t}, \dots, q_{Jt})$  and the ownership distribution  $\Delta_t$ . These two state variables comprise the state space of payoff-relevant variables for firms simultaneously choosing prices  $p_{jt}$  and investment  $x_{jt}$ . The consumer's state space consists of the quality of her currently owned product  $\tilde{q}_t$ , the firms' current offerings  $q_t$ , and the ownership distribution  $\Delta_t$ . This latter state variable is relevant to the consumer since it affects firms' current and future prices and investment levels. We assume consumers observe  $\Delta_t$  merely as a convenient way to impose rational expectations of future prices and qualities. Rationality requires consumers to act as if they condition on the ownership distribution since it influences innovation and future prices through firms' policy functions.

We restrict firms to sell only one product because the computational burden of allowing multi-product firms is prohibitive—the state space grows significantly and the optimization within each state becomes substantially more complex. Accounting for multiple products would be important if our focus were on price discrimination or product-line pricing and quality choices (Aizcorbe and Kortum 2005, Gordon 2009, and Nosko 2010). Our demand model captures the market features that are most relevant for our focus on endogenous innovation: consumers upgrade when the offered qualities are sufficiently higher than their currently owned quality, and consumers expect innovations to raise future quality and lower future prices per unit quality.

We do not consider entry and exit since they rarely occur in the CPU industry. If necessary, one could include entry and exit as in EP. We also do not consider secondary markets since computers and microprocessors are rarely resold. With resale, the ownership distribution would convey the set of used goods available for trade, as in the model with car resale in Chen, Esteban, and Shum (2010).

## 2.1 Consumers

We model consumers as owning one microprocessor at a time.<sup>10</sup> Utility for a consumer  $i$  from firm  $j$ 's new product with quality  $q_{jt}$  is given by

$$u_{ijt} = \gamma q_{jt} - \alpha p_{jt} + \xi_j + \varepsilon_{ijt} , \tag{1}$$

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switchover disruptions on the incentives to innovate.

<sup>10</sup>Cho (2008) estimates a dynamic model of computer replacement by a telecommunications firm using many computers.

where  $\gamma$  is the taste for quality,  $\alpha$  is the marginal utility of money,  $\xi_j$  is a brand preference for firm  $j$ , and  $\varepsilon_{ijt}$  captures idiosyncratic variation, which is i.i.d. across consumers, products, and periods.<sup>11</sup>

We assume brand preference only affects utility at the time of purchase. Utility from the no-purchase option is therefore

$$u_{i0t} = \gamma \tilde{q}_{it} + \varepsilon_{i0t}, \quad (2)$$

where  $\tilde{q}_{it}$  denotes the quality available to the consumer if no purchase is made this period.

With  $J+1$  choices in each period, we normalize  $\xi_0$  to be zero and exclude it from  $u_{i0t}$ . We expect  $\xi_j < 0$  for  $j > 0$  since in a given period, most consumers do not upgrade. We interpret the highest of these  $\xi_j$  as an upgrade switching cost and the differences between  $\xi_j$  and this maximum to be brand preferences. One could alternatively specify the  $\xi_j$  to enter the utility flow for the no-purchase option, but in our empirical application, having future utility depend solely on the product's quality seems more natural since conditional on quality, brand does not affect performance.

One could interpret the model as having two outside alternatives: one for consumers who have purchased previously and one for “non-owners” who have never purchased. For consumers with previous purchases,  $\tilde{q}_{it}$  is the quality of their most recent purchase. For consumers who have yet to make an initial purchase, utility from the no-purchase option depends on the application at hand. For CPUs, the outside good for “non-owners” might consist of using computers at schools and libraries or using old computers received from family or friends who have upgraded. To capture the notion that this outside alternative for non-owners improves as the frontier's quality improves, we define  $\bar{q}_t \equiv \max(q_t)$  and assume non-owners have  $\tilde{q}_{it}$  of  $q_t \equiv \bar{q}_t - \bar{\delta}_c$ . That is, the quality of the outside alternative for non-owners is always  $\bar{\delta}_c$  below the frontier quality. Furthermore, since everyone has access to this non-owner outside good,  $q_t$  is a lower bound of  $\tilde{q}_{it}$  for all consumers. To ensure our choice of  $\bar{\delta}_c$  does not drive the model's behavior, we check that consumers upgrade frequently enough that the quality of their most recent purchase rarely matches  $q_t$ .

Since the ownership distribution only has mass at vintages weakly above  $q_t$ , we define the ownership state variable  $\Delta_t = (\Delta_{\underline{q}_t,t}, \dots, \Delta_{k,t}, \dots, \Delta_{\bar{q}_t,t})$ , where  $\Delta_{k,t}$  is the fraction of consumers whose outside option has quality  $\tilde{q}_{it} = q_{kt}$ .

Each consumer maximizes her expected discounted utility, yielding a value function  $V$  that satisfies Bellman's equation. Omitting  $i$  and  $t$  subscripts for conciseness and using the prime superscript to denote next period values,

$$V(q, \Delta, \tilde{q}, \varepsilon) = \max_{y \in (0, \dots, J)} u_y + \beta \sum_{q', \Delta'} \int V(q', \Delta', \tilde{q}'_y, \varepsilon') f_\varepsilon(\varepsilon') d\varepsilon' h_c(q'|q, \Delta, \varepsilon) g_c(\Delta'|\Delta, q, q', \varepsilon), \quad (3)$$

where  $y$  denotes the optimal choice in the current period,  $h_c(\cdot|\cdot)$  is the consumer's beliefs about future product qualities,  $g_c(\cdot|\cdot)$  is the consumer's beliefs about the transition kernel for  $\Delta'$ ,  $f_\varepsilon$  is the

<sup>11</sup>As explained by Rust (1996), the *independence from irrelevant alternatives* (IIA) property of logit demand fails to hold in dynamic contexts since the attributes of all the products enter the continuation values.

density of  $\varepsilon$ , and  $\tilde{q}'_y$  is  $\max(\tilde{q}, \underline{q}')$  if  $y = 0$  and  $q_y$  otherwise. The evolution of  $\tilde{q}$  is trivial: if  $y = 0$  then  $\tilde{q}' = \max(\tilde{q}, \underline{q}')$ ; otherwise  $\tilde{q}' = q_y$ . Each consumer is small relative to the market so that her actions do not affect the evolution of  $\Delta$  to  $\Delta'$ .

Following Rust (1987), we assume  $\varepsilon$  are multivariate extreme-value and integrate over  $\varepsilon$  to obtain the smoothed Bellman equation

$$\bar{V}(q, \Delta, \tilde{q}) = \log \left( \sum_{j \in \{0, \dots, J\}} \exp \left\{ u_j - \varepsilon_j + \beta \sum_{q', \Delta'} \bar{V}(q', \Delta', \tilde{q}'_j) h_c(q'|q, \Delta) g_c(\Delta'|\Delta, q, p, q') \right\} \right), \quad (4)$$

from which we construct product-specific value functions:

$$v_j(q, \Delta, \tilde{q}) = u_j - \varepsilon_j + \beta \sum_{q', \Delta'} \bar{V}(q', \Delta', \tilde{q}'_j) h_c(q'|q, \Delta) g_c(\Delta'|\Delta, q, p, q'). \quad (5)$$

The conditional choice probabilities for a consumer owning product  $\tilde{q}$  are therefore

$$s_{j|\tilde{q}} = \frac{\exp\{v_j(q, \Delta, \tilde{q})\}}{\sum_{k \in \{0, \dots, J\}} \exp\{v_k(q, \Delta, \tilde{q})\}}. \quad (6)$$

Using  $\Delta$  to integrate over the distribution of  $\tilde{q}$  yields the market share of product  $j$ :

$$s_j = \sum_{\tilde{q} \in \{q, \dots, \bar{q}\}} s_{j|\tilde{q}} \Delta_{\tilde{q}}. \quad (7)$$

These market shares translate directly into the law of motion for  $\Delta$ , which tracks the ownership of products between  $q_t$  and  $\bar{q}$ . Assuming  $\bar{q}$  is unchanged between the current and next periods, the share of consumers owning a product of quality  $k$  at the start of the next period is

$$\Delta'_k(\Delta, q, p|\bar{q}' = \bar{q}) = s_{0|k} \Delta_k + \sum_{j=1, \dots, J} s_j I(q_j = k), \quad (8)$$

where the summation accounts for the possibility that multiple firms might have quality  $k$ . For quality levels not offered in the current period, this summation is zero. If a firm advances the quality frontier with a successful R&D outcome pushing its  $q'_j$  beyond the previous  $\bar{q}$  then  $\Delta'$  shifts: the second element of  $\Delta'$  is added to its first element, the third element becomes the new second element, and so on, and the new last element is initialized to zero. Formally, define the shift operator  $\Gamma$  on a generic vector  $y = (y_1, y_2, \dots, y_L)$  as  $\Gamma(y) = (y_1 + y_2, y_2, \dots, y_L, 0)$ . If the quality frontier advances at the end of the current period, we shift the interim  $\Delta'$  in equation (8) via  $\Gamma(\cdot)$ . Hence

$$\Delta'(\Delta, q, p) = \mathcal{I}(\bar{q}' = \bar{q}) \Delta'(\Delta, q, p|\bar{q}' = \bar{q}) + \mathcal{I}(\bar{q}' > \bar{q}) \Gamma(\Delta'(\Delta, q, p|\bar{q}' = \bar{q})). \quad (9)$$

The continuation ownership distribution  $\Delta'$  is therefore a deterministic function of  $(\Delta, q, p)$  except for the potential shift due to the stochastic innovation of frontier products.

## 2.2 Firms

Each period, firms make dynamic pricing and investment decisions. Each firm has access to an R&D process that governs its ability to introduce higher-quality products.<sup>12</sup> Firms choose a level  $x_j \in \mathbb{R}_+$  to invest in R&D. The outcome,  $\tau_j = q'_j - q_j$ , is probabilistic and stochastically increasing in  $x_j$ . We restrict  $\tau_j \in \{0, \delta\}$  and denote its probability distribution  $f(\cdot|x, q)$ . The dependence of  $\tau_j$  on  $q$  permits spillover effects in investment, which we model by specifying  $\tau_j$  to be stochastically increasing in  $(\bar{q} - q_j)$ , the degree to which the firm is behind the frontier. As such, innovations are easier when catching up to the frontier than when advancing it.<sup>13</sup>

Following Pakes and McGuire (1994), we specify the probabilities of successful and failed investments, respectively, as  $f(1|x, q) = ax/(1 + ax)$  and  $f(0|x) = 1/(1 + ax)$ , which yields closed-form solutions for optimal investment. We allow  $a$  to vary for the laggard according to the degree to which the firm is behind. In particular, we specify  $a_j(q) = a_{0,j} \max(1, a_1(\frac{\bar{q}-q_j}{\delta})^{1/2})$ , which reflects the increased difficulty of advancing the frontier relative to catching up to it. Linear and convex spillovers yield similar results to the concave  $a_j(q)$  we use.

The period profit function, excluding investment costs, for firm  $j$  is

$$\pi_j(p, q, \Delta) = M s_j(p, q, \Delta)(p_j - mc_j(q)) , \quad (10)$$

where  $M$  is the fixed market size,  $s_j(\cdot)$  is the market share for firm  $j$  from equation (7), and  $p$  is the vector of  $J$  prices. In section 3.2.3 we discuss the possibility of reallocating mass to the lowest vintage in  $\Delta$  to capture one effect of consumers entering the market, while retaining fixed  $M$  to ensure stationarity. Firm  $j$ 's constant marginal costs are given by

$$mc_j(q) = \lambda_0 + \lambda_1 (\bar{q} - q_j) , \quad (11)$$

where  $\lambda_1 < 0$  implies production costs are lower for non-frontier firms. In our application,  $|\lambda_1|$  is small enough that marginal costs are always positive.

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<sup>12</sup>Pillai (2009) finds innovation in the microprocessor industry depends in part on innovations by upstream manufacturers of semiconductor equipment. We implicitly assume these external forces do not vary over time.

<sup>13</sup>If a firm's recent investments have failed to increase its quality, the firm is more likely to be a laggard. Hence the spillover mimics, to a degree, the effect of including a state variable for cumulative R&D investments since the previous innovation. Actually including such a state variable significantly raises the computational burden.

Each firm maximizes its expected discounted profits, yielding the Bellman equation

$$W_j(q_j, q_{-j}, \Delta) = \max_{p_j, x_j} \pi_j(p, q, \Delta) - x_j + \beta \sum_{\tau_j, q'_{-j}, \Delta'} W_j(q_j + \tau_j, q'_{-j}, \Delta') f(\tau_j | x_j, q) h_{f_j}(q'_{-j} | q, \Delta) g_{f_j}(\Delta' | \Delta, q, p), \quad (12)$$

where  $h_{f_j}(\cdot | \cdot)$  is firm  $j$ 's beliefs about competitors' future quality levels, and  $g_{f_j}(\cdot | \cdot)$  is its beliefs about the transition kernel for  $\Delta$ , which is based on beliefs about consumers' choices given prices and qualities.

Firms simultaneously choose prices and investments to satisfy the first-order conditions

$$\frac{\partial W}{\partial p_j} = \frac{\partial \pi_j(p, q, \Delta)}{\partial p_j} + \beta \sum_{\tau_j, q'_{-j}, \Delta'} W_j(q_j + \tau_j, q'_{-j}, \Delta') h_{f_j}(q'_{-j} | q, \Delta) \frac{\partial g_{f_j}(\Delta' | \Delta, q, p)}{\partial p_j} f(\tau_j | x_j, q) = 0 \quad (13)$$

and

$$\frac{\partial W_j}{\partial x_j} = -1 + \beta \sum_{\tau_j, q'_{-j}, \Delta'} W_j(q_j + \tau_j, q'_{-j}, \Delta') h_{f_j}(q'_{-j} | q, \Delta) g_{f_j}(\Delta' | \Delta, q, p) \frac{\partial f(\tau_j | x_j, q)}{\partial x_j} = 0. \quad (14)$$

Recall the important dynamic trade-off—a higher price today implies more people will be available in the next period to purchase the product. The presence of  $\frac{\partial g_{f_j}(\Delta' | \Delta, q, p)}{\partial p_j}$  in  $\frac{\partial W}{\partial p_j}$  captures this benefit of raising price and leads to forward-looking firms pricing higher than myopic firms that ignore this dynamic aspect of demand.

### 2.3 Equilibrium

We consider pure-strategy Markov-Perfect Nash Equilibrium (MPNE) of this dynamic oligopoly game in which all state variables are indeed Markov. Our MPNE extends that of Ericson and Pakes (1995) to account for the forward-looking expectations of consumers. In brief, the equilibrium fixed point has the additional requirement that consumers possess consistent expectations on the probability of future states.

The equilibrium specifies that (1) firms' and consumers' equilibrium strategies depend only on current state variables, which comprise all payoff-relevant variables, (2) consumers have rational expectations about firms' policy functions, which determine future qualities and prices, and the evolution of the ownership distribution, and (3) each firm has rational expectations about competitors' policy functions for price and investment and about the evolution of the ownership distribution.

Formally, an MPNE in this model is the set  $\left\{ V^*, h_c^*, g_c^*, \left\{ W_j^*, x_j^*, p_j^*, h_{f_j}^*, g_{f_j}^* \right\}_{j=1}^J \right\}$ , which contains the equilibrium value functions for the consumers and their beliefs  $h_c^*$  about future product qualities, beliefs  $g_c^*$  about future ownership distributions, and the firms' value functions, policy functions, beliefs  $h_{f_j}^*$  over their  $J-1$  rivals' future qualities, and beliefs  $g_{f_j}^*$  about the future ownership distribution. The expectations are rational in that the expected distributions match the distributions from

which realizations are drawn when consumers and firms behave according to their policy functions. In particular,  $h_c^*(q'|q, \Delta, \tilde{q}) = \prod_{j=1}^J f(\tau = q'_j - q_j | x_j^*, q)$ ,  $h_{f_j}^*(q'_{-j}|q, \Delta) = \prod_{k \neq j}^J f(\tau = q'_k - q_k | x_k^*, q)$ , and  $g_c^*$  and  $g_{f_j}^*$  are derived from the law of motion for  $\Delta$  as described by equations (8) and (9).

In some of the counterfactuals and comparative statics, we impose symmetry, which implies  $W_j^* = W^*$ ,  $x_j^* = x^*$ ,  $p_j^* = p^*$ ,  $h_{f_j}^* = h_f^*$ , and  $g_{f_j}^* = g_f^*$  for all  $j$ . Symmetry obviously requires firm-specific parameters—brand intercepts  $\xi_j$  and investment efficiencies  $a_{0,j}$ —to be the same across firms.

Besanko et al. (2010) and Borkovsky, Doraszelski, and Kryukov (2010) document the existence of multiple equilibria in dynamic oligopoly models based on EP. To reduce multiplicity, we focus on equilibria that are limits to finitely repeated games: we use backwards induction to solve for an equilibrium of the  $T$ -period game and then let  $T \rightarrow \infty$ . For each  $T$  and for each state, we solve the system of first-order conditions in equations (13) and (14). Our numerical algorithm for computing equilibrium to the infinite horizon game therefore corresponds to value function iteration with (a) initial values of zero for  $\bar{V}$  and  $W$  and (b) equilibrium strategies being played within each state for each iteration, as opposed to merely playing best responses to strategies from the previous iteration. This refinement yields a unique equilibrium if the subgame within each state at each iteration has a unique equilibrium. Inspections of best-response functions at various states during convergence suggests this refinement indeed yields a unique equilibrium.

We relegate the algorithmic details of computing and simulating the MPNE to Appendix A. One issue worth highlighting is that to evaluate firms' first-order conditions, we must solve a fixed-point in  $\Delta'$  such that consumers' current beliefs about  $\Delta'$  match the  $\Delta'$  that results from the choice probabilities in equation (6).

## 2.4 Bounding the State Space

The state space in our model is unbounded since product qualities increase without bound. To numerically solve for equilibrium, we transform the state space to one that is finite by measuring all qualities relative to the current period's maximum quality  $\bar{q} = \max(q)$ . Our ability to implement this transformation without altering the dynamic game itself hinges on the following proposition.

**Proposition 1.** *Shifting  $q$  and  $\tilde{q}$  by  $\bar{q}$  has no affect on firms' payoffs and shifts consumers' payoffs in each state by  $\frac{\gamma\bar{q}}{1-\beta}$ , the discounted value of the reduced utility in each period. More formally,*

$$\begin{aligned} \text{Firms:} \quad & W_j(q_j - \bar{q}, q_{-j} - \bar{q}, \Delta) = W_j(q_j, q_{-j}, \Delta) \\ \text{Consumers:} \quad & V(q - \bar{q}, \Delta, \tilde{q} - \bar{q}, \varepsilon) + \frac{\gamma\bar{q}}{1-\beta} = V(q, \Delta, \tilde{q}, \varepsilon). \end{aligned} \tag{15}$$

The proof, which appears in Appendix B, rests on the following properties of the model: (1) log-quality  $q$  enters linearly in the utility function, so that adding any constant to the utility of each

alternative has no effect on consumers' choices; (2) Innovations are governed by  $f(\cdot)$ , which is independent of quality levels; and (3)  $\Delta$  is unaffected by the shift since it tracks the ownership shares of only those products within  $\bar{\delta}_c$  of the frontier. That is,  $\Delta$  is already in relative terms.

To facilitate writing the value functions in terms of a relative state space, we define  $\omega = q - \bar{q}$  and  $\tilde{\omega} = \tilde{q} - \bar{q}$  as analogs to the original state variables. We also define the indicator variable  $I_{\bar{q}} = 1$  if  $\bar{q}' > \bar{q}$  to indicate an improvement in the frontier product. We can then express the consumer's product-specific value function in equation (5) using the relative state space as

$$v_j(\omega, \Delta, \tilde{\omega}) = \gamma\omega_j - \alpha p_j + \xi_j + \beta \sum_{q', \Delta'} \left( \frac{\gamma\delta I_{\bar{q}}}{1-\beta} + \bar{V}(\omega', \Delta', \tilde{\omega}'_j) \right) h_c(I_{\bar{q}}, \omega' | \omega, \Delta) g_c(\Delta' | \Delta, \omega, p, I_{\bar{q}}), \quad (16)$$

where the outside alternative's  $p_0$  and  $\xi_0$  are zero and, in a slight abuse of notation,  $h_c(I_{\bar{q}}, \omega' | \omega, \Delta)$  and  $g_c(\Delta' | \Delta, \omega, p, I_{\bar{q}})$  are the analogs of the consumer's transition kernels for  $q'$  and  $\Delta'$  in the original state space.  $\frac{\gamma\delta I_{\bar{q}}}{1-\beta}$  is the discounted value of one  $\delta$ -step of quality each period, which must be explicitly added when an improvement in frontier quality causes  $\tilde{\omega}'_j$  to drop by  $\delta$  even though  $\tilde{q}'$  is unchanged.

Firm  $j$ 's value function in equation (12) using the relative state space becomes

$$W_j(\omega_j, \omega_{-j}, \Delta) = \max_{p_j, x_j} \pi_j(p, \omega, \Delta) - x_j + \beta \sum_{\tau_j, \omega'_{-j}, I_{\bar{q}}, \Delta'} W_j(\omega_j + \tau_j - I_{\bar{q}}, \omega'_{-j} - I_{\bar{q}}, \Delta') \\ h_{f_j}(I_{\bar{q}}, \omega'_{-j} | \omega, \Delta) g_{f_j}(\Delta' | \Delta, \omega, p, I_{\bar{q}}) f(\tau_j | x_j, \omega), \quad (17)$$

where  $\omega'_{-j}$  refers to competitors' continuation qualities prior to shifting down by  $\delta$  in the event that the frontier's quality improved. Again, we slightly abuse notation by using  $h_{f_j}(I_{\bar{q}}, \omega'_{-j} | \omega, \Delta)$ ,  $f(\tau_j | x_j, \omega)$ , and  $g_{f_j}(\Delta' | \Delta, \omega, p, I_{\bar{q}})$  as the analogs of the firm's transition kernels for competitors' qualities and  $\Delta'$ .

Finally, we invoke a knowledge-spillover argument to bound the difference between each firm's quality and the frontier quality. We denote the maximal difference in firms' qualities  $\bar{\delta}_f$  and modify the transition kernels  $f(\cdot)$  and  $h_{f_j}(\cdot)$  accordingly. We choose  $\bar{\delta}_f < \bar{\delta}_c$  since, in most markets, quality differences among new products are less than the quality gap between the frontier and products from which consumers have yet to upgrade. We also choose  $\bar{\delta}_f$  to be sufficiently large that firms never reach the bound in equilibria computed during estimation. Note that if firms were permitted to exit, quality differences would be bounded automatically by the exiting of firms with sufficiently low relative quality.

Our bounding approach differs from the EP framework for differentiated products, as detailed in Pakes and McGuire (1994) and Doraszelski and Pakes (2007).<sup>14</sup> In EP, the industry's long-

<sup>14</sup>The standard normalization in discrete choice models subtracts the mean utility of the outside good from all options. EP, however, subtract the outside good's quality from firms' qualities inside a concave function. Concavity implies the derivative of market share with respect to a firm's own quality goes to zero regardless of competitors' qualities. Since investment is costly, a relative quality above which investment is zero will exist, thereby establishing an upper bound. Firms exit when relative quality gets sufficiently low, which establishes the lower bound.

run innovation rate is solely determined by the exogenous innovation rate of the outside good. Improvements in the outside good provide a continual need for inside firms to invest to remain competitive. If the outside good never improves, the equilibrium has no investment and no innovation in the long run. In our model, the long-run rate of innovation is an equilibrium outcome that depends on consumer preferences, firms' costs, and the regulatory environment.

In essence, EP defines quality relative to the outside good and generates an upper bound by manipulating the behavior of lead firms, whereas we define quality relative to the frontier and generate a lower bound by truncating the degree to which firms and outside options can be inferior. Since industry leaders generate most of the sales, profits, and surplus, assumptions regarding severe laggards are more innocuous than assumptions restricting the benefits to innovation by frontier firms.

### 3 Empirical Application

This paper has two components: a theory component that develops a dynamic model of durable goods competition and an empirical component that applies the model to the CPU industry. In the empirical application, we account for important asymmetries between Intel and AMD by allowing them to differ in their brand fixed-effects and costs of production and innovation. In section 4, we present comparative statics for the symmetric case in which firms have identical brand intercepts and innovation efficiencies, to illustrate broader implications of the model.

#### 3.1 Data

Using data from 1993 to 2004, we construct empirical moments for the PC processor industry. Our data consists of PC processor unit shipments, product quality measures, and manufacturer prices, which are close to retail prices due to PC manufacturers' low margins.<sup>15</sup> The quarterly global unit shipment data, average selling prices (ASP), and sales-weighted blended unit production costs are from In-Stat/MDR, an industry research firm that specializes in microprocessors. We use PC processor speed benchmarks from [www.cpuscorecard.com](http://www.cpuscorecard.com) and [www.cpubenchmark.net](http://www.cpubenchmark.net) to construct a single index of quality comparable across firms and product generations. No benchmark covers all processors, but we can splice them together since many processors have scores from multiple benchmarks. All prices and costs are converted to base year 2000 dollars.

Aggregate computer ownership and penetration rates come from the Homefront study created by Odyssey, a consumer research firm that specializes in technology products.<sup>16</sup> Survey respondents

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<sup>15</sup>The PC manufacturing sector is extremely competitive with margins below 5 %, low concentration, and low entry costs. In 2002, 30 % of PCs were sold by unbranded "white box" manufacturers (J. Spooner, "Dell Eyes 'White-Box' Market," CNET News, August 20, 2002).

<sup>16</sup>The firm conducts semi-annual telephone surveys using a nationally representative sample of 1500 to 2500 households. The households do not belong to a pre-chosen panel, and the firm draws a new sample for each wave of the study. The survey data is available neither at the household level nor in panel form. To increase the accuracy of the relevant sample, approximately 500 additional PC-owning households are oversampled.

report the processor speed and manufacturer of their primary or most recently purchased PC. These data allow us to construct semi-annual observations of the ownership distribution for consumers who have purchased at least one computer. Figure 1 illustrates the evolution of this distribution at the product-generation level (Intel 286, 386, 486, Pentium, Pentium II, Pentium III, and Pentium IV) over time for Intel microprocessors. AMD’s distribution looks similar. We interpolate these semi-annual distributions to obtain quarterly data that we combine with the quarterly penetration rate of PCs in U.S. households to obtain the ownership distribution across all consumers, including non-adopters. We assume consumers who have yet to purchase a PC derive utility from the outside good equivalent to a PC that is 7.8 percent the speed of the frontier. For comparison, the 80286 processor (three generations before the Pentium) is 8.6 percent the speed of the Pentium.

Our model restricts each firm to offer only one product. Since AMD and Intel offer multiple products each period, we use average prices and qualities. We observe the CPU-weighted average selling price (ASP) as tracked by industry analysts. Ideally we would use sales of each processor to construct the corresponding CPU-weighted quality, but we only observe shipment quantities at the die (i.e., microprocessor design) level. We equally allocate a die’s quarterly sales across all processors available with its design.<sup>17</sup> We use the die-level quantities as weights to construct our measure of average quality. The parameter estimates are similar using die-weighted average prices instead of ASP.

We plot each firm’s ASP and frontier CPU price in the top row of Figure 2. Because relatively few consumers are willing to pay the high premiums charged for frontier processors, ASPs are less volatile and much lower than frontier CPU prices.

The second plot in the middle row presents Intel’s quality advantage (i.e., log-quality relative to that of AMD). Intel’s initial advantage is moderate in 1993 to 1994, then becomes large as AMD failed to offer competition to Intel’s successful Pentium. AMD’s introduction of the K6 processor in 1997 narrows the gap, but parity is not achieved until sales of the AMD Athlon gained traction in mid-2000.

The covariation in Intel’s share of sales, its quality advantage, and its ASP is evident by comparing their plots, vertically arranged on the right-hand side of Figure 2. In the first few years of the sample, Intel’s share climbs from .74 to .95 as its ASP declines and its quality advantage grows. Over the latter half of the sample, Intel’s share and ASP both decline as AMD’s quality matches, and sometimes exceeds, Intel’s quality. Over the whole sample, the correlation between Intel’s ASP and its quality advantage is .66, and the correlation between AMD’s ASP and Intel’s advantage is  $-.34$ . The correlation between Intel’s share and its quality advantage is .39. These correlations are consistent with our model and help identify the structural parameters.

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<sup>17</sup>Our data set contains 247 processors spanning 30 die—10 for AMD and 20 for Intel. On average, each die has 8.2 processors with the slowest being 62 % the speed of the fastest. Most quarters have sales for two or three AMD dies and three or four Intel dies.

Although production costs of a given processor fall over time, more complicated chip designs lead to stationary unit costs, as depicted in the first plot of the middle row in Figure 2. The significant correlation of .48 between each firm’s unit costs and its quality relative to its competitor motivates the marginal cost specification in equation (11).

In the bottom row of Figure 2, we present histograms of innovations, measured as quarterly changes in each firm’s frontier and average log-quality. The mean quarterly innovation rate is 10.2 percent for Intel and 11 percent for AMD. Fewer than one-fifth of the quarters have innovations exceeding 20 percent (using either average or frontier qualities) and 21 percent of the quarters have no improvements in frontier quality. The stochastic process of innovation in our model, in which quality improves by either zero or 20 percent, is therefore a reasonable approximation.

Finally, quarterly R&D investment levels, obtained from firms’ annual reports, steadily rise over time. Interestingly, AMD invests less than one-fourth the amount Intel does yet is able to offer similar, sometimes even higher, quality products beginning in 1999. Spillovers partly explain this asymmetry since AMD is usually in the position of playing catch-up.

### 3.2 Estimation

We estimate the cost parameters  $\lambda = (\lambda_0, \lambda_1)$  in equation (11) in a first stage using linear regression, yielding  $\hat{\lambda}$ . To estimate the dynamic parameters  $\theta = (\gamma, \alpha, \xi_{Intel}, \xi_{AMD}, a_{0,Intel}, a_{0,AMD}, a_1)$ , we use a method of simulated moments (MSM) estimator that minimizes the distance between a set of unconditional moments of our data and their simulated counterparts from our model. Hall and Rust (2003) refer to this type of estimator as a simulated minimum distance (SMD) estimator because it minimizes a weighted distance between actual and simulated moments. One may also view the estimator as taking the indirect inference approach of Smith (1993), Gouriéroux, Monfort, and Renault (1993), and Gallant and Tauchen (1996) in which the moments to match are derived from an auxiliary model that is easier to evaluate than the structural model of interest. Regardless of the label used, the estimator is in the class of generalized method of moments (GMM) estimators introduced by Hansen (1982) and augmented with simulation by Pakes and Pollard (1989).

For each candidate value of the  $K$ -vector  $\theta$ , we solve for equilibrium and simulate the model  $S$  times for  $T$  periods each, starting at the initial state  $(\omega_0, \Delta_0)$  in the data. The simulated minimum distance estimator  $\hat{\theta}_T$ , which we detail in Appendix C, is

$$\hat{\theta}_T = \underset{\theta \in \Theta}{\operatorname{argmin}} (m_{S,T}(\theta; \hat{\lambda}) - m_T)' A_T (m_{S,T}(\theta; \hat{\lambda}) - m_T), \quad (18)$$

where  $m_T$  is the  $L$ -vector of observed moments,  $m_{S,T}(\theta)$  is the vector of simulated moments, and  $A_T$  is an  $L \times L$  positive definite weight matrix. We use enough simulations that the variance in the estimator is due entirely to the finite sample size. As such, the efficient weight matrix is the inverse of the covariance matrix of the actual data’s moments. We use 10,000 bootstrap replications

to estimate this covariance matrix. Since we obtain the efficient weight matrix directly from the data, we do not need a two-step GMM estimator to obtain efficiency.

A valid concern with using moments based on simulated equilibrium outcomes is that the equilibrium may not be unique. Two-stage approaches in which policy functions are first estimated nonparametrically, as in Bajari, Benkard, and Levin (2007), permit the model to have multiple equilibria. Their assumption that the data arise from the same equilibrium is weaker than our assumption that the model has a unique equilibrium. Unfortunately, we do not have sufficient data to use a two-stage approach, given the recent evidence of severe bias of two-stage estimators with small samples (Su and Judd, 2010). As discussed in section 2.3, we only consider equilibria that are limits of finite horizon games to reduce the concern of multiple equilibria.

### 3.2.1 Moments to Match

We match a combination of simple moments and coefficients from linear approximations to firms' policy functions. One difference between our model and the real world requires care when choosing moments to match. For stationarity, we assume market size  $M$  is fixed, whereas the data exhibit an upward trend in sales, revenues, and R&D expenditures. As such, we choose moments that are stationary in both the data and the model. For example, we match investment per unit revenue, which is stationary in the data, instead of the upward trending R&D.

Our moment vector,  $m_T$ , consists of the following 15 moments:

- average prices and the coefficients from regressing each firm's price on  $q_{Intel,t} - q_{AMD,t}$ , and  $q_{own,t} - \bar{\Delta}_t$ , where  $\bar{\Delta}_t = \sum_{k=q_t}^{\bar{q}_t} k \Delta_{kt}$  is the mean quality currently owned in period  $t$ ,
- coefficients from regressing Intel's share of sales on a constant and  $q_{Intel,t} - q_{AMD,t}$ ,
- mean  $(\bar{q}_t - \bar{\Delta}_t)$ , which captures the rate at which consumers upgrade: if consumers upgrade quickly, all else equal, the average difference between  $\bar{q}_t$  and  $\bar{\Delta}_t$  will be low.
- mean innovation rates for each firm, defined as  $\frac{1}{T}(q_T - q_0)/\delta$ ,
- mean  $(q_{Intel,t} - q_{AMD,t})$  and share of quarters with  $q_{Intel,t} \geq q_{AMD,t}$ , and
- mean investment per unit revenue for each firm.<sup>18</sup>

These moments and their fitted values appear in Table 1.

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<sup>18</sup>R&D and revenue data correspond to firm-wide activity. In the absence of R&D expenditures for different aspects of their businesses, we assume Intel and AMD invest in their business units proportional to the revenue generated by each unit. For both firms, microprocessors comprise the bulk of revenues. According to Intel's 2003 annual report, its microprocessor unit delivered 87 % of its consolidated net revenue.

### 3.2.2 Identification

Experimentation with the structural model indicates the moments we seek to match are sensitive to the structural parameters. Being a nonlinear model, all the structural parameters influence all the moments, though the connections between some parameters and moments are particularly apparent.

The demand-side parameters  $(\alpha, \gamma, \xi_{Intel}, \xi_{AMD})$  are primarily identified by the pricing moments, the Intel share equation moments, and the mean ownership quality relative to the frontier quality. The pricing moments respond sharply to changes in any of these four parameters. The market share equation is primarily sensitive to  $\gamma$  and  $\xi_{Intel} - \xi_{AMD}$ . The mean  $(\bar{q}_t - \hat{\Delta}_t)$  decreases if consumers upgrade more quickly and is akin to an outside share equation that identifies the levels of  $\xi$ . As such, we interpret  $\xi_{Intel}$  as a hassle cost of upgrading one’s computer and  $\xi_{Intel} - \xi_{AMD}$  as a brand effect.

The supply-side parameters  $(a_{0,Intel}, a_{0,AMD}, a_1)$ , which govern the investment process, are primarily identified by observed innovation rates, quality differences, and investment levels. The investment efficiencies are chosen such that the observed investment levels (per unit revenue) yield innovation at the observed rates. The spillover parameter  $a_1$  is chosen to match the mean difference in quality across firms—a high spillover keeps the qualities similar. In principle, one could estimate the innovation parameters in a first stage. Our 48 quarters of data, however, are insufficient for this approach due to the highly stochastic nature of innovation.

The ability of our estimator to recover consumer preferences and firms’ innovation parameters is important for our empirical strategy of identifying the effect of competition on innovation. We do not observe variation in the number of firms. Our conclusions regarding the effect of competition on innovation therefore rely on estimating the costs and benefits of innovation, as determined by the structural supply and demand-side parameters.

One could consider variation in firms’ relative qualities as a form of market structure variation and investigate its relationship with innovation. In our data, innovation since the previous quarter is positively related to that quarter’s difference in firms’ qualities. We do not use these moments, however, since the p-values are .12 and .18 for AMD and Intel, respectively. We note in our discussion of firms’ policy functions in section 3.3.1, however, that the innovation policies exhibit this same positive correlation.

### 3.2.3 Estimates

We use the simulated minimum distance estimator in section 3.2 to estimate the dynamic parameters  $\theta$  given the first-stage marginal cost estimates  $\hat{\lambda}$ . We first fix a few model-setup parameters. We set the log-quality grid size  $\delta$  to .1823, which corresponds to 20 percent improvements between grid points. We set  $\bar{\delta}_c$  to 5.287, which corresponds to a maximum of 29  $\delta$ -steps between consumers’  $\tilde{q}$  and the frontier. Our choice of  $\delta$  and  $\bar{\delta}_c$  reflects the following considerations: (i) the ability to replicate “Moore’s Law” when firms innovate in 40 to 60 percent of the periods, (ii) a sufficiently high  $\bar{\delta}_c$

that consumers rarely reach the lowest grid point before upgrading, and (iii) a computationally manageable number of grid points. We choose  $\bar{\delta}_f$  to be eight  $\delta$  steps, far exceeding the observed maximum quality difference of 5.2  $\delta$  steps. Since our quantity data are quarterly and firms' pricing and product releases are roughly quarterly, we assume each period is three months and set  $\beta$  to .975.

We set the market size  $M$  to 400 million consumers. Determining the appropriate market size is difficult because the CPU market is global and a significant share of demand comes from corporations. Our choice for  $M$  appears sensible in that the model's implied market capitalizations for Intel and AMD are similar to the observed values.

The market size for microprocessors is arguably growing over time as new computer applications are developed and as complimentary components (e.g., memory, hard-drives, and monitors) become better and cheaper. Market expansion corresponds to adding new consumers with vintage  $q$  and increasing  $M$  accordingly. Unfortunately, increasing  $M$  results in a non-stationarity that is computationally burdensome. We therefore adjust  $\Delta'$  to reflect the composition effect of market expansion by adding a mass of consumers, equal to 2.6 percent of  $M$ , to the lowest vintage in  $\Delta'$  and re-normalize to maintain a fixed  $M$ . This arrival rate matches the average quarterly growth from 1993 to 2003 in computer ownership by U.S. households according to the U.S. Census Current Population Survey (CPS) Computer Ownership Supplement. The high demand from a mass of consumers with  $\bar{q} = q$  in each period raises equilibrium prices and, since inducing upgrades becomes less critical for sustained demand, lowers innovation rates.

We report the model's fit in Table 1 and the parameter estimates in Table 2. The model fits the 15 moments reasonably well, despite having only seven parameters.<sup>19</sup>

Table 2 provides the structural estimates and their standard errors. All the parameters are statistically significant given the relatively small asymptotic standard errors. Dividing the estimated quality coefficient by the price coefficient implies consumers are willing to pay \$21 for a unit increase in log quality per period. A consumer would therefore be willing to pay \$51 for a 20 percent faster CPU she planned to use for four years ( $\delta\gamma(1 - \beta^{16})/[(1 - \beta)\alpha]$ ). Dividing Intel's fixed effect by the price coefficient implies upgrading to a new computer is associated with a hassle cost of \$48. Dividing  $\xi_{Intel} - \xi_{AMD}$  by the price coefficient implies consumers are willing to pay \$194 for the Intel brand over the AMD brand. The model needs this strong brand effect to explain the fact that AMD's share never rises above 22 percent in the period during which AMD had a faster product. Intel and AMD's innovation efficiencies are estimated to be .001 and .0019, respectively, as needed for AMD to occasionally be the technology leader while investing much less. Intel's price elasticity for current sales with respect to an unexpected one-period price change is 2.16, compared to 1.77 for AMD. These elasticities are lower than the range reported in Prince (2008) for PC purchases,

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<sup>19</sup>Since we have more moments than estimated parameters, we can formally test the model's specification as being that which generated the data. Structural models rarely pass such tests, since the real world is typically too complicated for a tractable model to mimic perfectly.

perhaps reflecting the importance of the CPU to the PC’s performance.

### 3.3 Empirical Results

We use the baseline parameter estimates to compare seven industry scenarios in Table 3: (1) AMD-Intel duopoly, (2) symmetric duopoly, (3) monopoly, (4) symmetric duopoly with no spillovers, (5) myopic pricing duopoly, (6) myopic pricing monopoly, and (7) social planner. Scenario 1 is the baseline model using all the estimates in column 1 of Table 2. Scenario 2 modifies the model by using Intel’s firm-specific values for both firms since AMD’s low  $\xi$  hampers its ability to compete. Scenario 3 uses Intel’s parameters for the monopolist. Scenario 4 illustrates the effect of innovation spillovers. Scenarios 5 and 6 highlight the importance of accounting for the dynamic nature of demand by computing equilibrium when firms price myopically by solving  $\frac{\partial \pi_j(p,q,\Delta)}{\partial p_j} = 0$  instead of the dynamic first-order condition in equation (13). Finally, scenario 7 considers the social planner who maximizes the sum of discounted profits and discounted consumer surplus. The planner sets prices and investment for two products, but the outcome is nearly identical to the case of one product since the planner quickly transitions to states with investment in only the frontier.

For each scenario, we solve for optimal policies and simulate 10,000 industries each for 300 periods, starting from the initial state in our data. We then analyze the simulated data to characterize the equilibrium behavior of firms and consumers and to identify observations of particular interest. Finally, we consider various counterfactual experiments to further illustrate the properties of this industry and its implications for policy analysis.

Our characterizations of equilibrium behavior in sections 3.3.1 and 3.3.2 instill confidence that the model yields sensible outcomes. We set apart particular findings of interest as “observations” in section 3.3.3.

#### 3.3.1 Firm Behavior in Equilibrium

Figure 3 presents value functions, pricing, innovation, market shares, and period profits for the monopoly and the symmetric duopoly. Figure 4 presents these equilibrium outcomes for the same monopoly and the symmetric duopoly without spillovers. We evaluate the duopoly without spillovers as a theoretical exercise to illustrate the properties of the model. We suspect most industries exhibit some degree of innovation spillovers and explore further how equilibrium outcomes vary with the spillover’s magnitude in section 4.

We present the symmetric duopoly case since differences between policies for the leader and laggard reflect only their quality differences, as opposed to reflecting changes in both quality differences and firm-specific parameters. In both figures, the x-axis in the first two columns of plots is the ownership distribution state variable  $\bar{\Delta}$ . Demand is high when consumers’ average quality  $\bar{\Delta}$  is low. Accordingly, value functions and prices both decline as  $\bar{\Delta}$  increases for the monopolist (in column

1) and the duopolists (in column 2). In the second column, outcomes are separately presented for the leader and laggard when their qualities differ by  $4\delta$  and for the firms when they are tied. As expected, values, prices, and market shares are highest for the leader and lowest for the laggard, with the tied firms in between.

In the third column of both figures, we fix  $\Delta$  at its most frequent value in simulations of the symmetric duopoly with spillovers and vary the leader’s quality advantage on the x-axis. The laggard is  $8\delta$  behind at the leftmost value and tied for the lead at the rightmost value. Accordingly, the leader’s value function, prices, and shares decline as its advantage shrinks, whereas the laggard’s value, prices, and shares increase as it catches up to the leader.

The value functions, prices, market shares, and period profits match our intuition. The outcome of greatest interest is the innovation rate. As the ownership distribution becomes newer, the monopolist slightly increases innovation, whereas the duopolists slightly decrease innovation, both with and without the spillover. In the duopoly, returns to investment are driven more by business stealing than by the building of future demand. The business-stealing motive is greater for duopolists when consumers are primed to upgrade, as indicated by a low  $\Delta$ .

Innovation by the  $4\delta$  leader and tied firms are much higher in Figure 4 without spillovers than in Figure 3 with spillovers. The reason is that without spillovers, the laggard struggles to catch up and indeed gives up completely once he falls behind by  $7\delta$ . Equilibrium is thus characterized by high innovation initially as firms battle to be the reigning leader, after which innovation drops to zero for the laggard and below .5 for the leader. The innovation plot in the last column of Figure 4 depicts this storyline. Without spillovers, the leader increases innovation as the laggard gains, peaking when the laggard is  $\delta$  behind. With spillovers, the leader decreases innovation as the laggard catches up and firms take turns being leaders. Losing the current battle does not permanently lower profits when spillovers enable a return to leadership, which reduces the incentive to fight. With spillovers, the difference in value functions between the leader and laggard is \$75 billion, compared to over \$300 billion without spillovers, despite the similar differences in period profits reported in the bottom row of each figure.

The differences in innovation policies with and without spillovers yield dramatically different distributions of states visited, as depicted by the histograms in the top rows of figures 3 and 4. Without spillovers, the firms tend to be at their maximal degree of differentiation; with spillovers, they tend to be tied or off by one step. The ownership distributions encountered also differ: consumers tend to own older vintages without spillovers since they upgrade less often in response to the leader’s higher prices (given its significant quality advantage).

The change in period profits when a firm’s relative quality changes by one step—the x-axis in the bottom-right panel—represents the immediate impact of innovation on a firm’s net cash flow. The substantial difference in innovation with and without spillovers, despite the similar immediate effect on profits, suggests innovation is driven primarily by long-run considerations.

### 3.3.2 Consumer Behavior in Equilibrium

In Figure 5 we plot the choice probabilities at each ownership vintage, averaged across states encountered in the AMD-Intel duopoly. The lower a consumer’s vintage relative to the frontier, the more likely she is to upgrade. As reported in Table 3, when consumers upgrade in the AMD-Intel duopoly, the average improvement in quality is 261 percent, compared to 410 percent in the monopoly.

As consumers implement their policy functions, they generate a sequence of ownership distributions across time. Figure 6 depicts the average ownership distributions for the AMD-Intel duopoly and the monopoly. Because monopolists charge higher prices, consumers are less likely to upgrade from a given vintage to the frontier in the monopoly case. In addition, consumers in the duopoly usually have an option to upgrade to a non-frontier product. Both of these forces cause the ownership distribution to be older in the monopoly. Figure 6 also reveals that consumers essentially never reach the lowest vintage. The assumed lower bound therefore has little effect on equilibrium behavior.

### 3.3.3 Observations Specific to the Microprocessor Industry

Having established the sensibility of consumers’ and firms’ policy functions, we now compare the estimated model with counterfactuals of particular interest for the microprocessor industry. Here we evaluate the model and counterfactuals at the parameter estimates, whereas in the next section we present comparative statics to more broadly assess the model’s implications for the effect of competition on outcomes across industries characterized by different consumer preferences, depreciation rates, and innovation spillovers.

We first assess the importance of accounting for the dynamic nature of demand by comparing outcomes when Intel and AMD correctly use the dynamic pricing first-order condition in equation (13) to the outcomes when they price myopically in scenarios 5 and 6.

**Observation 1.** *Margins, defined as  $(p - mc)/mc$ , and profits are significantly higher when firms correctly account for demand being dynamic. The differences are larger for monopoly than duopoly.*

In Table 3 monopoly profits are 76 percent higher and margins are 156 percent higher when the monopolist accounts for the dynamic nature of demand, compared to myopic pricing. Industry profits for the AMD-Intel duopoly are 28 percent higher and margins are 58 percent higher when firms account for the dynamic nature of demand, compared to myopic pricing. Accounting for dynamic demand is more important for the monopolist because competition is solely with itself, whereas the duopolists are primarily concerned with each other. Moreover, duopolists are less concerned about the effect of current pricing on future demand since future demand is a shared resource.

This result highlights the importance of accounting for dynamic demand when analyzing the pricing of durable goods. Standard practice in the empirical industrial organization and marketing

literatures is to observe prices and use first-order conditions from a static profit maximization to infer marginal costs. Observation 1 suggests marginal cost estimates computed in this manner for durable goods will be too high. Prices are high, in part, because firms want to preserve future demand, not only because marginal costs are high. Since the incentive to preserve future demand is increasing in market concentration, this over-estimation of costs will be greatest for concentrated markets.

In the next three observations, we compare market outcomes under alternative market structures for the microprocessor industry. The monopoly counterfactual corresponds to a world in which AMD never existed, not a world in which Intel merges with AMD, since no such merger would ever be pursued. As such, the monopolist sells and invests in one product, not two.

**Observation 2.** *Regarding the effect of competition on innovation in the CPU industry, we find*

- i. Innovation is 4.2 percent higher with a monopoly than with the AMD-Intel duopoly. The difference is more pronounced when comparing the monopoly to a symmetric duopoly pitting Intel against another Intel, with or without spillovers.*
- ii. Equilibrium investments for monopoly and duopoly market structures are below the socially optimal levels chosen by the planner.*
- iii. In the counterfactuals with firms pricing myopically, the AMD-Intel duopoly innovates more than monopoly.*

The average industry investment levels, reported in millions of dollars in Table 3, for the duopoly, monopoly, and social planner are, respectively, 830, 1672, and 6672 per period. The resulting innovation rate for the industry's frontier product is 0.599 for the duopoly, 0.624 for the monopoly, and 0.869 for the planner. The symmetric duopoly's innovation rate is only 0.501 because the intense price competition when Intel faces a copy of itself reduces investment returns.

The finding that innovation by a monopoly exceeds that of a duopoly reflects two features of the model: the monopoly must innovate to induce consumers to upgrade, and the monopoly is able to extract much of the potential surplus from these upgrades because of its substantial pricing power. If competition with itself were reduced by a steady flow of new consumers into the market, the monopoly would reduce innovation below that of the duopoly. We illustrate this result with a comparative static in the next section.

Observation 2.iii illustrates the importance of correctly accounting for the implications of durability when evaluating incentives to innovate, since the effect of competition on innovation is reversed when firms (or researchers) do not account for the dynamic nature of demand for durable goods.

The absence of technology spillovers in the monopoly is a potential factor in the monopolist's higher innovation compared to a duopoly in which firms mimic, to some degree, each other's innovations. As we report in Table 3, the innovation rate in the symmetric duopoly with no spillovers

(scenario 5) is actually lower than the innovation rate in the symmetric duopoly with spillovers (scenario 3). The direct effect of removing the spillover is to increase the incentive to innovate since innovations cannot be copied. The direct effect, however, is dominated by the equilibrium effect of one firm eventually dominating the industry, as evidenced by the innovation policies and histogram of  $q$  difference in Figure 4. The absence of a threat from the weak laggard, who eventually gives up and stops innovating, induces the leader to reduce investment. The presence of the laggard nonetheless keeps margins lower than in the monopoly. Thus, market power, not an absence of spillovers, provides the incentive for rapid innovation by the monopolist, compared to the duopolist. In the next section, we consider spillovers of varying degrees between the estimated level and no spillover.

Importantly, our model yields higher innovation with competition when evaluated using different values for price and quality preferences. As such, our model indeed lets the data speak on this fundamental question. In the next section, we present comparative statics to show that competition fosters higher innovation when consumers highly value quality and are relatively insensitive to price.

Of course, policymakers are more concerned with surplus and profits than with innovation *per se*. We compute firms' profits as the discounted sum of per-period profits and consumer surplus directly from the value functions as  $\frac{M}{\alpha} \sum_{\tilde{q}=q_t}^{\tilde{q}_t} \bar{V}(q_0, \Delta_0, \tilde{q}) \cdot \Delta_{\tilde{q},0}$ . We acknowledge that measuring consumer surplus for a product that has transformed our world on so many levels is an almost futile effort. As such, we focus on differences in surplus across scenarios rather than levels.

**Observation 3.** *Regarding the effect of competition on surplus, we find*

- i. The AMD-Intel duopoly generates 4.2 percent more consumer surplus than the monopoly.*
- ii. The AMD-Intel duopoly generates 1 percent less social surplus than the monopoly. The duopoly and monopoly generate 92.9 and 94 percent, respectively, of the planner's social surplus.*
- iii. Consumers' share of social surplus is 88 percent in the AMD-Intel duopoly, compared to 83.4 percent in the monopoly.*

Table 3 reports the aggregate discounted CS and industry profits for each of the scenarios we consider.<sup>20</sup> The AMD-Intel duopoly CS of \$2.98 trillion corresponds to \$298 billion per year, using an annual discount factor of .9. Although both the AMD-Intel and symmetric duopolies generate more CS than the monopoly, higher industry profits enable the monopolist to generate more social surplus than the duopolies.

As noted in observation 3.iii, CS comprises more than 83 percent of social surplus whether the industry is a monopoly or duopoly. Moreover, consumers are the primary benefactors of innovation opportunities, regardless of market structure, as evidenced by comparisons with (unreported) counterfactuals in which firms are barred from innovation. Monopoly profits are 2.6 percent higher with

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<sup>20</sup>The compounding effect of the monopoly's higher innovation rates implies the consumer surplus gain in duopoly relative to monopoly is larger the shorter the time horizon. Using the 48-quarter horizon of our data, the gain in CS when moving from the monopoly to the AMD-Intel duopoly is 7.1 %, instead of 4.2 % using 300 quarters.

innovation than without innovation, whereas CS in the monopoly is 64.2 percent higher with innovation. Duopoly profits are actually 13 percent lower with innovation, whereas CS in the duopoly is 65.7 percent higher with innovation.

To put the 4.2 percent CS gain due to competition from AMD in perspective, the CS gain from an increase in frontier quality by one  $\delta$ -step is \$55.4 billion.<sup>21</sup> The \$121 billion higher CS under duopoly, compared to monopoly, therefore equals the CS gain from 2.2 innovations, which is roughly one year’s worth of innovations (under either monopoly or duopoly). Again, we see that the difference in CS between duopoly and monopoly are small relative to the overall gains from innovation.

Recently Intel paid AMD \$1.25 billion to settle claims that Intel’s anti-competitive practices foreclosed AMD from many consumers. To study the effect of such practices on innovation and pricing, and ultimately consumer surplus and firms’ profits, we perform a series of counterfactual simulations in which we vary the portion of the market to which Intel has exclusive access. Let  $\zeta$  denote this portion. Period profits for  $j = \text{Intel}$  are then

$$\hat{\pi}_j(p, q, \Delta) = M [\zeta \hat{s}_j(p_j, q_j, \Delta) + (1 - \zeta) s_j(p, q, \Delta)] (p_j - mc_j(q)), \quad (19)$$

where  $\hat{s}_j(p_j, q_j, \Delta)$  is Intel’s market share in the sub-market in which it competes only with the outside good (i.e.,  $\Delta$ ). Note that Intel must set the same price in each sub-market and consumers are randomly assigned to each market each period.

**Observation 4.** *As AMD is excluded from an increasing portion of the market,*

- i. margins monotonically rise and innovation exhibits an innovated-U with a peak at  $\zeta = .5$ ,*
- ii. consumer surplus rises initially, peaking at  $\zeta = .4$ , then declines, eventually falling below the consumer surplus with no foreclosure.*

In Figure 7 we plot margins, innovation rates, consumer surplus, and social surplus when the foreclosed portion of the market varies from zero to one. Not surprisingly, share-weighted margins rise monotonically as AMD is increasingly barred from the market. Industry innovation peaks at 4.8 percent higher than the estimated AMD-Intel duopoly innovation rate when AMD is barred from half the market, but then drifts down to the 4.2 percent higher innovation of the monopoly. Consumer surplus is actually higher when AMD is barred from a portion of the market, peaking when the restriction is 50 percent. Although the CS gains are small, this finding highlights the importance of accounting for innovation in antitrust policy. The decrease in current-period consumer surplus from higher prices can be more than offset by higher innovation leading to higher future surplus.

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<sup>21</sup>We evaluate the gain in CS from Intel advancing when AMD is two steps behind and  $\Delta$  is at its most common value. The gains are less than the upper-bound  $M\delta\gamma/(\alpha(1 - \beta)) = \$61.5$  billion since not all consumers upgrade immediately to the improved product. The gain converges to \$61.5 billion as the  $\Delta$  distribution shifts to older vintages.

## 4 Comparative Statics

We present comparative statics in preferences for price and quality, depreciation of the good's quality, the magnitude of innovation spillovers, and product substitutability. In addition to being of interest themselves as characterizations of outcomes for a wide array of durable goods markets, these results serve to assess the robustness of our earlier findings specific to the microprocessor industry.

### 4.1 Comparative Static in Consumer Preferences

Our primary empirical result is that Intel would innovate more if it were not competing against AMD. We now illustrate in Figure 8 that the relationship between competition and innovation hinges on consumer preferences, which is consistent with Dorfman and Steiner (1954) and Lee (2005) who find that price and quality preferences primarily determine R&D intensity.

**Observation 5.** *Comparative statics in the quality and price coefficients,  $\gamma$  and  $\alpha$ , reveal*

- i. Innovation is increasing in  $\gamma$  and decreasing in  $\alpha$  for both monopoly and duopoly.*
- ii. The effect of competition on innovation is increasing in  $\gamma$  and decreasing in  $\alpha$ , except where both  $\gamma$  is low and  $\alpha$  is high, as Figure 8 depicts.*
- iii. Innovation is higher for the duopoly than the monopoly when  $\gamma$  is high and  $\alpha$  is low.*
- iv. Consumer surplus is higher for the monopoly than the duopoly when  $\gamma$  is low and  $\alpha$  is high. This result illustrates again that higher innovation in the monopoly can more than offset higher prices, yielding higher consumer surplus than obtained in the duopoly.*

We first note that our estimates of .2764 and .0131 for  $\gamma$  and  $\alpha$  in the microprocessor industry are far from the region of preferences for which competition increases innovation.

Part (i) is intuitive. As consumers are willing to pay more for quality, either due to a higher coefficient on quality or a lower coefficient on price, firms innovate more. We plot these monotonic relationships in the top two panels of Figure 8 for the duopoly and monopoly, respectively.

Part (ii) is less obvious. The higher slope of the duopoly in the top panel relative to the monopoly in the second panel implies the duopoly eventually innovates more than the monopoly as  $\gamma$  increases and  $\alpha$  falls, both of which increase consumers' willingness to pay for quality. But why is duopoly innovation more sensitive to preferences than is monopoly innovation? To gain insight, first express average industry innovation in the duopoly as a weighted average:

$$Pr(q_{1t} = q_{2t}) E [1 - (1 - f(\tau_1 = 1 | x_{1t}^*(q_t, \Delta_t)))^2] + \sum_{k=1}^{\delta_f} Pr(q_{2t} = q_{1t} - k) E [f(\tau_1 = 1 | x_{1t}^*(q_t, \Delta_t))], \quad (20)$$

where E integrates over  $\Delta$ ,  $Pr(\cdot)$  are the probability weights, and firms are ordered within each period such that  $q_{1t}$  is the frontier quality. The first term reflects the mechanical benefit of having

two firms: when firms are tied, innovation by either firm advances the frontier. By comparison, the average monopoly innovation rate is  $E[f(\tau_1 = 1|x_{1t}^*(\Delta_t))]$ . Differentiating these innovation rates with respect to  $\gamma$  (or similarly  $\alpha$ ) reveals that two factors contribute to innovation being more sensitive to preferences in the duopoly than in the monopoly: the effect of  $\gamma$  on firms' investment policies  $x^*(\cdot)$  and on which states are encountered (i.e., the probability weights). As detailed in Appendix D, both channels lead to the duopoly increasing innovation faster than the monopoly as  $\gamma$  increases (or, similarly, as  $\alpha$  decreases). Hence, innovation in the duopoly eventually exceeds innovation in the monopoly as consumers are willing to pay more for quality.

## 4.2 Comparative Static in Depreciation

Although quality does not depreciate in our empirical application to microprocessors, augmenting the model to accommodate depreciation is easy, as detailed in Appendix E. Figure 9 presents a comparative static relating depreciation and innovation.

**Observation 6.** *As depreciation increases,*

- i. Innovation declines in both the monopoly and the duopoly.*
- ii. Margins increase in both the monopoly and the duopoly.*
- iii. Consumer surplus declines in both the monopoly and the duopoly.*
- iv. Discounted profits increase in both the monopoly and the duopoly.*

Two forces affect equilibrium behavior when depreciation increases. First, the ownership distribution ages more quickly, which reduces the need for firms to innovate to induce upgrade purchases. Second, consumers expect to use each purchase over fewer periods (since they upgrade more quickly), which reduces the discounted utility derived from each purchase. These forces have opposing effects on prices, with the latter effect shifting the pricing policy function lower and the former effect lowering the  $\Delta$  values at which we evaluate the policy function. The higher prices from lowering  $\Delta$  dominates the shift in the pricing policy function, causing a moderate net increase in prices as depreciation increases. The margins plotted in Figure 9 reflect this rise.

In both the monopoly and duopoly, discounted lifetime profits increase by greater proportions than the margins increase since firms sell more units and investment costs decline. Consumer surplus falls in both the monopoly and duopoly, since consumers pay higher prices for goods that are less durable and of lower quality (since innovation declines).

One might expect duopoly innovation to decline by less than monopoly innovation as depreciation increases, since the monopolist faces competition only from the durability of its own products, whereas duopolists face competition from past units sold as well as each others' current offerings. The difference in discounted utility derived from competing offerings that differ in quality by one step, however, shrinks as the unit's expected time in use declines due to depreciation. This lower

difference implies a reduced competitive gain from innovation, which reduces the business-stealing incentive to innovate in the duopoly.

### 4.3 Comparative Static in the Market Growth Rate

**Observation 7.** *Innovation increases in the duopoly as  $M$  grows due to entry by new consumers, and does so at a faster rate than in the monopoly.*

We present the market growth comparative static in two steps since computing the equilibrium when the market grows each period is computationally impractical due to the resulting nonstationarity (see section 3.2.3). In the top panel of Figure 10, we increase the proportion of consumers who enter the market each period with  $\tilde{q} = \underline{q}$ , while renormalizing market size to keep  $M$  fixed. This reallocation of consumers to  $\underline{q}$  reduces competition from past sales (i.e.,  $\Delta$ ) in both monopoly and duopoly. Since competition from past sales is the monopolist's *only* competition, innovation in the monopoly decreases. Duopolists, on the other hand, are primarily concerned with competition from each other since their qualities tend to be closer to each other than to consumers' vintages. Duopolists therefore increase innovation in response to the increased demand from the reallocation.

In the lower panel, we present the comparative static for equilibrium innovation as  $M$  increases. Innovation increases faster in the duopoly than in the monopoly. Combining the two effects, innovation increases in the duopoly as  $M$  grows due to entry by new consumers, and does so at a faster rate than in the monopoly.<sup>22</sup> Hence, for sufficiently high market growth due to entry by new consumers, innovation is higher in the duopoly than in the monopoly.

Increasing the market growth rate is similar to increasing depreciation in that both cause the ownership distribution to age faster. Increasing the market growth rate, however, does not lower the expected utility derived over each purchase's useful life, as occurs with increased depreciation. The competitive gain from innovation, due to consumers deriving higher utility over many periods when purchasing the better of two products, is therefore not lowered by market growth.

### 4.4 Comparative Static in the Innovation Spillover

To investigate further the effect of spillovers, initially noted in our discussion of the policy plots in figures 3 and 4, we present, in Figure 11, symmetric-duopoly outcomes when the spillover effect varies from its estimated value (in the AMD-Intel duopoly) to no spillover.

**Observation 8.** *As the spillover declines from its estimated value to zero,*

- i. Innovation, consumer surplus, and social surplus steadily rise until the spillover is sufficiently*

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<sup>22</sup>Since the two components of market growth by entry of new consumers have opposing effects on monopoly innovation, the sign of the net effect in the monopoly is not obvious.

*small that a severely lagging firm concedes the market by ceasing to innovate. At this point, innovation plunges and both surplus measures decline.*

*ii. Margins and the difference in firms' qualities increase gradually at first and then sharply when the spillover is sufficiently small that the laggard concedes the market by ceasing to innovate.*

*iii. For moderate spillovers (30 % to 40 % of the estimated spillover), the duopoly has innovation, consumer surplus, and social surplus exceeding those in the monopoly.*

One might expect the surplus measures with no spillover to be lower than with the estimated spillover (of  $a_1 = 3.94$ ) since margins are 43 percent higher and innovation is 13 percent lower with no spillover. However, these measures are averages over the 300 periods simulated for each of the 10,000 simulated industries, and the no-spillover duopoly is initially a fierce battle to avoid being the losing firm that concedes the market. During this initial period, innovation is extremely high and margins are relatively low, since the firms have similar qualities. Hence the early periods, which receive greater weight in the discounted sum of utility flows, deliver substantial discounted surplus. That is, the surplus is heavily front-loaded in the no-spillover industry.

For comparison, the monopolist's values relative to the estimated-spillover symmetric duopoly are 2.34 for margins, .949 for consumer surplus, 1.004 for social surplus, and 1.246 for innovation. The peak duopoly innovation rate, when  $a_1$  is 40 percent of the estimated spillover, exceeds innovation in the monopoly by  $1.297/1.246 = 4.1$  percent. Consumer surplus and social surplus is maximized by the duopoly with 30 percent of the estimated spillover, yielding surplus gains relative to the monopolist of 20 percent and 10 percent, respectively.

Scott (1984) and Levin et al. (1985) find that differences in technological opportunity and appropriability conditions explain much of the variation in R&D intensity across industries. Since innovation spillovers reduce a firm's ability to appropriate profits from its innovations, Observation 8 supports their finding.

The inverted-U relationship between spillovers and innovation, combined with the monotonic relationship between spillovers and margins, implies an inverted-U relationship between margins and innovation. Thus innovation spillovers may be added to the list of possible structural causes for the inverted-U relationship between margins and innovation identified by Aghion et al. (2005).

## 4.5 Comparative Static in Product Substitutability

Product substitutability is governed by the variance of the idiosyncratic utility shock  $\varepsilon$ . As  $1/\text{var}(\varepsilon)$  approaches zero, firms enjoy local monopolies with no product substitutability. As  $1/\text{var}(\varepsilon)$  approaches infinity, products become perfect substitutes and the market has a "winner-take-all" flavor.

**Observation 9.** *Regarding the effect of product substitutability on innovation,*

- i. Innovation in the duopoly increases as substitutability increases, until  $\text{var}(\varepsilon)$  becomes too small for firms with similar qualities to coexist. Beyond this “shakeout” threshold, the laggard eventually concedes the market as evidenced by the sharp increase in the quality difference.*
- ii. Innovation in the monopoly exhibits an inverted-U as substitutability increases.*

Vives (1990) considers investments in product quality by duopolists facing logit demand and finds increased innovation with greater substitutability, which matches Observation 9.i until the shakeout threshold is reached. Vives (2008) shows R&D on cost-reducing technologies is unaffected by product substitutability in the logit model for nondurable goods.

#### 4.6 Relating to Aghion et al. (2005)

In the model of Aghion et al. (2005), a monopolist would never innovate. As such, they vary competition not by the number of firms, but by the degree to which duopolists collude when tied. As competition increases, due to less collusion, a firm with inferior technology decreases investment and firms at the same technology level increase investment. The former is the Schumpeterian effect since the lower profits in the tied state reduce the laggard’s incentive to innovate, whereas the latter effect is the “escape-the-competition” effect since each tied firm increases investment as the profit gap widens between a tied firm and a leader firm. When competition is low, the industry spends more time in the tied state since the laggard innovates rapidly, leading to a tied state, and tied firms innovate slowly. The escape-the-competition effect therefore dominates when competition is low, which causes an increase in competition to increase average industry innovation over time. When competition is high, the industry tends to be in the unlevel state, leading the Schumpeterian effect on laggard’s innovation to reduce average industry innovation when competition increases further.

Our model differs from Aghion et al. (2005) in many ways. Their firms invest to decrease costs of a nondurable good, whereas our firms invest to increase quality of a durable good. Their firms’ technology levels differ by at most one innovation step, whereas our firms can differ by multiple steps. Time is continuous in their model and industry profits depend only on technology differences, which implies leaders (and monopolists) never innovate. Industry profits in our model increase in the level of firms’ technologies, which implies monopolists and leaders may innovate.

To better relate to Aghion et al. (2005), we transform our model to use nondurable goods and consider a measure of competition more similar to their ability-to-collude measure: product substitutability as measured by the variance of the idiosyncratic utility shock  $\varepsilon$ .<sup>23</sup> More intense competition via greater product substitutability (i.e., lower variance of  $\varepsilon$ ) raises the profit gain when a tied firm

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<sup>23</sup>In the nondurable model, consumers are myopic and there is no ownership distribution. We also assume no outside good is available since constant industry revenue in Aghion et al. (2005) implies firms essentially compete only within an industry. For Figure 12, firms differ by no more than one quality step, though the results are qualitatively the same when greater differences are allowed.

becomes a leader, and reduces the profit gain when a laggard becomes tied for the lead. This pattern matches the effect of increased competition via less collusion. As illustrated in Figure 12, this nondurable version of our model yields Proposition 1 of Aghion et al. (2005), which states that innovation by the laggard decreases with greater competition, and innovation by the tied (neck-in-neck) firms increases. The declining share of periods in which firms are tied also matches their Proposition 4, which states that the expected technological gap between firms increases with competition. Our nondurable model, however, does not generate the inverted-U of their Proposition 2, since the leader in our model innovates faster as competition increases, whereas the leader in their model never innovates.

We apply this same measure of competition to our durable goods model and find that their Proposition 1 no longer holds: both the laggard and tied firms increase innovation when product market competition increases. Our analysis therefore shows that their Proposition 1 depends on whether the good is durable and their Proposition 4 depends on whether the leader invests.

## 5 Conclusion

In this paper, we estimate a dynamic model of durable goods oligopoly with endogenous innovation and use it to assess the effect of competition on innovation in the PC microprocessor industry. Consumers are better off under a duopoly due to lower margins: consumer surplus is higher with AMD competing against Intel than without. However, in support of Schumpeter’s hypothesis, industry innovation is higher with Intel as a monopolist than when it is competing with AMD.

Two forces drive innovation: competition between firms for the technological frontier and competition with the installed base to induce consumers to upgrade. Duopolists face both forces, whereas a monopolist only faces the latter. This latter effect highlights the importance of product durability, as the absence of depreciation necessitates innovation to induce upgrades. Another important distinction in durable goods markets is between replacement and first-time purchases. Market growth—the addition of potential first-time purchasers—can mitigate competition with the installed base. Rapid market growth reduces the innovation incentives for a monopolist because it can exploit demand from first-time buyers, leading the duopoly to innovate faster than the monopolist. Our finding that Intel would innovate more rapidly as a monopolist could be reversed if markets for microprocessors grew more rapidly.

We conduct several comparative statics to assess further the robustness of our findings and to explore our model’s implications. Our results demonstrate that the relationship between competition and innovation depends on consumer preferences and industry characteristics. In particular, innovation in the duopoly is more sensitive to preferences than in the monopoly, which implies increased innovation with competition when consumers highly value quality and have low price sensitivity.

We also show that R&D spillovers have an inverted-U relationship with industry innovation. High

spillovers limit the leader’s ability to retain his lead and insufficient spillovers lead the laggard to give up, both of which reduce the leader’s innovation. Moderate spillovers, however, strike a balance that enables both the laggard to “stay in the game” and the leader to appropriate gains from innovations.

To study microprocessors, we extend the framework of Ericson and Pakes (1995) to accommodate durable goods by including the ownership distribution as an endogenous state variable. The industry’s long-run innovation rate is endogenous in our model, whereas in EP the long-run innovation rate is determined by the exogenous rate of improvement in the outside good. Because innovation can have a larger effect on discounted surplus than does pricing, welfare-based policy analysis should use models with endogenous innovation.

Accounting for the durable nature of products in an equilibrium setting has important implications for firm and consumer behavior and market outcomes. We show that prices and innovation are lower when firms ignore the effect of current sales on future demand. Moreover, the predicted effect of competition from AMD on industry innovation is reversed if firms price myopically.

Extending our model to allow for endogenous product durability, as in Rust (1986) for a monopolist, would be interesting. The monotonic increase in duopoly profits as depreciation exogenously increases in Observation 6, combined with the observed near-perfect durability of AMD and Intel microprocessors, suggests a prisoner’s dilemma: firms would like the industry to sell less durable goods, but they cannot commit to doing so.

One of our goals is to demonstrate the value of structural empirical methods to investigate the effect of competition on innovation. We hope future work will adopt this approach to examine other industries in depth to complement insights from cross-sectional studies of this important issue.

## Appendix A: Solving and Simulating Industry Equilibrium

Besanko et al. (2010) and Borkovsky, Doraszelski, and Kryukov (2010) document the existence of multiple equilibria in dynamic oligopoly models based on Ericson and Pakes (2005). To reduce multiplicity, we focus on equilibria that are limits to finitely repeated games: we use backwards induction to solve for an equilibrium of the  $T$ -period game and then let  $T \rightarrow \infty$ . For each  $T$  and for each state, we solve the system of first-order conditions in equations (13) and (14). Our numerical algorithm for computing equilibrium to the infinite horizon game therefore corresponds to value function iteration with (a) initial values of  $\bar{V}^0 = 0$  and  $W^0 = 0$  and (b) equilibrium strategies being played within each state for each iteration, as opposed to merely playing best responses to strategies from the previous iteration.

Given  $f(\tau_j = 1|x, q) = a_j(q)x/(1+a_j(q)x)$ , we can simplify the investment first-order condition in equation (14) to

$$x_j - \left( \frac{a_j(q)}{1 - (\beta a_j(q)(EW^+(p_j) - EW^-(p_j)))^{-1/2}} - a_j(q) \right)^{-1} = 0, \quad (21)$$

where

$$EW^+(p_j) = \sum_{q'_{-j}, \Delta'} W_j(q_j + \delta, q'_{-j}, \Delta') h_{f_j}(q'_{-j}|q, \Delta) g_{f_j}(\Delta'|\Delta, q, p)$$

and

$$EW^-(p_j) = \sum_{q'_{-j}, \Delta'} W_j(q_j + 0, q'_{-j}, \Delta') h_{f_j}(q'_{-j}|q, \Delta) g_{f_j}(\Delta'|\Delta, q, p)$$

are the expected continuation values conditional on positive and negative innovation outcomes, respectively. The dependence of these expectations on  $p_j$  is through the effect of price on the ownership transition to  $\Delta'$ .

For each iteration  $k = 1, 2, \dots$ , we follow these steps:

1. Simultaneously solve firms' first-order conditions in equations (13) and (14) for  $\{x_j^*, p_j^*\}_{j=1}^J$  at each state given continuation values determined by  $W^{k-1}$  and  $\bar{V}^{k-1}$  for firms and consumers, respectively. Since the FOC depend on consumers' current choices which in turn depend on their rational expectations of  $\Delta'$ , for each conjectured  $\{x_j, p_j\}_{j=1}^J$  we solve for the fixed point in  $\Delta'$  such that consumers' expectations for  $\Delta'$  are realized. Denote  $\Delta'^*$  this fixed point when firms play  $\{x_j^*, p_j^*\}_{j=1}^J$ .
2. Let  $W^k$  equal the discounted payoffs given firms' current policies  $\{x_j^*, p_j^*\}_{j=1}^J$ , continuation ownership distribution  $\Delta'^*$ , and continuation values based on  $W^{k-1}$ .
3. For each consumer state, which adds  $\tilde{\omega}$  to the industry state vector, evaluate the consumer's smoothed value function  $\bar{V}^k$  given firms' current policies  $\{x_j^*, p_j^*\}_{j=1}^J$ , continuation ownership of  $\Delta'^*$ , and continuation values based on  $\bar{V}^{k-1}$ .
4. Check for convergence in the sup norms of  $|\bar{V}^k - \bar{V}^{k-1}|$  and  $|W^k - W^{k-1}|$  with a tolerance of 1e-10. If convergence is not achieved, return to step (1).

To simulate the converged model, we first specify an initial state for the industry  $(\omega_0, \Delta_0)$ . In our first quarter, AMD is 1.7  $\delta$ -steps behind Intel. Hence we start 70 percent of the simulations with AMD two steps behind Intel and 30 percent with AMD one step behind. Then for each simulated period  $t = 0, \dots, T$ , we implement each firm's optimal price and investment according to the equilibrium policy functions, process the evolution of ownership given consumers' equilibrium choice probabilities, and process the stochastic innovation outcomes according to  $f(\cdot|\cdot)$ .

A challenge in solving our model is that  $\Delta$  is a high-dimensional simplex. We approximate this continuous state variable with a discretization that restricts  $\Delta \in \{\Delta^d\}_{d=1}^D$ . Let  $\rho_d(\Delta')$  denote the distance between the exact continuation  $\Delta'$ , as implied by equations (8) and (9), and the  $d^{th}$  distribution of our discretization. Several candidate distance metrics are available: the Kullback-Leibler divergence measure, sum of squared errors of PDFs or CDFs, and the mean, among others. Since we are using the approximation to obtain firms' and consumers' continuation values, the distance metric should be based on moments of the distribution most relevant to future profitability, pricing, and investment. For logit demand systems the mean is the most relevant moment. Fixing consumers' conditional choice probabilities and firms' relative qualities, we generate random ownership distributions and regress the resulting profits on moments of the random  $\Delta$ s. The mean is easily the best predictor of a  $\Delta$ 's profitability, with an  $R^2$  of .995. We therefore define

$$\rho_d(\Delta'_{t+1}) = \left| \sum_k k \Delta'_{k,t+1} - \sum_k k \Delta_k^d \right|, \text{ for all } d \in (1, \dots, D), \quad (22)$$

where the summation is over the discrete qualities from  $\underline{q}$  to  $\bar{q}$  tracked by  $\Delta$ .

We generate  $\{\Delta^d\}_{d=1}^D$  using a distribution parameterized by a scalar and choose the scalar's discrete grid such that mean qualities are .25 apart and range from 9 to 29, relative to  $\bar{q}$  fixed at 30. We use the logit, which has CDF for the  $k^{th}$  quality level of  $z \exp(q_k)/(1 + z \exp(q_k))\kappa$ , where  $z$  is the scalar parameter and  $\kappa = z \exp(\bar{q})/(1 + z \exp(\bar{q}))$  is a normalization constant.

In computing equilibrium, we use a cubic spline to interpolate between  $\Delta$  grid points since solving the firms' first-order conditions requires differentiable continuation values. When simulating the model, rather than interpolating policy functions, we force  $\Delta$  to remain on the grid by randomizing  $\Delta_{t+1}$  to be one of

the two closest  $\Delta_d$ , with probabilities proportional to the distances between these closest  $\Delta_d$  and the exact continuation  $\Delta$ .

## Appendix B: Transforming to a Relative State-Space

*Proof of Proposition 1* : We prove the proposition for the case of a finite horizon, using backwards induction, since this approach enables us to impose rational expectations regarding future outcomes.

Consider the finite game with  $T$  periods in which a consumer starting at state  $(q_1, \Delta_1, \tilde{q}_1, \varepsilon_1)$  maximizes expected discounted utility

$$V^T(q_1, \Delta_1, \tilde{q}_1, \varepsilon_1) = \max_{\{y_t(q_t, \Delta_t, \tilde{q}_t, \varepsilon_t) \in (0, 1, \dots, J)\}_{t=1}^T} \mathbb{E} \left[ \sum_{t=1}^T \beta^t (\gamma q_{y_t, t} - \alpha p_{y_t, t} + \xi_{y_t} + \varepsilon_{y_t, t}) \right], \quad (23)$$

where  $q_{0,t} = \tilde{q}_t$  and  $p_{0,t} = 0$  in each period,  $y_t(q_t, \Delta_t, \tilde{q}_t, \varepsilon_t)$  is the consumer's policy function, and the expectation is taken with respect to information available at time  $t$ . In this game each firm  $j$  maximizes expected discounted net profits

$$W_j^T(q_{j1}, q_{-j,1}, \Delta_1) = \max_{\{p_{jt}(q_t, \Delta_t), x_{jt}(q_t, \Delta_t)\}_{t=1}^T} \mathbb{E} \left[ \sum_{t=1}^T \beta^t (M s_{jt}(p_t, q_t, \Delta_t)(p_{jt} - mc_j) - x_{jt}) \right], \quad (24)$$

where  $M$  is market size,  $s_{jt}(\cdot)$  is the market share for firm  $j$  as defined in equation (7),  $p_t$  is the vector of  $J$  prices,  $x_{jt}$  is investment by firm  $j$ , and  $mc_j$  is firm  $j$ 's constant marginal cost of production.

In period  $T$  firms and consumers play a standard static differentiated products game given the state of the industry as described by  $(q_T, \Delta_T)$ . Since consumers' utility functions are linear in the quality index, consumers' choices are insensitive to shifts in all qualities ( $q_t$  and  $\tilde{q}$ ) by some constant  $\hat{q}$ . The market share function therefore satisfies  $s_{jt}(p_t, q_t, \Delta_t) = s_{jt}(p_t, q_t - \hat{q}, \Delta_t)$ , which implies firms' prices are insensitive to shifts in all qualities. The period  $T$  value functions  $V^T$  and  $W^T$  therefore satisfy

$$\begin{aligned} \text{Firms: } W_j^T(q_{jt}, q_{-j,t}, \Delta_t) &= W_j^T(q_{jt} - \hat{q}, q_{-j,t} - \hat{q}, \Delta_t) \\ \text{Consumers: } V^T(q_t, \Delta_t, \tilde{q}_t, \varepsilon_t) &= \gamma \hat{q} + V^T(q_t - \hat{q}, \Delta_t, \tilde{q}_t - \hat{q}, \varepsilon_t). \end{aligned} \quad (25)$$

Note that each consumer's utility shifts by  $\gamma \hat{q}$  when all qualities shift by  $\hat{q}$ .

Now consider equilibrium outcomes in period  $T-1$  taking as given the period  $T$  equilibrium payoffs. Each consumer solves

$$\begin{aligned} V^{T-1}(q_{T-1}, \Delta_{T-1}, \tilde{q}_{T-1}, \varepsilon_{T-1}) &= \max_{y \in (0, 1, \dots, J)} \gamma q_{y, T-1} - \alpha p_{y, T-1} + \xi_y + \varepsilon_{y, T-1} \\ &+ \beta \sum_{q_T \varepsilon_T} \int V^T(q_T, \Delta_T, \tilde{q}_T, \varepsilon_T) dF_\varepsilon(\varepsilon_T) \\ &\prod_{j=1}^J f(q_{jT} - q_{j, T-1} | x_{j, T-1}, q_{T-1}), \end{aligned} \quad (26)$$

where  $\tilde{q}_T = \max(q_{y, T-1}, \bar{q}_T - \delta_c)$  is the transition of  $\tilde{q}$  accounting for the maximum allowed difference between the frontier product's quality  $\bar{q}_T$  and each consumer's  $\tilde{q}$ , and the deterministic transition to  $\Delta_T$  is based on consumers' choices, as detailed in equation (8). Since each consumer is small relative to  $M$ , her actions do not affect the transition of  $\Delta$ .

Each firm  $j$  solves

$$\begin{aligned} W_j^{T-1}(q_{j, T-1}, q_{-j, T-1}, \Delta_{T-1}) &= \max_{\substack{p_{j, T-1} \\ x_{j, T-1}}} M s_{j, T-1}(p_{T-1}, q_{T-1}, \Delta_{T-1})(p_{j, T-1} - mc_j) - x_{j, T-1} \\ &+ \beta \sum_{q_T} W_j^T(q_{j, T}, q_{-j, T}, \Delta_T) \prod_{j=1}^J f(q_{jT} - q_{j, T-1} | x_{j, T-1}, q_{T-1}). \end{aligned} \quad (27)$$

In these equations defining  $V^{T-1}$  and  $W^{T-1}$ , the products' future qualities are uncertain. Rational expectations regarding this uncertainty are achieved by using the firm's investments in period  $T-1$  to determine the distribution of  $q_T$ . Recall that  $f(\cdot|x_{jt}, q_t)$  is the probability distribution of  $j$ 's investment outcome, which is restricted to be either no improvement in quality or improvement by one  $\delta$ -step.

Now consider these same maximizations at a state with all qualities shifted by  $\hat{q}$ :

$$\begin{aligned}
V^{T-1}(q_{T-1} - \hat{q}, \Delta_{T-1}, \tilde{q}_{T-1} - \hat{q}, \varepsilon_{T-1}) &= \max_{y \in (0,1,\dots,J)} \gamma(q_{y,T-1} - \hat{q}) - \alpha p_{y,T-1} + \xi_y + \varepsilon_{y,T-1} \\
&+ \beta \sum_{q_T \varepsilon_T} \int V^T(q_T - \hat{q}, \Delta_T, \tilde{q}_T - \hat{q}, \varepsilon_T) dF_\varepsilon(\varepsilon_T) \\
&\prod_{j=1}^J f(q_{jT} - \hat{q} - (q_{j,T-1} - \hat{q})|x_{j,T-1}, q_{T-1} - \hat{q})
\end{aligned} \tag{28}$$

and

$$\begin{aligned}
W_j^{T-1}(q_{j,T-1} - \hat{q}, q_{-j,T-1} - \hat{q}, \Delta_{T-1}) &= \max_{\substack{p_{j,T-1} \\ x_{j,T-1}}} M s_{j,T-1}(p_{T-1}, q_{T-1} - \hat{q}, \Delta_{T-1})(p_{j,T-1} - mc_j) \\
&- x_{j,T-1} + \beta \sum_{q_T} W_j^T(q_{j,T} - \hat{q}, q_{-j,T} - \hat{q}, \Delta_T) \\
&\prod_{j=1}^J f(q_{jT} - \hat{q} - (q_{j,T-1} - \hat{q})|x_{j,T-1}, q_{T-1} - \hat{q}).
\end{aligned} \tag{29}$$

Substitute the right-hand sides of (25) into (29) and (28). Then note that  $f(q_{jT} - \hat{q} - (q_{j,T-1} - \hat{q})|x_{j,T-1}, q_{T-1} - \hat{q}) = f(q_{jT} - q_{j,T-1}|x_{j,T-1}, q_{T-1})$  by algebra and the assumption that the spillover aspect of investment outcomes depends on quality differences between the investing firm and the frontier product. As such, firms' investment choices are unaffected by the  $\hat{q}$  shift. Consumers' and firms' discounted continuation values are therefore insensitive to the  $\hat{q}$  shift. Since current flow utility is insensitive to the quality shift (by linearity), consumers' period  $T-1$  choices (i.e.,  $s_{j,T-1}$ ) must be insensitive to the shift, which further implies firms'  $T-1$  prices are insensitive to the shift. Implementing these equivalences converts (29) into (27), exactly, and converts (28) into (26), except for a  $-(\gamma\hat{q} + \beta\gamma\hat{q})$  term that does not affect the consumer's choice. The modified (28) is

$$\begin{aligned}
V^{T-1}(q_{T-1} - \hat{q}, \Delta_{T-1}, \tilde{q}_{T-1} - \hat{q}, \varepsilon_{T-1}) &= \max_{y \in (0,1,\dots,J)} \gamma(q_{y,T-1} - \hat{q}) - \alpha p_{y,T-1} + \xi_y + \varepsilon_{y,T-1} \\
&+ \beta \sum_{q_T \varepsilon_T} \int (-\gamma\hat{q} + V^T(q_T, \Delta_T, \tilde{q}_T, \varepsilon_T)) dF_\varepsilon(\varepsilon_T) \\
&\prod_{j=1}^J f(q_{jT} - q_{j,T-1}|x_{j,T-1}, q_{T-1}).
\end{aligned} \tag{30}$$

By induction, the optimal consumer policies  $y_t(q_t, \Delta_t, \tilde{q}_t, \varepsilon_t)$  and firm policies  $p_t(q_{jt}, q_{-jt}, \Delta_t)$  and  $x_t(q_{jt}, q_{-jt}, \Delta_t)$  are insensitive to shifts in all qualities for all  $t$ . The firm's value functions  $W^t$  are also insensitive to  $\hat{q}$  shifts and the consumers' value function  $V^t$  is shifted by  $\gamma\hat{q} \sum_{t'=0}^{T-t} \beta^{t'}$ .

To complete the proof, choose  $\hat{q} = \bar{q}_t$ , the quality of the frontier product in period  $t$ . □

## Appendix C: A Simulated Minimum Distance Estimator

Our presentation of the assumptions and details of our estimator follows Hall and Rust (2003). The model presented in section 2 generates a stochastic process for  $\mu_t = \{\omega_t, \Delta_t, p_t, x_t, s_t\}$ , where  $\omega$  denotes qualities relative to the frontier,  $\Delta$  is the ownership distribution,  $p$  denotes prices,  $x$  denotes investments, and  $s$  denotes

market shares. The transition density,  $f_\mu$ , for this Markov process is given by

$$\begin{aligned}
f_\mu(\omega_{t+1}, \Delta_{t+1}, p_{t+1}, x_{t+1}, s_{t+1} | \omega_t, \Delta_t, p_t, x_t, s_t, \theta) &= \prod_{j=1}^J f(\omega_{j,t+1} - \omega_{j,t} | \omega_t, x_t) \\
&\times g(\Delta_{t+1} | \Delta_t, s_t) \\
&\times I\{p_{t+1} = p(\omega_{t+1}, \Delta_{t+1})\} \\
&\times I\{x_{t+1} = x(\omega_{t+1}, \Delta_{t+1})\} \\
&\times I\{s_{t+1} = s(\omega_{t+1}, \Delta_{t+1})\},
\end{aligned} \tag{31}$$

where  $\theta$  denotes the vector of  $K$  parameters to be estimated. Note that  $f_\mu$  is degenerate since prices, investments, and market shares are deterministic functions of the state variables  $\omega_{t+1}$  and  $\Delta_{t+1}$ . The model would need to be modified, perhaps by adding aggregate shocks, if we were to use maximum likelihood since the data would almost surely contain observations having zero likelihood. This degeneracy, however, is not a problem for the SMD estimator we define below because it is based on predicting moments of the distribution  $\mu_t$ , not particular realizations of  $\mu_t$  given  $\mu_{t-1}$ .

For each candidate value of  $\theta$  encountered, we solve for equilibrium and simulate the model  $S$  times for  $T$  periods each, starting at the initial state  $(\omega_0, \Delta_0)$ , which we observe in the data. These  $S \times T$  simulated periods each have three stochastic outcomes—each firm's investment outcome and the random transition of  $\Delta_t$ . The set of i.i.d.  $U(0,1)$  draws for these outcomes, denoted  $\{\{U_t^n\}_{t=1}^T\}_{n=1}^S$ , is held fixed throughout the estimation procedure to preserve continuity of the estimator's objective function. The set of simulated industry outcomes is denoted  $\{\{\mu_t(\theta, U_{<t}^n, \omega_0, \Delta_0)\}_{t=1}^T\}_{n=1}^S$ , where the subscript in  $U_{<t}^n$  indicates  $\mu_t^n$  depends on only the first  $t-1$  realizations of  $U^n$ .

The vector of moments using actual data is denoted  $m_T \equiv m(\{\mu_t^{actual}\}_{t=1}^T)$  and the simulated moment vector is the average over the  $S$  simulations:

$$m_{S,T}(\theta) = \frac{1}{S} \sum_{n=1}^S m(\{\mu_t(\theta, U_{<t}^n, \omega_0, \Delta_0)\}_{t=1}^T), \tag{32}$$

where the initial state  $(\omega_0, \Delta_0)$  corresponds to the first quarter of our data.

The simulated minimum distance estimator  $\hat{\theta}_T$  is then defined as

$$\hat{\theta}_T = \underset{\theta \in \Theta}{\operatorname{argmin}} (m_{S,T}(\theta) - m_T)' A_T (m_{S,T}(\theta) - m_T), \tag{33}$$

where  $A_T$  is an  $L \times L$  positive definite weight matrix.

We make the following assumptions.

**Assumption 1.** For any  $\theta \in \Theta$  the process  $\{\mu_t(\theta, U_{<t}^n, \omega_0, \Delta_0)\}$  is ergodic with unique invariant density  $\Psi(\mu|\theta)$  given by

$$\Psi(\mu'|\theta) = \int f_\mu(\mu'|\mu, \theta) d\Psi(\mu|\theta). \tag{34}$$

**Assumption 2.** The structural model presented in section 2 is correctly specified. As such, a  $\theta^* \in \Theta$  exists for which each simulated sequence  $\{\mu_t^n\}, n = 1, \dots, S$  from the initial state  $(\omega_0, \Delta_0)$  has the same probability distribution as the observed sequence  $\{\mu_t\}$ .

This assumption enables us to use the standard GMM formula for the asymptotic covariance matrix of  $\hat{\theta}_T$ . We could alternatively relax this assumption and bootstrap the covariance matrix.

Define the functions  $E[m|\theta]$ ,  $\nabla E[m|\theta]$ , and  $\nabla m_{S,T}$  as

$$\begin{aligned} E[m|\theta] &= \int m(\mu) d\Psi(\mu|\theta) \\ \nabla E[m|\theta] &= \frac{\partial}{\partial \theta} E[m|\theta] \\ \nabla m_{S,T} &= \frac{\partial}{\partial \theta} m_{S,T}(\theta). \end{aligned} \tag{35}$$

**Assumption 3.**  $\theta^*$  is identified; that is, if  $\theta \neq \theta^*$  then  $E[m|\theta] \neq E[m|\theta^*] = E[m(\{\mu_t^{actual}\}_{t=1}^T)]$ . In addition,  $\text{rank}(\nabla E[m|\theta]) = K$  and  $\lim_{T \rightarrow \infty} A_T = A$  with probability 1, where  $A$  is an  $L \times L$  positive definite matrix.

The optimal weight matrix is  $\Omega(m, \theta^*)^{-1} \equiv E[(m(\mu) - E[m(\mu)])(m(\mu) - E[m(\mu)])']^{-1}$ , the inverse of the covariance matrix of the moment vector, where the expectation is taken with respect to the ergodic distribution of  $\mu$  given  $\theta = \theta^*$ . Using  $A_T = [\text{cov}(\{\mu_t^{actual}\}_{t=1}^T)]^{-1}$  as a consistent estimate of the optimal weight matrix, the estimator  $\hat{\theta}_T$  has the property

$$\sqrt{T}(\hat{\theta}_T - \theta^*) \implies N\left(0, (1 + 1/S) (\nabla E[m|\theta^*]' \Omega(m, \theta^*)^{-1} \nabla E[m|\theta^*])^{-1}\right). \tag{36}$$

We choose  $S$  to be sufficiently high (10,000) that simulation error has a negligible effect.

## Appendix D: Decomposing the Effect of the Quality Coefficient on Industry Innovation

As discussed in Observation 5, two factors contribute to innovation being more sensitive to preferences ( $\gamma$ ) in the duopoly than in the monopoly: the effect of  $\gamma$  on firms' investment policies  $x^*(\cdot)$  and on which states are encountered.

To evaluate the effect of  $\gamma$  on firms' investment policies, we condition on typical  $\Delta$  values for the monopoly and duopoly and, in Figure 14, plot the effect of  $\gamma$  on firms' investment levels and innovation rates, the marginal effect of investment on the probability of an innovation ( $\frac{\partial f(x^*)}{\partial x}$ ), the marginal effect of  $\gamma$  on investment ( $\frac{\partial x^*}{\partial \gamma}$ ), and the marginal effect of  $\gamma$  on innovation ( $\frac{\partial f(x^*)}{\partial \gamma} = \frac{\partial f(x^*)}{\partial x} \frac{\partial x^*}{\partial \gamma}$ ). This last marginal effect, plotted in panel 6, is higher for the leader and for each tied firm than for the monopolist, and is much higher for *either* tied firm innovating. Hence changes in innovation policy functions contribute to the industry innovation increasing more in the duopoly than in the monopoly as  $\gamma$  increases. Interestingly, for low  $\gamma$ , the monopolist's investment is more sensitive to  $\gamma$  than duopolists' investments, but the marginal effect of investment on innovation is sufficiently higher for the duopolists that the ultimate effect on innovation is greater in the duopoly.

The effect of  $\gamma$  on industry innovation through investment policies  $x^*(\cdot)$ , however, can potentially be mitigated by the equilibrium transiting to states with lower duopoly innovation or higher monopoly innovation. Quality preferences can effect the evolution of two state variables: the ownership distribution  $\Delta$  and, in the duopoly, the quality difference  $q_{1t} - q_{2t}$ . The effect of  $\gamma$  on realized ownership distributions is small and has little impact on innovation in both the duopoly and monopoly since firms' innovation policies are relatively insensitive to  $\Delta$ , as illustrated by the innovation policies in panels 7 and 8 of Figure 3. The quality difference in panel 5 of Figure 14, however, widens as  $\gamma$  increases, which has two distinct effects on innovation. First, the leader innovates more with a wider lead, as illustrated by the innovation policy in panel 9 of Figure 3. Second, the share of periods with tied firms declines. Since the frontier advances when *either* tied firm innovates, one might expect this factor to put downward pressure on innovation as  $\gamma$  increases. However, as seen in panel 1 of Figure 14, the gap between the probability of either tied firm innovating and an individual tied firm innovating increases in  $\gamma$ . This larger gap offsets the lower probability of being tied, as revealed by the nearly flat product of the gap and the probability in panel 5. The net effect of  $\gamma$ 's influence on states encountered is therefore the positive effect of higher innovation by the duopoly leader as the quality difference widens.

## Appendix E: Adding Depreciation to the Model

To allow for physical depreciation of the durable good, as needed for Observation 6, we modify the transition kernels for  $\Delta$  and  $\tilde{q}$ . Let  $\phi$  denote the probability that each consumer's  $\tilde{q}_t$  declines by one  $\delta$ -step. The post-depreciation ownership share for each vintage  $k$  in  $\Delta'$  is then

$$\Delta'_k = \begin{cases} \Delta'_k(\Delta, q, p) + \phi \Delta'_{k+\delta}(\Delta, q, p) & \text{if } q_k = \underline{q}' \\ (1 - \phi) \Delta'_k(\Delta, q, p) + \phi \Delta'_{k+\delta}(\Delta, q, p) & \text{if } \underline{q}' < q_k < \bar{q}' \\ (1 - \phi) \Delta'_k(\Delta, q, p) & \text{if } q_k = \bar{q}' \end{cases} \quad (37)$$

where  $\Delta'(\cdot)$  is given in equation (9), the first line enforces the lower bound for  $\tilde{q}'$ , and the third line acknowledges that the frontier does not gain mass from a higher vintage. The consumer's continuation values in equations (3), (4), and (5) must also integrate over the realization of this stochastic depreciation for the consumer's  $\tilde{q}'$ .

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**Table 1:** Empirical and Simulated Moments

Moment	Actual	Fitted	Actual SE
Intel Price Equation:			
Average Intel Price	219.7	206.2	5.9
$q_{Intel,t} - q_{AMD,t}$	47.4	27.3	17.6
$q_{Intel,t} - \bar{\Delta}_t$	94.4	43.0	31.6
AMD Price Equation:			
Average AMD Price	100.4	122.9	2.3
$q_{Intel,t} - q_{AMD,t}$	-8.7	-22.3	11.5
$q_{AMD,t} - \bar{\Delta}_t$	16.6	5.9	15.4
Intel Share Equation:			
constant	0.834	0.846	0.007
$q_{Intel,t} - q_{AMD,t}$	0.055	0.092	0.013
Potential Upgrade Gains:			
Mean $(\bar{q}_t - \bar{\Delta}_t)$	1.146	1.100	0.056
Mean Innovation Rates:			
Intel	0.557	0.597	0.047
AMD	0.610	0.602	0.079
Relative Qualities:			
Mean $q_{Intel,t} - q_{AMD,t}$	1.257	1.352	0.239
Mean $\mathcal{I}(q_{Intel,t} \geq q_{AMD,t})$	0.833	0.929	0.054
Mean R&D / Revenue:			
Intel	0.114	0.101	0.004
AMD	0.203	0.223	0.009

Simulated moments are averages over 10,000 simulations of 48 quarters of data.

**Table 2:** Parameter Estimates

Parameter	Estimate	Std. Error
Price, $\alpha$	0.0131	0.0017
Quality, $\gamma$	0.2764	0.0298
Intel Fixed Effect, $\xi_{Intel}$	-0.6281	0.02314
AMD Fixed Effect, $\xi_{AMD}$	-3.1700	0.0790
Intel Innov, $a_{0,Intel}$	0.0010	0.00022
AMD Innov, $a_{0,AMD}$	0.0019	0.0002
Spillover, $a_1$	3.9373	0.1453
Stage-1 Marginal Cost Equation		
Constant, $\lambda_0$	44.5133	1.1113
$\max(0, q_{competitor,t} - q_{own,t}), \lambda_1$	-19.6669	4.1591

**Table 3:** Industry Measures under Various Scenarios

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	AMD-Intel	Symmetric		No Spillover	Myopic Pricing		Social
	Duopoly	Duopoly	Monopoly	Duopoly	AMD-Intel	Monopoly	Planner
Industry Profits (\$billions)	408	400	567	382	318	322	-267
Consumer Surplus	2978	3012	2857	3068	2800	2762	4032
Social Surplus	3386	3412	3424	3450	3118	3084	3765
CS as Share of Monopoly CS	1.042	1.054	1.000	1.074	0.980	0.967	1.411
SS as Share of Monopoly SS	0.989	0.997	1.000	1.007	0.911	0.901	1.100
SS as Share of Planner SS	0.929	0.906	0.940	0.916	0.828	0.819	1
Margins	3.434	2.424	5.672	3.478	2.176	2.216	0.000
Price	194.17	146.73	296.98	157.63	140.06	143.16	43.57
Frontier Innovation Rate	0.599	0.501	0.624	0.438	0.447	0.438	0.869
Industry Investment (\$millions)	830	652	1672	486	456	787	6672
Mean Quality Upgrade %	261	148	410	187	175	181	97
Intel or Leader Share	0.164	0.135	0.143	0.160	0.203	0.211	0.346
AMD or Laggard Share	0.024	0.125		0.091	0.016		0.014

Reported values are based on 10,000 simulations of 300 periods each. Profits, surplus, and investments are reported in billions of dollars. Profits and surplus are discounted back to period 0. Social surplus is the sum of consumer surplus and industry profits. Symmetric duopoly uses Intel’s firm-specific parameters for both firms. Under “myopic pricing” firms choose price ignoring its effect on future demand. The “no spillover” duopoly uses symmetric firms, both with Intel’s parameters. The social planner offers two products. The monopolist offers one product. Margins are computed as  $(p - mc)/mc$ . Price and margins are share-weighted averages. In the symmetric duopoly, both firms have Intel’s  $\xi_j$  and  $a_{0,j}$ . The social planner sells two products, but the results are nearly identical for a single-product planner.

Figure 1: Ownership Distribution of Intel CPUs

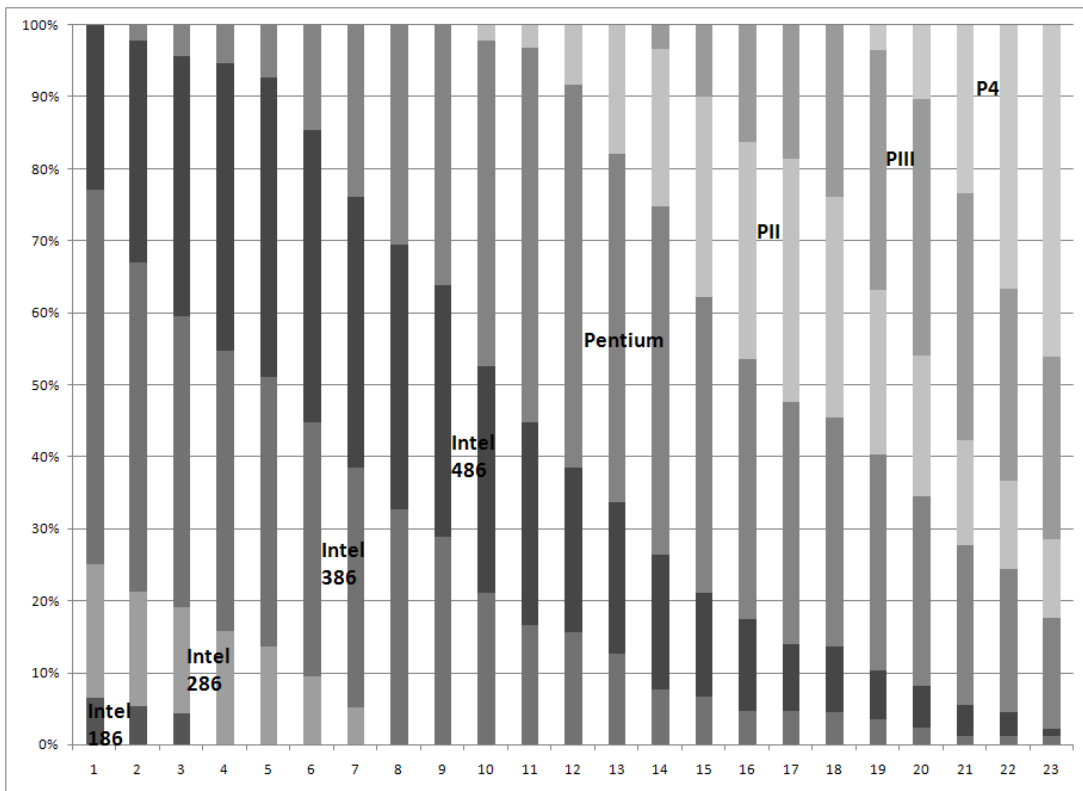
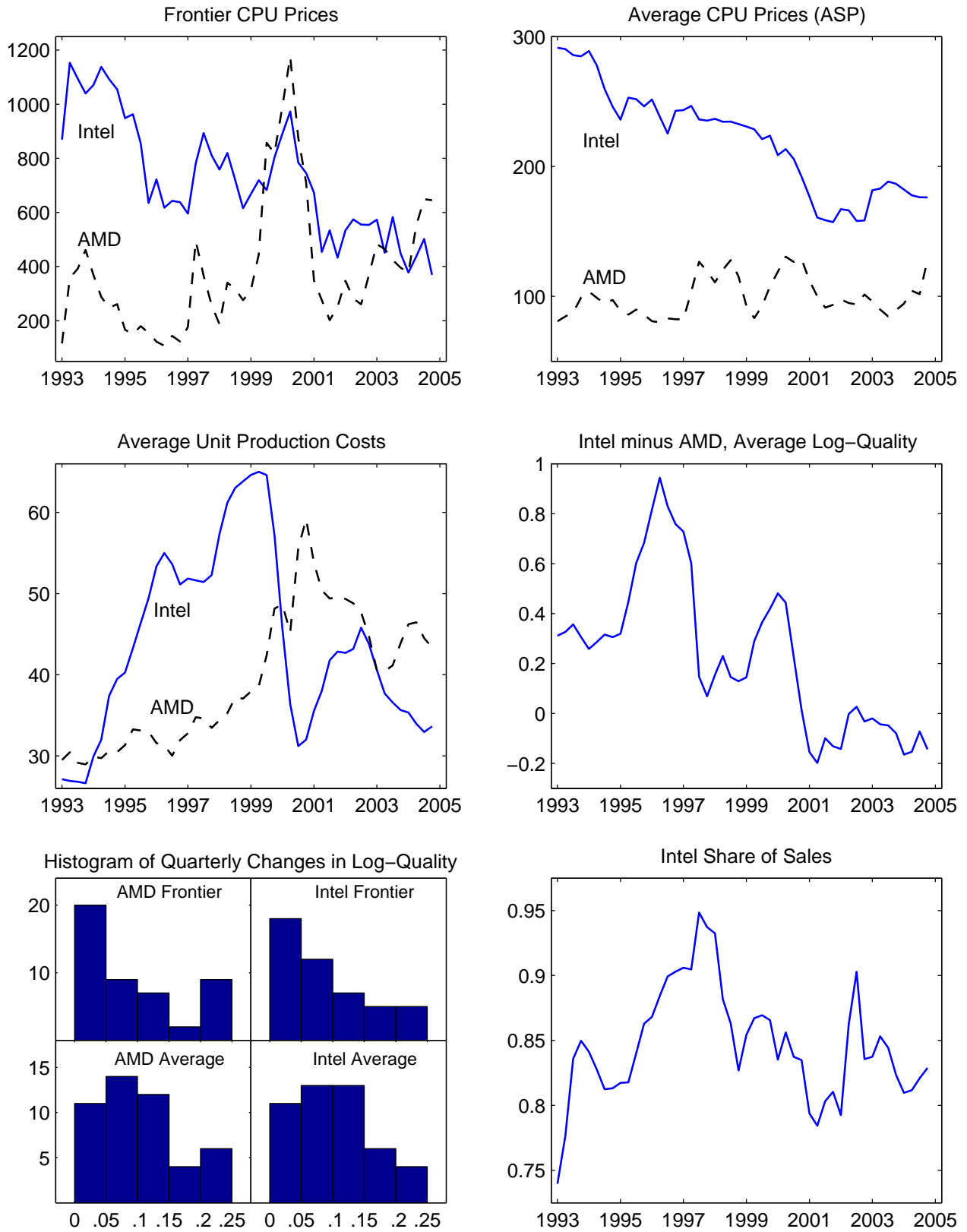
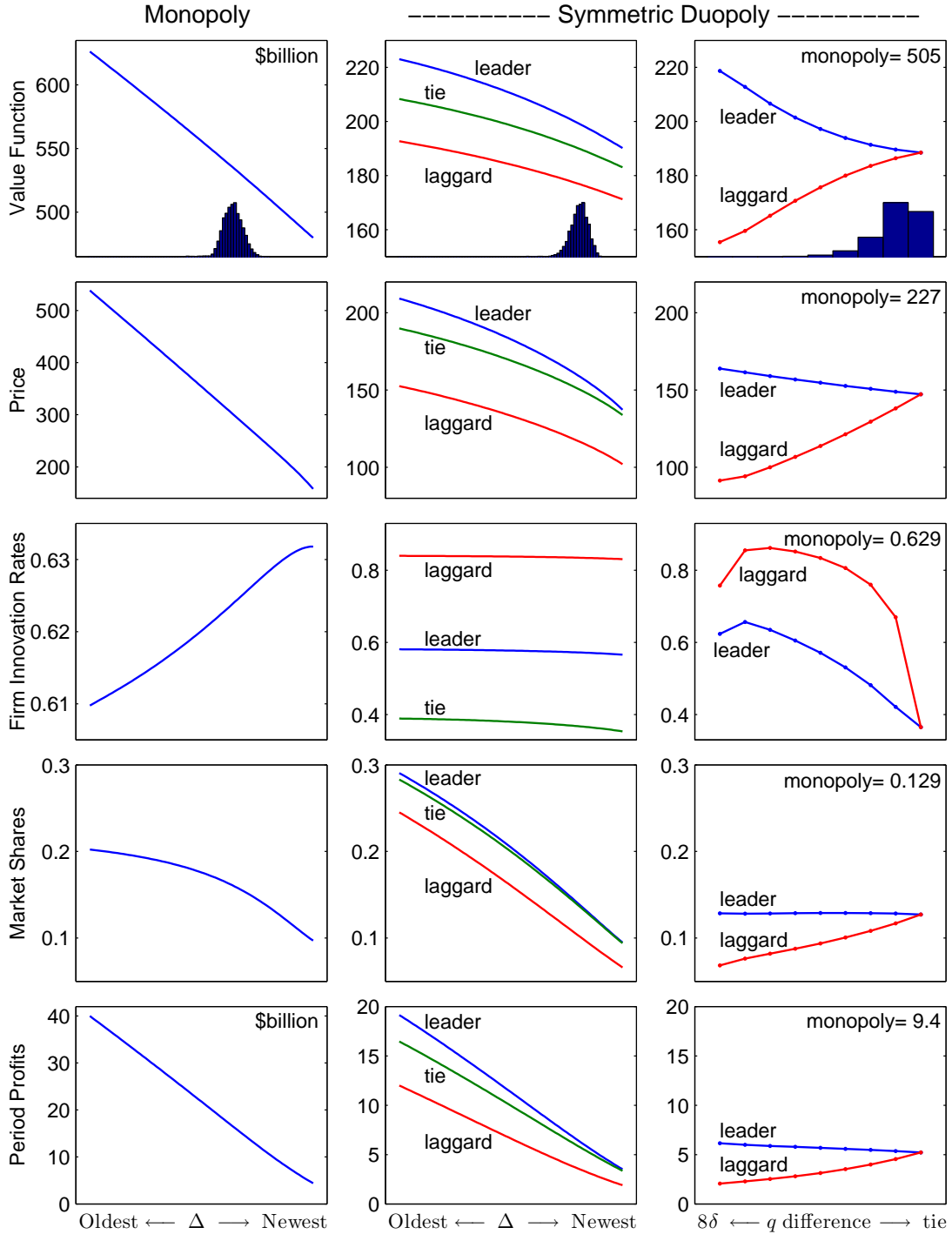


Figure 2: CPU Prices, Qualities, and Shares: 1993 Q1 to 2004 Q4



**Figure 3: Value and Policy Functions: Monopoly and Symmetric Duopoly:** Column 1 corresponds to the monopolist. Columns 2 and 3 correspond to the symmetric duopoly. In columns 1 and 2, the x-axis is the average quality in the ownership distribution  $\Delta$ . In column 2, values are reported for two scenarios: when the firms are tied and when their qualities differ by 4  $\delta$ -steps. In column 3,  $\Delta$  is fixed at its most frequent value in the duopoly simulations (16.5  $\delta$ -steps below  $\bar{q}$ ) and the x-axis is the quality difference between the leader and laggard, which ranges from 8 to 0  $\delta$ -steps. Histograms in the first row provide simulated frequencies of each state.



**Figure 4: Value and Policy Functions: Monopoly and Symmetric, No Spillover**

**Duopoly:** Column 1 corresponds to the monopolist. Columns 2 and 3 correspond to the symmetric duopoly with no spillovers. In columns 1 and 2, the x-axis is the average quality in the ownership distribution  $\Delta$ . In column 2, values are reported for two scenarios: when the firms are tied and when their qualities differ by 4  $\delta$ -steps. In column 3,  $\Delta$  is fixed at 16.5  $\delta$ -steps below  $\bar{q}$  (to match column 3 in Figure 3) and the x-axis is the quality difference between the leader and laggard, which ranges from 8 to 0  $\delta$ -steps. Histograms in the first row provide simulated frequencies of each state.

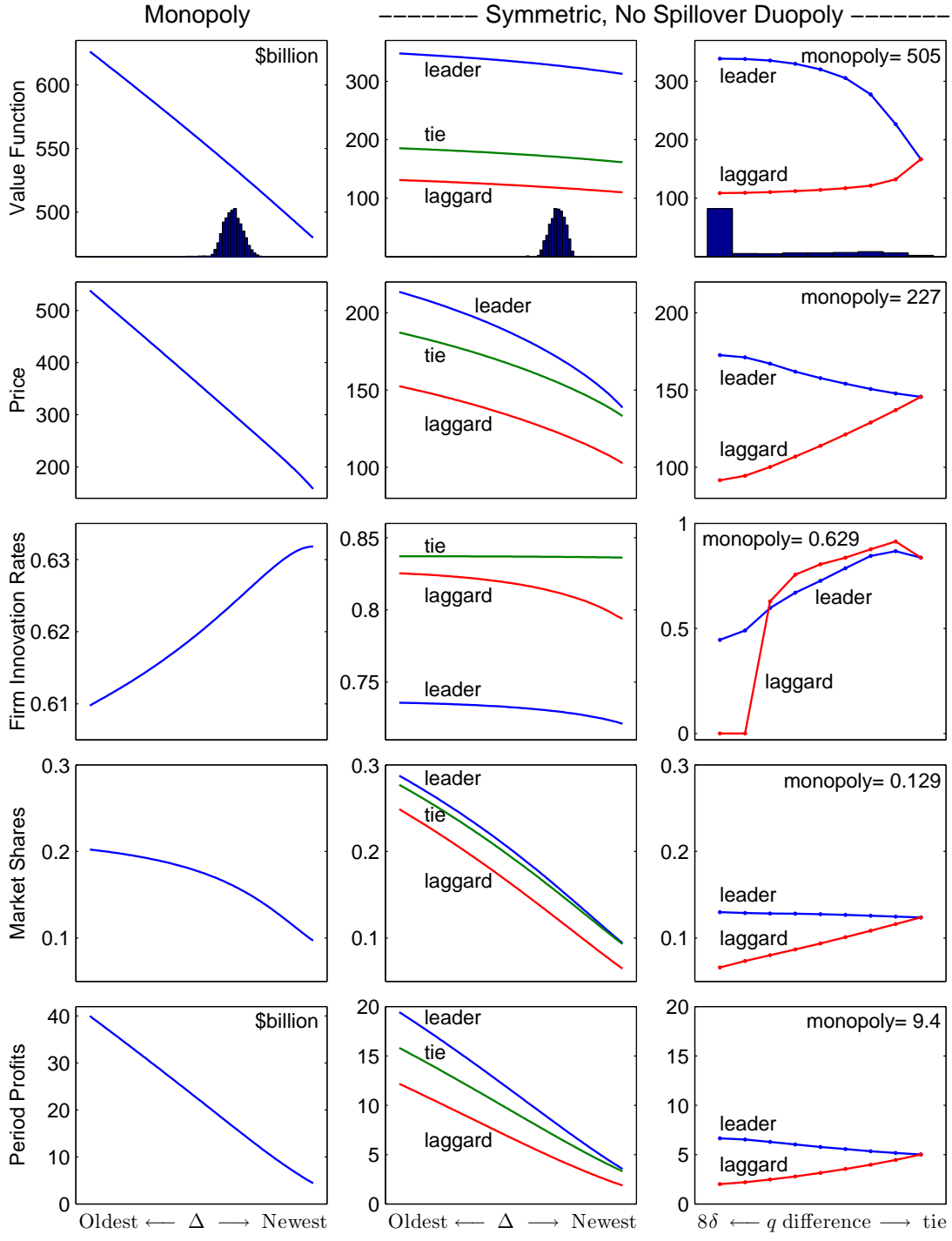


Figure 5: Purchase Probabilities by Vintage, Duopoly Case

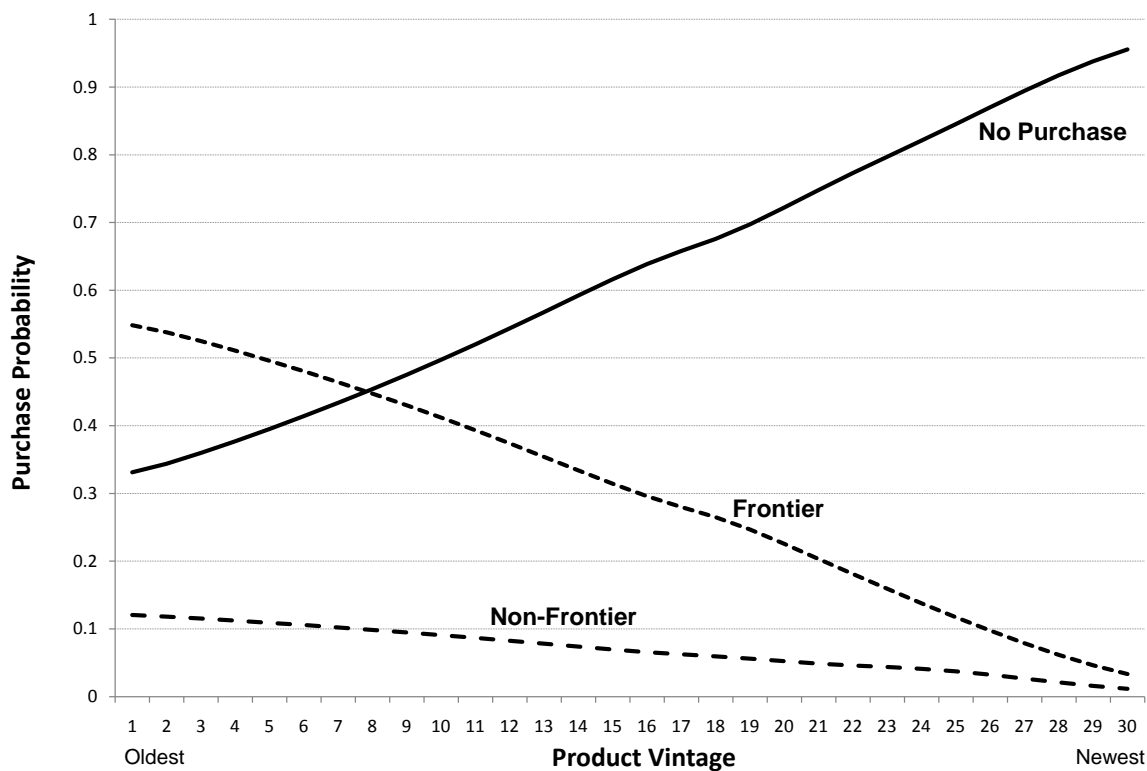


Figure 6: Ownership Distribution, Duopoly and Monopoly Cases

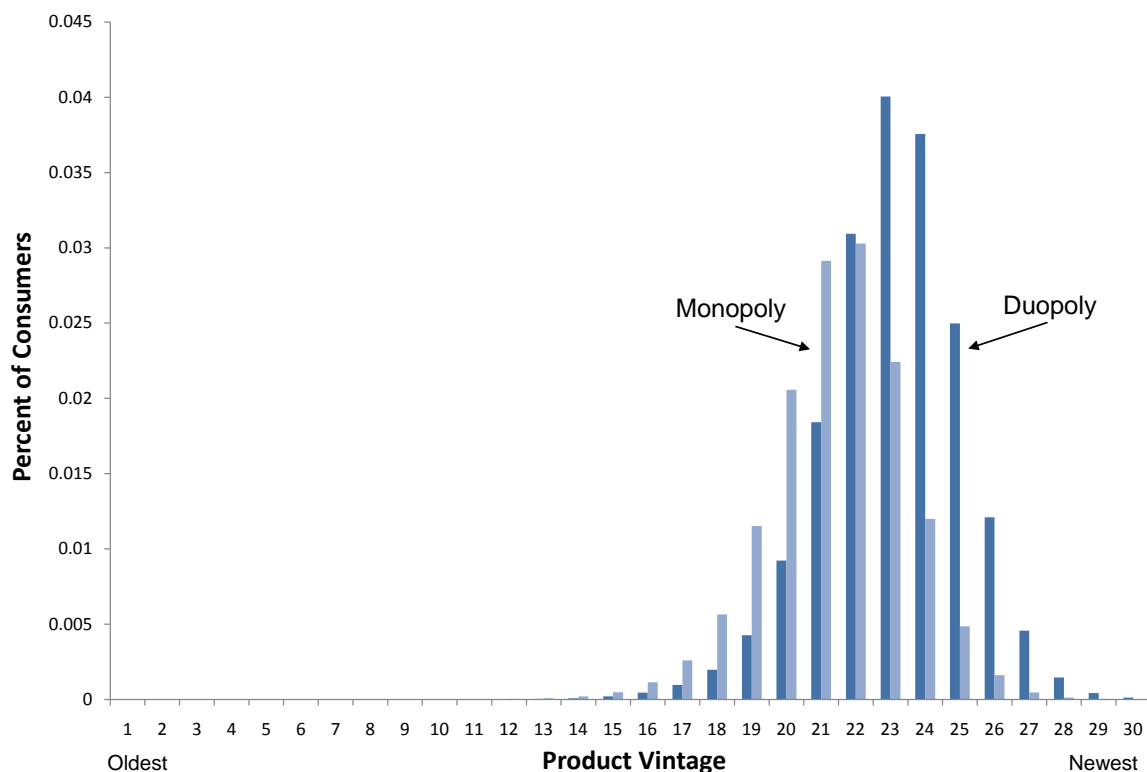


Figure 7: Market Restriction

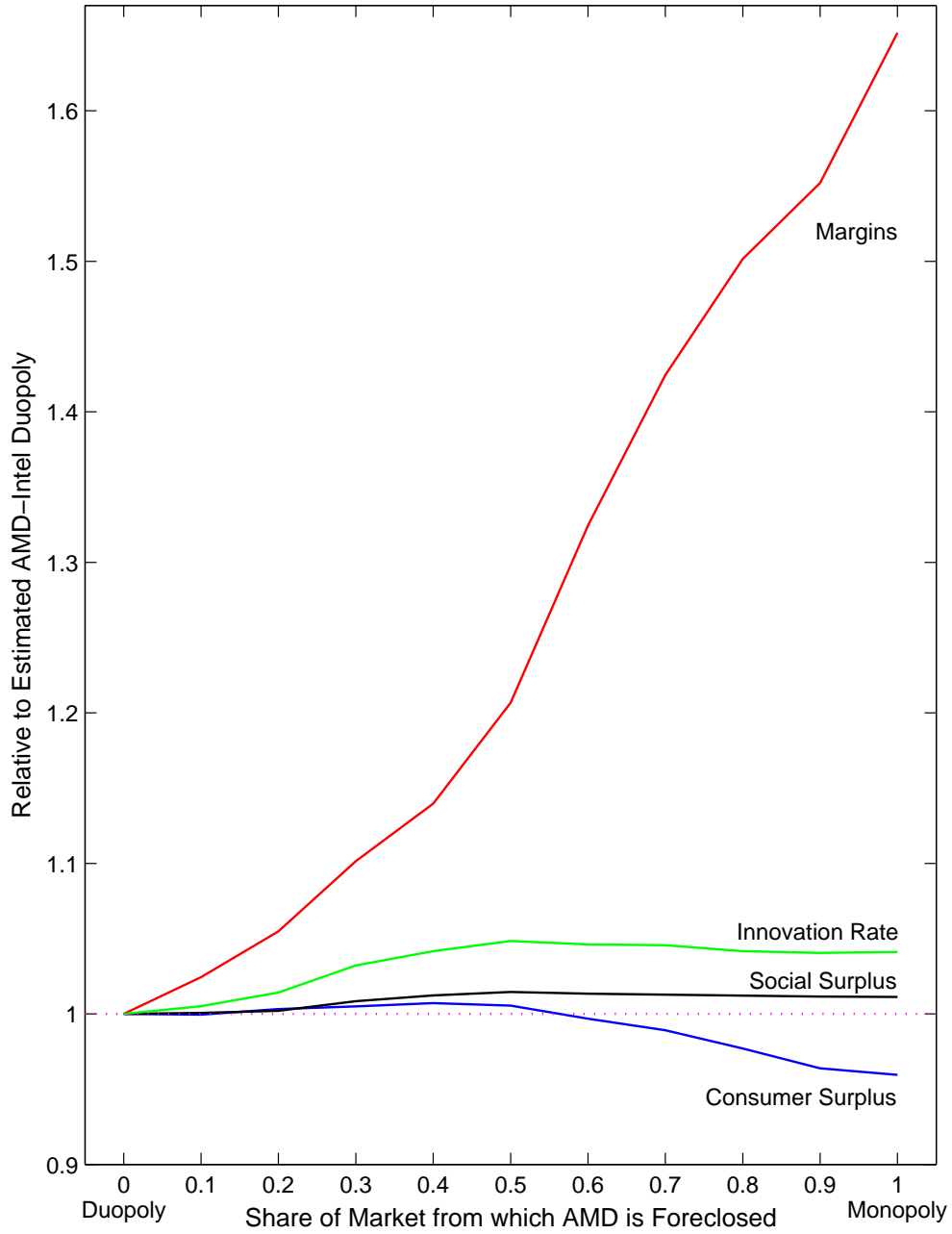
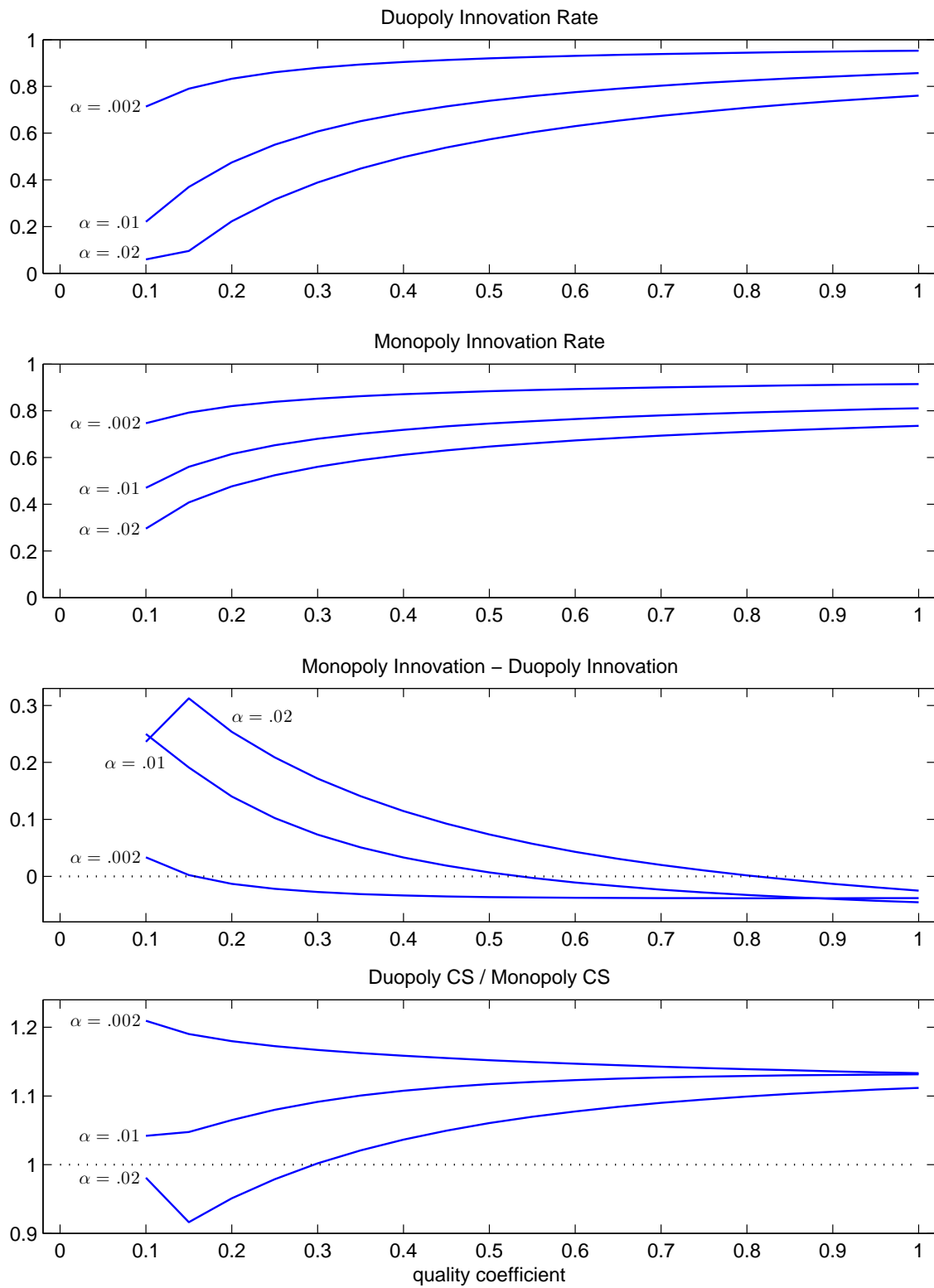
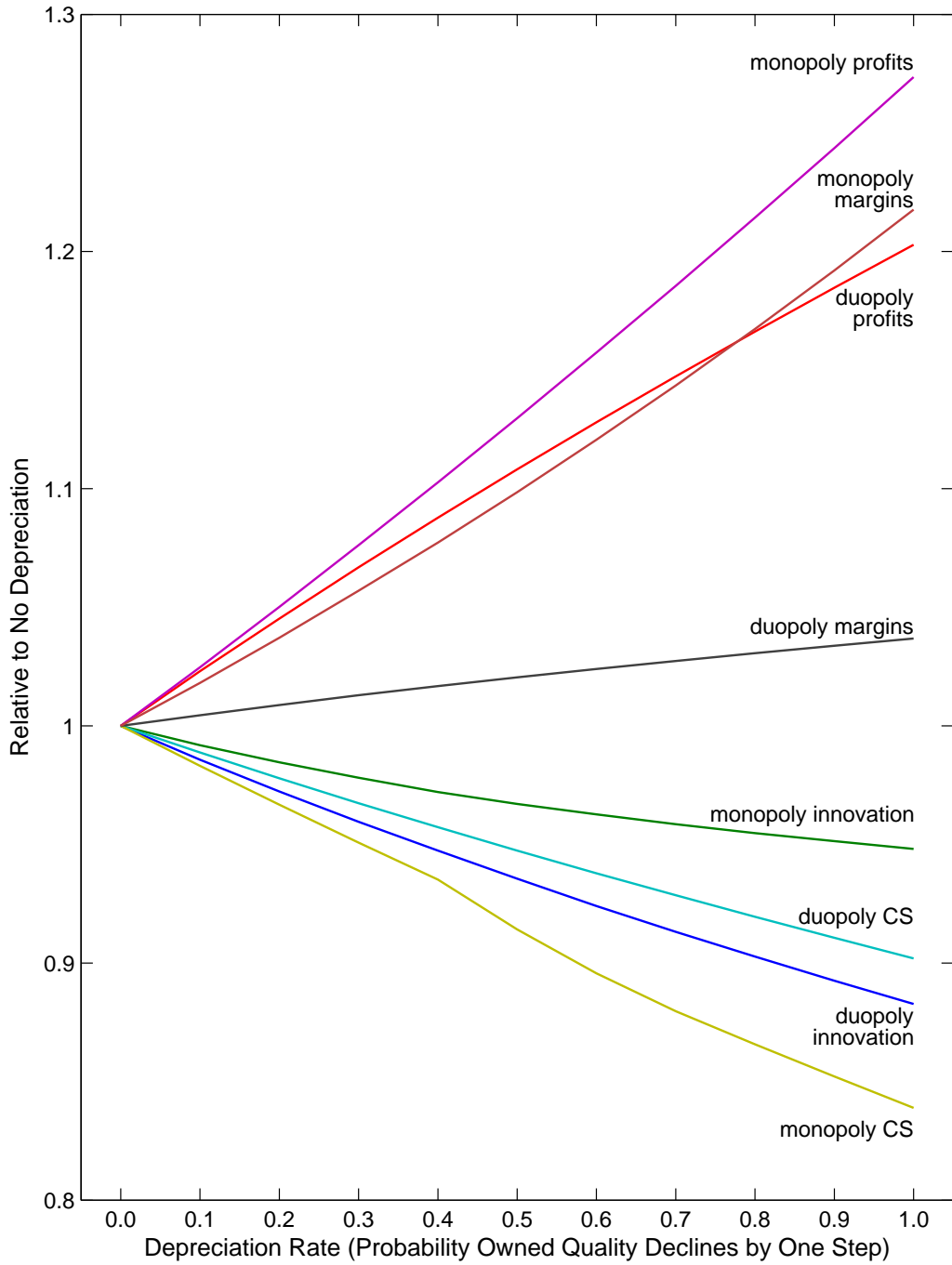


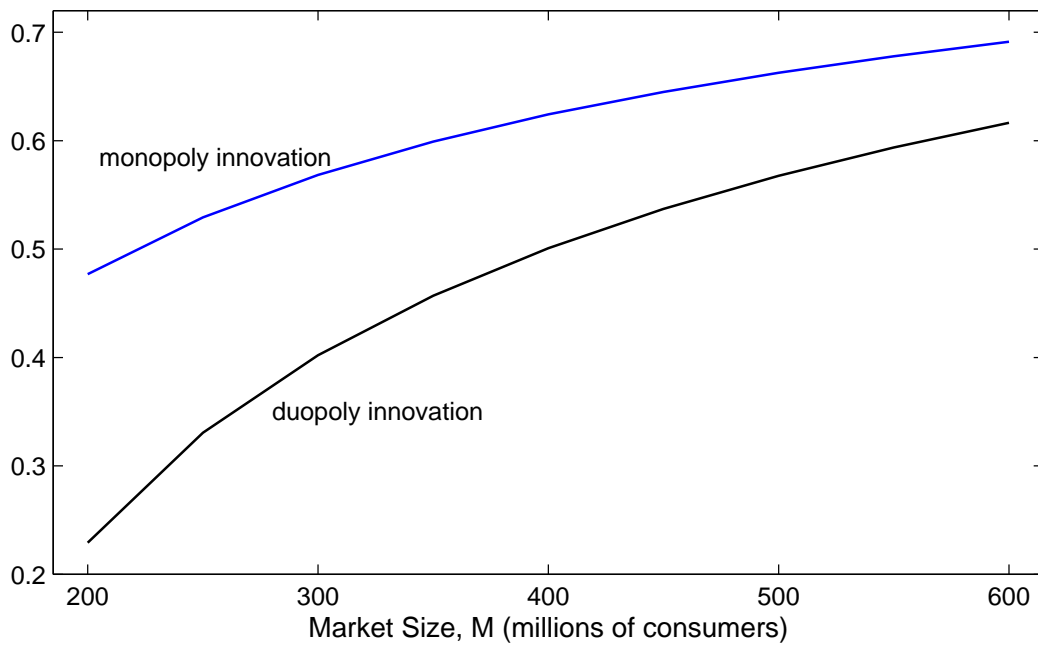
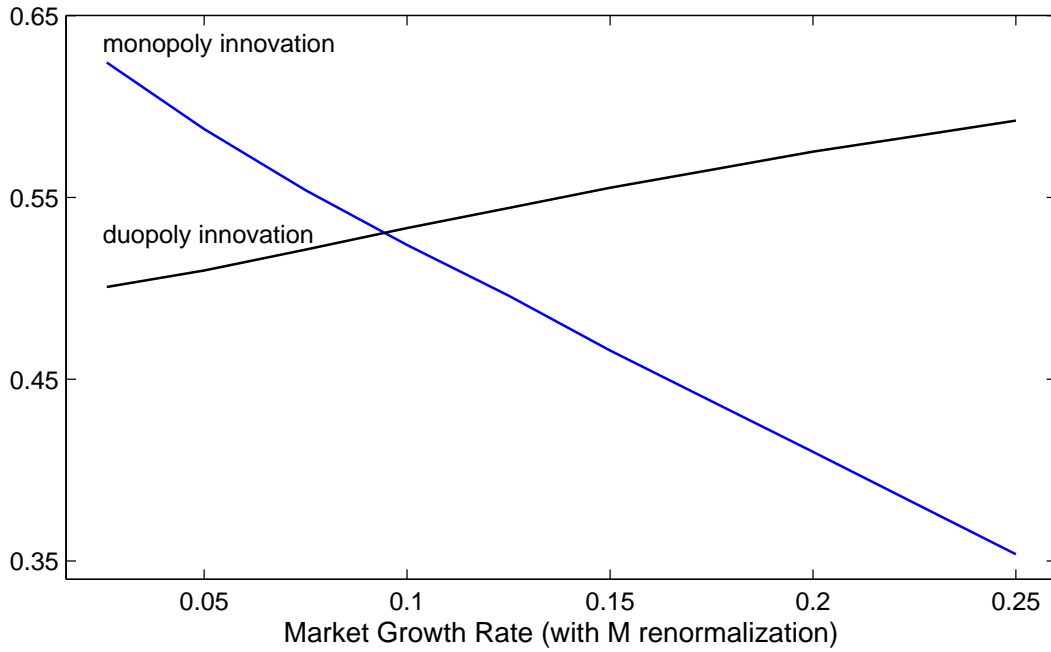
Figure 8: Monopoly versus Duopoly Innovation as  $(\alpha, \gamma)$  Vary



**Figure 9: Equilibrium Outcomes in the Monopoly and Symmetric Duopoly as Depreciation Varies:** Depreciation is measured as the quarterly probability that  $\tilde{q}$  declines one  $\delta$ -step)



**Figure 10: Innovation in the Monopoly and Symmetric Duopoly as Market Growth and M Vary**



**Figure 11: Symmetric Duopoly Innovation as the Spillover Varies:** For comparison, the monopolist's values relative to the estimated-spillover symmetric-duopoly are 2.34 for margins, .949, for consumer surplus, 1.004 for social surplus, and 1.246 for innovation.

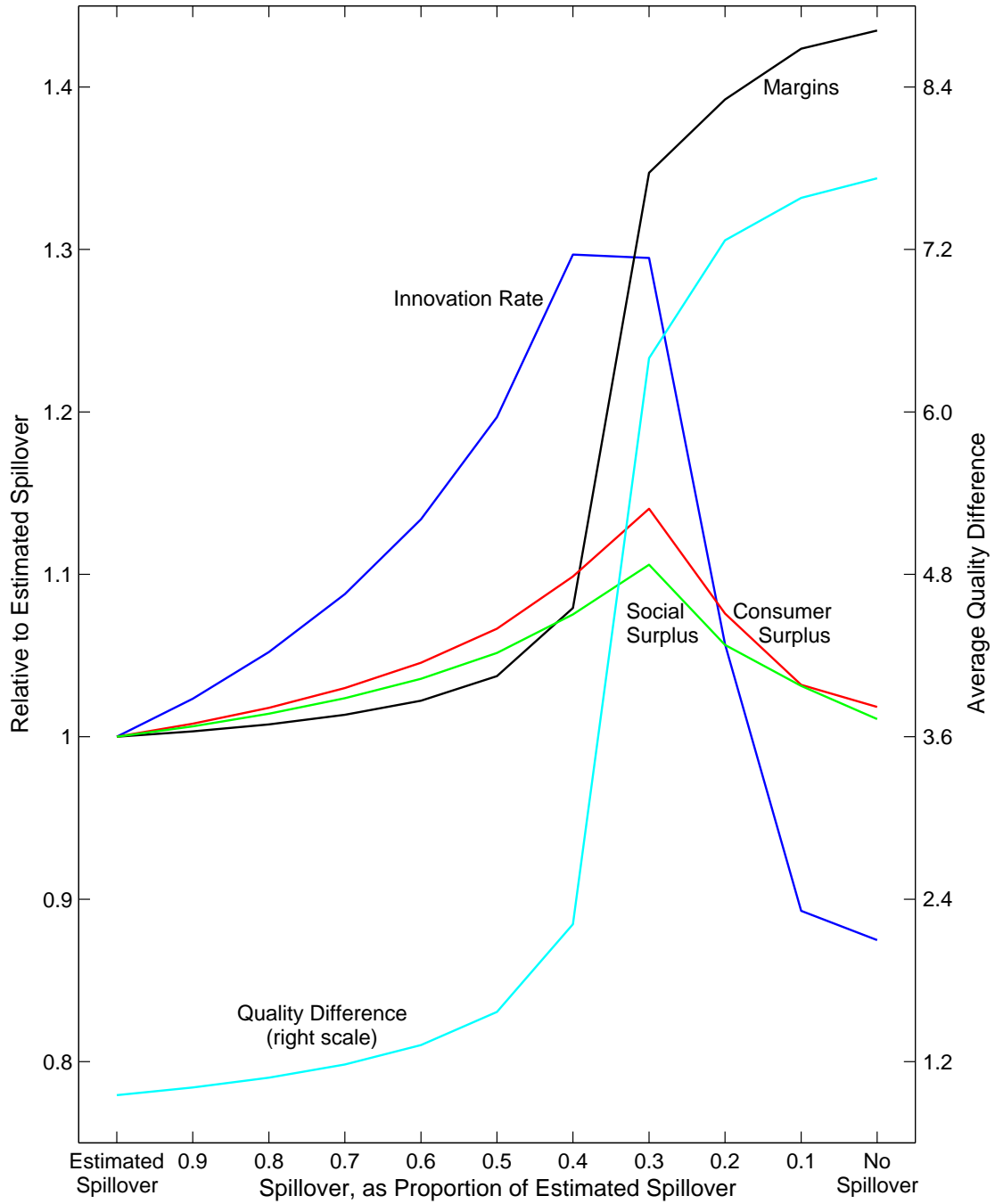


Figure 12: Innovation in the Symmetric Duopoly with Nondurable Goods as Product Substitutability Varies

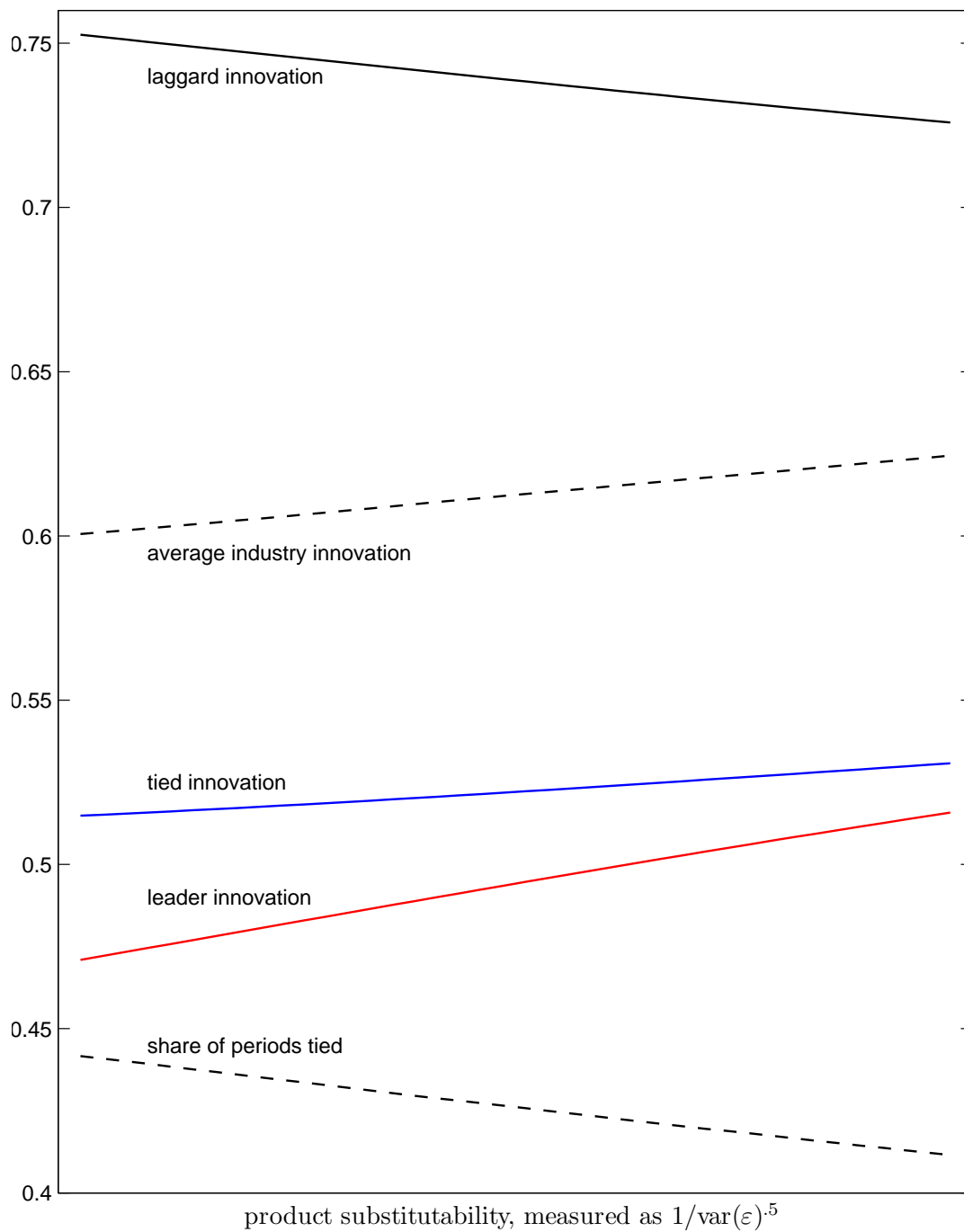
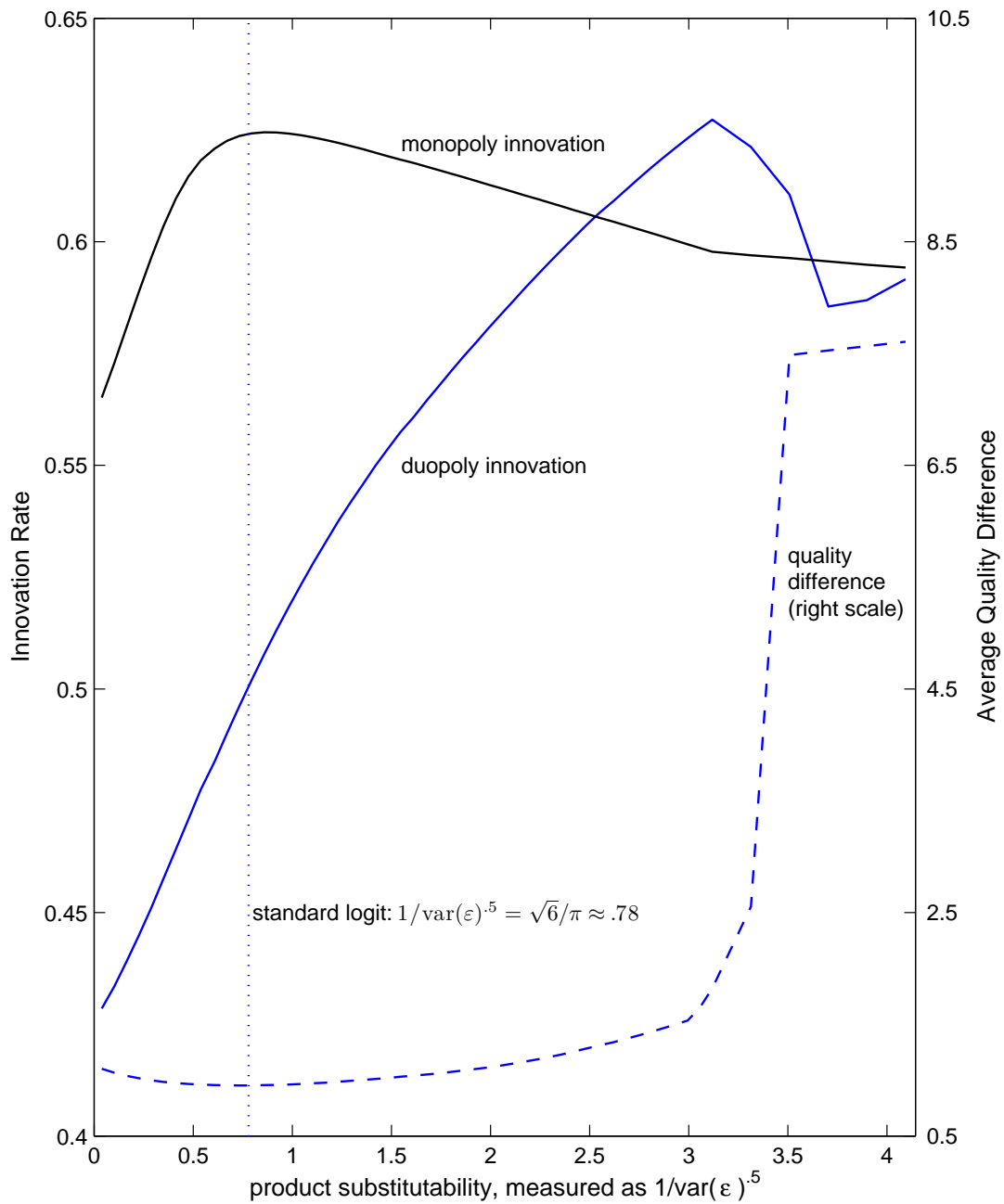


Figure 13: Innovation in the Monopoly and Symmetric Duopoly as Product Substitutability Varies



**Figure 14: Decomposing Changes in Innovation as  $\gamma$  Increases:** Panels 1 and 3 plot the effect of the quality coefficient,  $\gamma$ , on innovation and investment by firms in a symmetric duopoly and monopoly for particular  $\Delta$  values of 7.25 and 3.5  $\delta$ -steps below the frontier, on average across consumers. All panels except panel 5 (bottom-left) use the legend in panel 1 and condition on these same  $\Delta$  values, which we chose to match their respective simulated averages. Panel 2 plots the derivative of firms' innovation probabilities with respect to investment and, for the tied duopolists, the derivative of *either* firm advancing the frontier. Panel 4 is the derivative of investment with respect to  $\gamma$ , and panel 6 is the derivative of innovation with respect to  $\gamma$ . Panel 5 reveals simulated summary measures of which states are visited as  $\gamma$  varies.

