The incentives of a monopolist to degrade interoperability: Theory and evidence from PCs and servers

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Abstract

We consider the incentives of a monopolist to leverage into a complementary market by degrading interoperability. In a framework incorporating heterogeneous consumers' demand, we derive explicit conditions for the incentives to hold that are amenable to empirical testing. Essentially, in the absence of perfect price discrimination, leveraging becomes a method to extract more rents from the monopoly market. We test these predictions in the context of Microsoft's alleged strategic incentives to leverage market power from personal computer to server operating systems in the late 1990s. We find robust empirical evidence that these incentives exist and that they have grown stronger over time. Moreover, in a dynamic extension of our model, we show why a monopolist in this market has further long run incentives to limit interoperability.

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1 Introduction

Many antitrust cases in high-tech industries now revolve around interoperability and compatibility issues. For example, the European Microsoft case has explicitly focused on the question whether Microsoft deliberately limited interoperability between its personal computer operating system (monopoly product) and rivals' server operating systems (complementary products) to foreclose competitors from the market for workgroup server operating systems. Microsoft's share of server operating systems rose substantially from 20% at the start of 1996 to over 60% by the end of 2001 (see Figure 1) and the European Commission (2004) alleged that some of this increase was due to interoperability constraints. The possibility of such leveraging of market power from the PC to the server market seemed to be suggested by Microsoft itself. In 1997 Microsoft's Chairman Bill Gates wrote in an internal memo: "What we're trying to do is to use our server control to do new protocols and lock out Sun and Oracle specifically....the symmetry that we have between the client operating system and the server operating system is a huge advantage for us".

The rationality of such strategies has been strongly challenged in the past by the Chicago school critique of leverage theory. Suppose one firm has a monopoly for one good but competes with other firms in a market for another good and both goods are used in fixed proportions by consumers. The Chicago school observed that the monopolist in the first market did not have to monopolize the second market to extract monopoly rents from the market. Indeed, whenever there was product differentiation in the second market, the monopolist in the first could only benefit from the presence of other firms.[1] Following the lead of authors in the Chicago tradition[2], there has been much work on trying to derive efficiency explanations for exclusionary practices that were previously seen as anticompetitive. For example, price discrimination has been put forward as an explanation for tying strategies[3].

More recently, studies of exclusive dealing (see Bernheim and Whinston 1998) and tying[4] have shown that rational foreclosure in market for complements is possible in well specified models.[5] Most of these models have the feature that exclusionary strategies are not necessarily profitable in the short run. However, exclusionary strategies through their impact on investment, learning by doing, etc, can make current competitors less effective in the future, making the exclusionary strategy profitable. In the context of the Microsoft case we present a model in Appendix E that is of this type and is driven by application network effects, an argument that has been central in the Microsoft cases.

In this paper we suggest a different theory of foreclosure through interop-

[1]For a formal statement of this point, see Whinston (1990), Proposition 3.

[2]For example, Bork (1978).

[3]Bowman (1957), Adams and Yellen (1976); Schmalensee (1982, 1984), McAfee, McMillan and Whinston (1989).

[4]See Whinston (1990), Farrell and Katz (2000), Choi and Stefaniadis (2001), Carlton and Waldman (2002) among others.

[5]See Rey and Tirole (2003) for a comprehensive review of this literature and Whinston (2001) for an informal survey in relation to some aspects of the U.S v. Microsoft case.

erability degradation that relies on an immediate benefit for the monopolist: The reduction or elimination of competition reestablishes the ability of the monopolist to price discriminate between customers with high and low demand elasticities for PCs. If customers with high elasticity of demand for PCs also have low willingness to pay for servers, server purchases can be used for second degree price discrimination. The monopolist will lower the price for the PC operating system and extract surplus from customers with low elasticity of PC demand by charging higher server operating system prices. Competition on the server market will eliminate the ability to price discriminate in such a way. By reducing interoperability, the PC operating system monopolist can reduce competition on the server market, reestablishing the ability to price discriminate. We show in a simple example that in the absence of horizontal product differentiation between servers, this effect will lead the monopolist to foreclose rivals in the server market even if their product is arbitrarily better than the product of the PC operating system monopolist. With product differentiation between servers (and server operating systems) there is a second effect that limits the incentives to reduce interoperability. Reducing interoperability can then have a negative impact on the PC sales of the monopolist.

The goal of this paper is to estimate the foreclosure incentives of the monopolist. Such incentives are generally very difficult to measure, but the price discrimination theory allows one to do so primarily on the basis of estimating demand elasticities. For the argument we are making, modelling the heterogeneity between buyers is essential for generating foreclosure incentives. But a model of customer heterogeneity is also a central feature of recent approaches for estimating demand systems in differentiated product markets. We therefore first develop the theory on the basis of a discrete choice model with random coefficients as used in demand estimations by Berry, Levinsohn, and Pakes (1995) or Nevo (2000a, 2001). Customer heterogeneity is captured by the distribution of the coefficients in the utility function across the population. In the context of this model we show the role of consumer heterogeneity in generating foreclosure incentives. We also show that the correlation between the demand elasticity for PCs and willingness to pay for servers is critical for generating a positive markup on the server operating system of the PC OS monopolist. We also show how operating system prices can be inferred from the estimation of PC demands by using the optimality conditions for the monopolist's pricing

We then bring this model to the data. In order not to restrict heterogeneity between different consumers too much, we separately estimate demands for different consumer groups like small and large businesses that we can distinguish in the data. These are groups across which the monopolist cannot easily discriminate [6]. By looking at components of demand we can reduce the dependence of our estimates on assumptions about the distribution of ran-

[6] There has recently emerged some price discrimination between Windows XP versions for Home vs. Professional (business users). Discrimation against the more price inelastic large business in favour of the small business user would be virtually impossible as a large firm could always arbitrage away price differences through disguising itself as a smaller firm.

dom coefficients in the model. This way of allowing for general heterogeneity between specific groups of consumers in the PC market and elsewhere, although explicitly recognized, for example, by the European Commission[7] in the Hewlett Packard-Compaq merger examination, has not been widely used in demand studies. Building on the findings of Genakos (2004), we use data from the US PC market since 1995 and estimate a structural demand not just across the entire server market but also for three customer segments (home, small business and large business). We use this to infer Microsoft's margins on PC and server operating systems.

We then estimate the response of PC demand and Microsoft server demand as a reaction to an increase in server quality of rivals for given Microsoft prices. This allows us to directly infer the "relative output effects" of interoperability decisions. Combining these estimates with those of server margins we then can quantify the marginal incentives of Microsoft to reduce interoperability, based on this effect alone. We show that Microsoft has had consistently incentives to reduce such interoperability and that these incentives have been growing over time as Microsoft has gained market share (see Figure 1). This is precisely the prediction of the theory. We have therefore shown that intertemporal theories, for example those based on applications network effects, are not needed to generate anticompetitive incentives to re-

[7] "*Because, among other elements, individual consumers show different purchasing patterns,..., the market for PCs could be broken down between consumers and commercial customers.*" Case No COMP/M. 2609-HP/COMPAQ, Office for Official Publications of the European Communities.

duce interoperability by Microsoft. These dynamic effects only make such foreclosure incentives stronger.

The paper is structured in the following way. Section 2 gives a formal overview of the argument in the paper. In section 3 we present the demand model and present the theoretical results that relate foreclosure incentives to price discrimination. Section 4 details the econometrics of demand estimation, the demand data and discusses the implications for software margins. Section 5 discusses the methods used to assess demand responses to interoperability degradation and discusses the implications of our estimates for the incentives for foreclosure. Section 6 concludes. In the Appendices we give more details of estimation techniques, derivations, data and a dynamic extension to the static model.

2 An overview

In this section we develop the basic conditions that have to hold to generate incentives to foreclose competitors from the market by degrading interoperability. We will develop the theory exclusively focusing on the maximization problem of the PC operating system monopolist ("the monopolist"), leaving the optimal decisions of other players in the background. This the only information necessary to make inferences about the incentives for foreclosure in the empirical part of the paper.

Let $\mathbf{p}_J = \hat{\mathbf{p}}_J + \boldsymbol{\omega}_J$ be the vector of total price for a PC, with element p_j, which is the sum of the vector of hardware prices $\hat{\mathbf{p}}_J$ and the vector PC operating system prices $\boldsymbol{\omega}_J$. Since there is a monopolist in the operating system market for PCs $\omega_J = \omega \cdot \mathbf{1}$. Similarly let $\mathbf{p}_k = \hat{\mathbf{p}}_k + \boldsymbol{\omega}_k$ be the vector of total price for a server of model k, which can again be broken down in hardware and software prices. We use $k = \Omega$ when referring to the monopolist's server. Define $a_k \in [0, 1]$ as an interoperability parameter affecting some quality characteristic of a server k. We set $a_\Omega = 1$ for the monopolist and $a_k = a \leq 1$ for competitors in the server market. We define $q(\mathbf{p}_j, \mathbf{p}_k, a)$ as the total demand for PCs and $q_\Omega(\mathbf{p}_j, \mathbf{p}_k, a)$ the demand for servers that run the monopolist's server operating system. The idea is that a is some interoperability parameter that can be affected by the monopolist. Clearly, increased interoperability will increase total PC demand but will decrease the demand for server operating systems offered by the monopolist. Total profits of the monopolist are then given by:

$$\Pi(\mathbf{p}_j, \mathbf{p}_k, a) = (\omega - c)q(\mathbf{p}_j, \mathbf{p}_k, a) + (\omega_\Omega - c_\Omega)q_\Omega(\mathbf{p}_j, \mathbf{p}_k, a),$$

where ω_Ω is the monopolist's price for the server operating system and c and c_Ω are the corresponding marginal costs.[8]

We are ultimately interested in the marginal incentive of the monopolist to decrease interoperability. There will be such an incentive if:

$$(\omega - c) \left. \frac{dq(\mathbf{p}_j, \mathbf{p}_k, a)}{da} \right|_{\omega, \omega_\Omega} + (\omega_\Omega - c_\Omega) \left. \frac{dq_\Omega(\mathbf{p}_j, \mathbf{p}_k, a)}{da} \right|_{\omega, \omega_\Omega} < 0$$

where the derivatives are total derivatives of the respective output measures holding the monopolist's operating system prices constant. Hence, this deriv-

[8] The marginal cost can be thought of as being very close to zero in software markets.

ative contains the direct effect of interoperability as well as the impact of the price responses to a change in interoperability by all rival software producers and all hardware producers. Rearranging terms we obtain that there is an incentive to decrease interoperability at the margin if:

$$\frac{\omega_\Omega - c_\Omega}{\omega - c} > -\frac{\left.\frac{dq(\mathbf{p}_j,\mathbf{p}_k,a)}{da}\right|_{\omega,\omega_\Omega}}{\left.\frac{dq_\Omega(\mathbf{p}_j,\mathbf{p}_k,a)}{da}\right|_{\omega,\omega_\Omega}} \tag{1}$$

Intuitively, degrading interoperability increases the PC monopolist's server sales but reduces PC sales. This implies that the right hand side of (1) (which we call the "relative output effect") is always strictly positive. Incentives for interoperability degradation will be larger the more the reduction in quality of the rivals will lead to substitution towards the monopolist's server operating system and the less buyers refrain from buying PCs as a result of lower server qualities. We will estimate these quantities directly in section 5.

On the other side of the inequality, the relative value of PC and server operating system sales matters (we call this the "relative margin effect"). Interoperability degradation will only be profitable if the margin on the server operating system of the monopolist ($\omega_\Omega - c_\Omega$) sufficiently exceeds the margin on the PC operating system ($\omega - c$). As we will show this can never be the case if there is no heterogeneity between consumers. In that case the "one monopoly profit theory" holds and the monopolist will price the server at marginal cost. We will explain in the next section that positive margins on the server are the result of second degree price discrimination between consumers with more and less elastic demand for PCs. Heterogeneity in demand elasticities between populations among which the monopolist cannot directly discriminate will therefore be crucial in generating positive server operating system margins.

The margins on operating systems are essentially unobservable. For our econometric estimations we only have prices of PCs bought inclusive of an operating system. While there do exist some list prices that allow us to infer an order of magnitude, we will have to estimate margins from the data. This estimation will therefore use the profit maximizing pricing behavior of the monopolist to infer such margins. However, there are some modelling choices that have to be made. Given the complementarity between software and hardware as well as between PCs and server, the move order in price setting will be important for determining the pricing incentives for the monopolist. We will assume in the paper that the hardware and software companies set their prices simultaneously. Then the price the software company charges is directly added to whatever price the hardware company charges for the computer. This assumption seems consistent with what we observe in the market as Microsoft effectively controls the price of the software paid by end users through licensing arrangements[9]. Our assumption greatly simplifies the analysis of the monopolist's problem: While the optimal software price does

[9] An alternative sequential set up would be if the software company moves first. Its pricing incentives are not affected by whether the software producer charges the hardware firm or if it charges the consumer directly. However in this case the pricing incentives of the software company have to take into account the price reactions of the hardware company. This would add an additional layer of complexity to the model which we currently abstract from.

depend on the expected prices for the hardware, we do not have to solve for the pricing policies of the hardware producers to analyze the pricing incentives of the software firm. The first order conditions for the monopolist is then given by:

$$q + (\omega - c)\frac{\partial q}{\partial \omega} + (\omega_\Omega - c_\Omega)\frac{\partial q_\Omega}{\partial \omega} = 0 \tag{2}$$

$$q_\Omega + (\omega - c)\frac{\partial q}{\partial \omega_\Omega} + (\omega_\Omega - c_\Omega)\frac{\partial q_\Omega}{\partial \omega_\Omega} = 0 \tag{3}$$

Denoting $\frac{\partial q}{\partial \omega}\frac{1}{q} = \varepsilon_\omega$, the semi-elasticity of the impact of a proportional change in price (ω) on quantity demanded (q)[10], we can solve equations (2) and (3) for the profit margins:

$$(\omega - c) = \frac{\frac{q_\Omega}{q}\varepsilon_\omega^\Omega - \varepsilon_{\omega_\Omega}^\Omega}{\varepsilon_\omega \varepsilon_{\omega_\Omega}^\Omega - \varepsilon_{\omega_\Omega}\varepsilon_\omega^\Omega} \tag{4}$$

$$(\omega_\Omega - c_\Omega) = \frac{\frac{q}{q_\Omega}\varepsilon_{\omega_\Omega} - \varepsilon_\omega}{\varepsilon_\omega \varepsilon_{\omega_\Omega}^\Omega - \varepsilon_{\omega_\Omega}\varepsilon_\omega^\Omega} \tag{5}$$

We will show further below that the semi-elasticities on the right hand side of these two equations can be estimated on the basis of PC data alone. Note that the estimates of the margins for server and PC operating systems are importantly affected by the interaction of the two markets. As our later analysis will show, either of the price cost margins can be negative. To obtain some preliminary intuition, consider the benchmark in which the server

[10] Recall that q indicates total PCs and total PC operating systems (because each PC needs one of the monopolist's operating systems). There are rival server operating sytsems, however, so we need to denote the monopolist's offering by script Ω.

market becomes perfectly competitive, i.e. $\varepsilon^{\Omega}_{\omega_\Omega} \to \infty$. Then the PC operating system margin of the monopolist goes to $w - c \to \frac{1}{\varepsilon_\omega}$ and the server operating system margin $\omega_\Omega - c_\Omega \to 0$. Hence, a naive estimation of PC operating system margins that ignored server margins would systematically generate incorrect results. Indeed, when there are incentives to use the server operating system price for second degree price discrimination, it would look as if the monopolist would not be fully exploiting its monopoly power. We will show this in section 3. We discuss the estimation of these margins on the basis of demand elasticity estimates in section 4.

Before we develop a theory of second degree price discrimination as an explanation for foreclosure incentives, we first discuss why we focus on the inequality in (1). One might think that interoperability would be chosen optimally by the monopolist so that (1) should hold with a strict equality. To see why we should not expect such an outcome, first note that interoperability always refers to one of many quality characteristics of the firm. For any given quality characteristic the optimal choice may be zero interoperability, i.e. a corner solution. This means the monopolist would want to reduce quality of the server rivals further if he could. At the same time there are many reasons why it will be impossible for a monopolist to reduce all interoperability to zero, i.e. making rival server operating systems non-functional. One reason is that there are different server market segments. For example, in European Commission (2004) it was claimed that Microsoft had an incentive to exclude rivals in workgroup server markets, but not in the markets for web servers or enterprise servers[11] (where Microsoft had a small market share). This means that there is always some incentive to maintain some interoperable communications protocols for server markets in which Microsoft does not have a strong market share. These would not be measured in inequality (1), which only considers incentives arising from the market for workgroup servers that we will concentrate on. However, the incentive to degrade interoperability only on quality dimensions relating to the workgroup server operating system market are of interest to evaluate Microsoft's foreclosure incentives for that particular market. This strongly suggests that in the presence of foreclosure incentives we should find a strict incentive to foreclose at the margin. There are further reasons why we would see an inequality instead of an equality[12].

As we will show below, the relative size of the relative output effect and the relative margin effect change as the monopolist's market share in the server market increases. This means that after entry into the server market a PC operating monopolist should have increasing incentives for foreclosure as market share grew. This does indeed fit the broad pattern of Microsoft's behavior. Before Microsoft entered the server market interoperability has

[11] Enterprise servers are high end corporate servers that manage vast amounts of mission critical data in large corporations. They need very high levels of security and typically use custom written written software. Web servers host the web-sites of companies and are also used for e-commerce.

[12] First, there are time lags between the design of the less interoperable software and its diffusion on the market. Second, other server OS vendors such as Novell, Sun and more recently Linux sought to overcome the fall in interoperability through a variety of measures such as developing "bridge" products, redesigning their own software, reverse engineering, etc. Finally, since the late 1990s anti-trust action in the US and EU may have somewhat slowed down Microsoft's desire to reduce interoperability.

generally been high among server operating systems because they were either open standard (e.g. Unix) or open source (e.g. Linux). When Microsoft first entered the server market it based its protocols on these open standards[13]. During this period there was an incentive to have high interoperability given the low market share of Microsoft in the server market. Any quality degradation would have had excessive costs in terms of reduced PC operating system sales. Our empirical work shows that as Microsoft's share in the server market grew, it started to have a greater incentive to reduce the quality of rival server products. Interoperability degradation began to occur, but at the margin Microsoft had an incentive to reduce interoperability further.

3 Second Degree Price Discrimination and Foreclosure Incentives: A theoretical Framework

3.1 The Model of Demand

We model the demand for "workgroup" purchases. A buyer i of type w has demand for a PC workgroup which consists of w PCs and one server. We assume that each buyer can connect his workgroup to one server or not connect it. There are J producers of PCs[14] and K producers of servers indexed by j and k respectively. A buyer i with workgroup size w who

[13] For example, Windows NT security interface was Kerberos that was developed by researchers at MIT. Microsoft's original file system protocols, CIFs, was also an open standard.

[14] For notationally simplicity we are associating one producer with one PC hardware type. In the empirical work we of course allow for multi-product firms.

buys the PCs from producer j and the server from producer k in market t (which we suppress for notational simplicity until the econometric section) has conditional indirect utility:

$$u_{ijk}(w) = w\left[x_j\beta_i^* + A_k y_k \gamma_i^* - \alpha_i^*[p_j + \frac{1}{w}p_k] + \xi_j + \xi_k + \xi_{jk} + \varepsilon_{ijk}\right] \quad (6)$$

The term $x_j\beta_i^*$ captures the quality assessment of buyer i about the PC from producer j. The characteristics of the PC are captured by the vector x_j while the number of PCs that the buyer needs for his workgroup are captured by w. The quality of the server purchased is reflected by the expression $A_k y_k \gamma_i^*$. The vector y_k represents the attributes of the server and the server software, while A_k is a diagonal matrix that captures the degree to which each dimension of the server interoperates with the PC operating system (Windows). We normalize quality by assuming that $A = I$ whenever server producer k has the Windows operating system[15]. In A_k we denote the elements of the diagonal a_{km} (≤ 1). We will assume that A_k is the same for all non-Microsoft servers. In the simplest case of one server characteristic we can think of non-Microsoft server quality as a which indicates the degree to which a server running a non-Windows operating system interoperates with Windows on PCs.

The total price for the workgroup is given by $wp_j + p_k$. We can allow for two part tariffs by having p_k take the form $p_k(w) = p_{k1} + wp_{k2}$. This can allow for typical pricing structures in which there is a fixed price for the server operating system and a pricing component based on the number of

[15] If there are multiple versions of Windows operating system we normalize the most recent version to generate the matrix $A = I$

users (i.e. w Client Access Licences - CALs - have to be purchased). We can accommodate such pricing without any problems in our approach. All that is really important for the pricing structure is that there is some fixed component to the pricing of the monopolist's server operating system. For simplicity we will exposit all of the analysis below ignoring licenses based on client user numbers.

The term ξ_j and ξ_k represent PC and server specific unobserved factors in utility and ξ_{jk} is a cross-effect between PC's and servers [16]. The term ε_{ijk} represents a buyer specific shock to utility for the particular workgroup solution selected. We will model this in our empirical work as having i.i.d extreme value distributions. Following Berry et al (1995) allow random coefficients on the parameter vector $(\beta_i^*, \gamma_i^*, \alpha_i^*)$. Heterogeneity in the parameters in the population will be critical for our theory as we will show below, because foreclosure incentives arise in this set up from the ability of the monopolist to use PC and server operating system pricing for second degree price discrimination. Not buying any server is included in this setup by allowing y_k to be the null vector. The buyer can decide not to purchase at all, which is represented by x_j and y_k both being null. We do not allow pure server purchases, i.e. x being null and y not, which is justified by complementarity.

This set up includes some strong abstractions from reality. We are assuming that purchases are independent of the server or PC stock and that

[16] The latter may be important to control for differences in server value between laptop and desktop models.

purchase decisions are only about the setup of a whole "workgroup". If server systems are used for serving one workgroup we effectively assume that the whole system is scalable by the factor $1/w$. Effectively, we are capturing all potential effects of pre-existing stocks of servers and PCs (together with their operating systems) captured by the heterogeneity in the parameter vector $(\beta_i^*, \gamma_i^*, \alpha_i^*)$. Since we are assuming that this distribution is invariant over time, we are implicitly assuming that (modulo some time trend) the distribution of stocks of computers is essentially invariant. Also note that scalability of workgroups implies that we are not allowing for any difference in firm size directly. All such differences will be incorporated into the distribution of parameters $(\beta_i^*, \gamma_i^*, \alpha_i^*)$ including a (heterogenous) constant. The idea is to make the relationship between size and purchases less dependent on functional form. However, we can distinguish between large and small businesses in the data. We can therefore control to some extent for firm size by relying on different distributional patterns across the sub-groups for which we are segmenting the market.

To derive demand, we can first define the set of realizations of the unobserved variables that lead to the choice of system jk. Formally let this set be

$$B_{jk}(x, y, p, a, w) = \{\alpha_i^*, \beta_i^*, \gamma_i^*, \xi_j, \xi_k, \xi_{jk}, \varepsilon_{ijk} | u_{ijk}(w) \geqslant u_{ilm}(w), \text{for all } l, m\}$$

The probability that a buyer of workgroup size w will purchase system

jk in period t is given by:

$$s_{jk}(w) = \int_{B_{jk}(x,y,p,a,w)} dP(\alpha_i^*, \beta_i^*, \gamma_i^*, \xi_j, \xi_k, \xi_{jk}, \varepsilon_{ijk}|w) \tag{7}$$

where $dP(.)$ is the population distribution function. The total demand for PCs of type j from users of system jk is then given by $q_{jk} = M \int w s_{jk}(w) d\Gamma(w)$, where $\Gamma(w)$ is the population distribution of workgroup sizes and $M \int w d\Gamma(w)$ is the maximum number of PCs that could possibly be sold to all buyers of all types. This means that M is the maximal number of potential workgroups. Let $s_j(w) = \sum_{k=0}^{K} s_{jk}(w)$, then the demand for PC j is given by:

$$q_j = M \int w s_j(w) d\Gamma(w) \tag{8}$$

The demand for server k from users of system jk is analogously given by $M \int s_{jk}(w) d\Gamma(w)$ and total demand for server k is given by:

$$q_k = M \int s_k(w) d\Gamma(w) \tag{9}$$

where $s_k = \sum_{j=1}^{J} s_{jk}$. Note that we are summing up from 1 to J here, because the index 0 indicates the choice where there is no PC - and therefore no server - bought. The demand for PC operating systems is then given by $q = M \int w s(w) d\Gamma(w)$, where $s = \sum_{j=1}^{J} s_j$. Let Ω be the set of server sellers k that run the server operating system sold by the same firm as the PC operating system. Then the demand for server operating systems for firm Ω is given by $q_\Omega = M \int \sum_{k \in \Omega} s_k(w) d\Gamma(w)$ and the demand for all servers is given by $q_S = M \int \sum_{k=1}^{K} s_k(w) d\Gamma(w)$.

This concludes the exposition of the base model. We will now explore some of the issues that arise in simplified versions of this model, which allow us to get more insight in how to interpret our econometric results.

3.2 A simple example

In this section we discuss a simple model that sharply demonstrates how the desire to maintain price discrimination between different buyer groups will lead to foreclosure incentives. Consider a market for PC operating systems and server operating systems. We will abstract for now from the purchase of the hardware associated with the purchase of the operating systems. To bias our results as much as possible in the direction of the one monopoly profit theory we also assume that the PC operating system and server operating system are perfect complements in the market in the sense that they are consumed in fixed proportions one to one.[17] There is a single PC operating system, $J = 1$, and there are two server operating systems: Ω of the monopolist for the PC operating system and Ω' of the rival ($K = 2$).

There are two groups of consumers called "small business" and "large business" denoted by superscripts S and L. They differ in their price sensitivity α and the value they put on server quality γ. We assume that small businesses are more price sensitive than large ones, i.e. $\alpha^S > \alpha^L$. For the small firms servers have no value, i.e. $\gamma^S a_k v_k = 0$.[18]Only large busi-

[17]All of these assumptions are made to make the benchmark model extremely simple. We relax all of them in the model that we estimate below.

[18]This assumption is not made for purpose of realism. All that is needed in the general model in thes next section is that the small business segment has a larger probability of

nesses have demand for servers, i.e. a large business (on average) values a $\gamma a_k v_k$ with $a_{\Omega'} = a < a_{\Omega} = 1$ and $v_0 = -\infty$.[19] The central assumption here is that the more price sensitive small business group also has the lower valuation for server quality. To make the model as simple as possible we assume $\beta = \xi_j = \xi_k = \xi_{jk} = 0$ for both groups. The random utility term ε^n_{ijk} is the same for both groups and perfectly correlated across k, i.e. $\varepsilon^S_{ij\Omega} = \varepsilon^S_{ij\Omega'} = \varepsilon^L_{ij\Omega} = \varepsilon^L_{ij\Omega'}$. The last assumption implies that the two servers are perfect substitutes up to a potential quality difference between them. We can then write demand for the system of PC operating system in group $n = (S, L)$ as $D^n(\omega) = D(\alpha^n \omega - \max_k\{\gamma^n a_k v_k - \omega_k\})$. We assume that the demand function $D(\cdot)$ is log-concave and that the absolute price elasticity for the small business demand for PCs is greater than that of the large business demand, i.e. $\frac{\partial D^S(\omega)}{\partial \omega} \frac{\omega}{D^S} < \frac{\partial D^L(\omega)}{\partial \omega} \frac{\omega}{D^L}$. This will be the essential driving force of our results. For simplicity, we assume that marginal costs for producing an operating system are zero ($c = c_{\Omega'} = c_{\Omega} = 0$).

3.2.1 The one monopoly profit theory

Let us first assume that the PC operating system monopolist can set different prices for small and large businesses on the PC operating system. The price to the small business segment is then simply the monopoly price and we only have to consider the pricing behavior in the market for large businesses.

choosing a no server option.

[19] The assumption that $v_0 = -\infty$ guarantees that large firms only buy both server and PC operating systems or nothing.

Equilibrium then has the following properties:

Proposition 1 *If* $v_\Omega > av_{\Omega'}$ *then the monopolist sells the server operating system and makes the profits of a monopolist in both markets with server OS quality level* v_Ω. *If* $v_\Omega < av_{\Omega'}$ *then the monopolist's rival sells the server operating system in all Pareto undominated equilibria. There is a continuum of Pareto undominated equilibria (among the firms). The worst for the monopolist has the same profits as in the case* $v_\Omega > av_{\Omega'}$, *while the best has the monopoly profits of a firm that can offer the quality* $av_{\Omega'}$.

Proof. Suppose $v_\Omega > av_{\Omega'}$. Then the best outcome a monopolist owning both technologies could get is to set $\omega + \omega_\Omega$ such that it maximizes $\left(\omega^L + \omega_\Omega\right) D(\omega^L + \omega_\Omega - v_\Omega)$. Let this solution be denoted by W^*. Consider any equilibrium price offered by firm Ω', $\omega^*_{\Omega'}$. The monopolist can always set $\omega_\Omega < v_\Omega - av_{\Omega'} + \omega^*_{\Omega'}$ and $\omega^L = W^* - \omega_\Omega$ to make all the sales and achieve the monopoly price. In particular, there is no trembling hand perfect equilibrium with $\omega^*_{\Omega'} < 0$, so that there is typically even a strictly positive ω_Ω for which this is possible. Hence, the unique equilibrium outcome has the PC OS monopolist sell the bundle at the monopoly price.

Now suppose $v_\Omega < av_{\Omega'}$. It is easy to construct equilibria in which firm Ω' is excluded and the monopolist makes the same profits as in the other case. However, any such equilibrium must be Pareto dominated by another equilibrium that allows the monopolist to make the same profits and allows firm Ω' to make a strictly positive profit. We therefore concentrate on equilibria in which the better technology is offered. Fix $\omega^*_{\Omega'} \in [0, av_{\Omega'} - v_\Omega]$. We show that any such price can be charged in a sub-game perfect equilibrium of the game. Consider the following strategy for the monopolist: Set $\omega_\Omega = \omega^*_{\Omega'} - [av_{\Omega'} - v_\Omega]$ and set ω to maximize:

$$\omega D(\omega + \omega^*_{\Omega'} - av_{\Omega'})$$

All customers buy the server OS from firm Ω'. This clearly is an equilibrium since the monopolist cannot improve on the outcome by inducing its own server product to be purchased. Conditional on that and the price of firm 2, is set optimally. Furthermore, there are clearly no incentives for firm 2 to deviate. ■

This proposition illustrates the one monopoly profit theory. The presence of a competitor can never reduce the profits of the monopolist in his monopoly market. Given the monopoly on the PC operating system, the monopolist can extract at least the monopoly profits achievable with his own system. Furthermore, complete exclusion of a superior technology is not possible.[20]

The one monopoly theory result implies that there is no incentive to degrade the quality of a rival by, for example, decreasing interoperability with

[20] There is a caveat to this statement: The profits of the alternative system are not fully extractable in all equilibria and this leads to the typical problem of oligopoly in complementary products. The overall price of the equilibrium system is too high relative to the price a monopolist would charge given he owned the better software. This effect is there in all but the equilibrium in which the monopolist extracts all the profits. However, greater profit extraction by the monopolist would also generate problems of dynamic efficiency, because they would reduce the incentives to develop alternative products. This illustrates that, even in markets in which the one monopoly profit theory holds, concerns about the extraction of rents due to market power are not innocuous because of issues of dynamic investment incentives.

a rival's server operating system. To see this, note that quality degradation of the rivals product has no effect on profits if $v_\Omega > av_{\Omega'}$. Since the monopolist can always extract all benefits through the PC OS price, the presence of a competitor in the server OS market does not limit market power of the PC OS monopolist at all. For the case $v_\Omega < av_{\Omega'}$ a rigorous conclusion is more difficult, since we have a continuum of equilibria. However, a reduction of the quality of the rival can only harm the PC OS monopolist in this case, since it eliminates the best available equilibria from the point of view of the monopolist and does not enhance monopoly profits in the worst case. Furthermore, all equilibria in which the monopolist can extract some of the rents from firm 2's quality improvement use weakly dominated strategies for firm 1. It is therefore standard in the Bertrand equilibrium literature to exclude such equilibria, leaving only the equilibrium with the lowest profit for firm 1 in the case of $v_\Omega < av_{\Omega'}$.[21] In this sense we then have a model in which a pure one monopoly profit theory holds.

3.2.2 Second degree price discrimination and foreclosure incentives

We now show that these conclusions dramatically change, when the PC OS monopolist cannot price discriminate on its PC operating systems sales between large and small business customers. If the firm controlling the PC OS also had a monopoly in the server OS market, it could still achieve price dis-

[21] More precisely, we exclude weakly dominated strategies that are not limit points of sequences of undominated strategies as, for example, Allen, Deneckere, Faith and Kovenock (2000).

crimination through the use of the server price. To see this note that optimal price setting by a monopolist would imply:

$$1+\frac{\omega^*}{D^S(\omega^*)}\frac{\partial d(\omega^*)}{\partial\omega}=0$$

and

$$1+\frac{\omega^*+\omega_\Omega^*}{D(\omega^*+\omega_\Omega^*-v_\Omega)}\frac{\partial D(\omega^*+\omega_\Omega^*-v_\Omega)}{\partial(\omega+\omega_\Omega)}=0$$

If the small business firms have a strictly more elastic demand function than the large business firms, the price on the server operating system will be higher than the quality of the server in order to exploit the lower PC demand elasticity of the large business market segment. In other words, the profit maximizing server operating system price of the monopolist is $\omega_\Omega^* > v_\Omega$. Hence, the monopolist is using the server purchases of the large business segment to achieve a form of second degree price discrimination. Since we have only two types of consumers the outcome coincides with the outcome of third degree price discrimination in this case. If we had more groups with different demands we would still only have two prices and could not achieve the outcome of third degree price discrimination. Note, that second degree price discrimination requires raising the price of the server. What is critical here is that the absolute elasticity of demand is lower for the consumer group with the higher willingness to pay for servers. In other words price discrimination allows to extract more from consumers with low α and high γ.

In the case of duopoly in the server operating system market, competition eliminates the possibility of extracting rents through the server price and thus undermines the scope for second degree price discrimination. This generates an incentive to reduce the quality of the rival in order to restore the ability to price discriminate.

To show this formally recall that firms simultaneously set ω, ω_{Ω}, and $\omega_{\Omega'}$. Then consumers decide which firm to purchase from.[22] We consider two cases: (1) the monopolist has the higher quality server software ($v_{\Omega} > av_{\Omega'}$) and (2) the monopolist has the lower quality server software ($v_{\Omega} < av_{\Omega'}$).

We consider the case in which the monopolist has the high quality software first. We first show that the monopolist cannot set a price exceeding its quality advantage, i.e. $\omega_{\Omega} \leq v_{\Omega} - av_{\Omega'}$. Suppose otherwise, then $\omega_{\Omega} - (v_{\Omega} - av_{\Omega'}) > 0$ and firm Ω' could induce the sale of its product at some strictly positive price $\omega_{\Omega'}$ slightly below $\omega_{\Omega} - (v_{\Omega} - av_{\Omega'})$ and make strictly positive profits. Since in any equilibrium in which firm Ω' makes sales $\omega_{\Omega'} \geq 0$ it follows that the monopolist could move sales to itself at some price $\omega_{\Omega} = (v_{\Omega} - av_{\Omega'}) + \omega_{\Omega'} - \varepsilon > 0$, which would generate strictly positive profits on the server sales and slightly increase demand for PC OSes to $D(\omega + \omega_{\Omega'} - av_{\Omega'} - \varepsilon)$. Hence, such a move is strictly profit improving, contradicting the assumption that firm Ω' makes the server sales. Therefore, in

[22] This is the condition of a standard Bertrand game with differences in quality. Note that we do not assume that consumers split evenly between firms in the case of indifference, which would lead to an equilibrium existence problem. Instead we allow for the possibility that buyers all go to one firm despite indifference. The equilibria we obtain this way are the same as those in a model with a smallest money unit, when the size of the money unit goes to zero. These are therefore equilibria that are robust to the strategy space.

equilibrium $\omega_1 \leq v_\Omega - av_{\Omega'}$. This shows that the monopolist is unable to fully extract monopoly rents from second degree price discrimination. Given the assumption of log-concavity of demand, demand elasticities are increasing in price and by standard arguments from third degree price discrimination it now follows that the prices set by the monopolist in the market are $\omega^e > \omega^*$, $\omega^e + \omega_\Omega^e < \omega^* + \omega_\Omega^*$ and $\omega_\Omega^e = v_\Omega - av_{\Omega'}$, where the superscript e stands indicates equilibrium values. The competing server OS company sets $\omega_{\Omega'} = 0$.

Note that the competitor limits the margin on the server OS for the monopolist to $v_\Omega - av_{\Omega'}$, which in turn limits the ability of firm Ω' to profits strictly below those under third degree price discrimination by a monopolist. It is now clear how interoperability degradation will help the monopolist. By reducing the quality of its rival through degraded interoperability with the PC operating system, the monopolist can increase its market power in the server OS market, increasing the scope for price discrimination:

Proposition 2 *Suppose $v_\Omega > av_{\Omega'}$. Then the monopolist has an incentive to degrade the quality of its rival at least up to the point that $v_\Omega - av_{\Omega'} = \omega_\Omega^*$.*

Proof. Profits of firm 1 in equilibrium are given by:

$$\Pi(\omega^e, \omega_\Omega^e(a)) = \omega^e D^S(\omega^e) + (\omega^e + \omega_\Omega^e(a))D(\omega^e + \omega_\Omega^e(a) - v_\Omega)$$

By the envelope theorem

$$\frac{d\Pi}{da} = -v_\Omega D(\omega^e + \omega_\Omega^e(a) - v_\Omega)\left[1 + \frac{(\omega^e + \omega_\Omega^e(a))}{D(\omega^e + \omega_\Omega^e(a) - v_\Omega)} \frac{\partial D(\omega^e + \omega_\Omega^e(a) - v_\Omega)}{\partial(\omega + \omega_\Omega)}\right]$$

which is negative since $\omega^e + \omega^e_\Omega < \omega^* + \omega^*_\Omega$ whenever the constraint of $\omega_{\Omega'} = 0$ is binding, i.e. when $\omega^e_\Omega = v_\Omega - av_{\Omega'}$. ■

Reducing a rival's quality increases the market power of the monopolist in the server market and allows it to get closer to the "full" monopolist's profit.[23] The only role of competition in the case $v_\Omega > av_{\Omega'}$ is to limit the rent extraction possibilities of the PC OS monopolist on his server product. This simply prevents second degree price discrimination. While the degradation of interoperability is anti-competitive in the sense that it reduces the ability of firm Ω to compete, all that competition achieves is to limit second degree price discrimination. Since the welfare effects of such discrimination are ambiguous serious welfare harm might not be demonstrated. However, in the case $av_{\Omega'} > v_\Omega$ the same incentives are at play and can potentially generate dramatic welfare effects:

Proposition 3 *Suppose $v_\Omega < av_{\Omega'}$. Then the PC OS monopolist will want to reduce the quality of the rival's product to the level $\omega^*_\Omega(v_\Omega) - v_\Omega$. He will reduce interoperability whenever this allows him to reduce the rival's quality level below its own through degraded interoperability.*

As long as it is possible to make interconnection infeasible for the monopoly firm on the PC it will therefore be in the interest of the PC OS monopolist to

[23]It should be clear to the reader that we could rewrite the above model so that there are no differences in the qualities of the server OS vendors but that their marginal cost of selling an OS differed. All results would go through simply replacing the wording "high quality" by "low cost" and the word "low quality" by "high cost". Mathematically there is no difference between raising rival's costs and reducing rival's quality in this model.

exclude an arbitrarily better product of the rival from the market in order to gain market power in the server market. The reason is that the monopolist cannot extract the benefits from the improved server OS through the PC price in any form. His profits are the same if he uses his own product. But by reducing the quality of the competitors product through interoperability degradation it is again possible to price discriminate more effectively. The PC OS monopolist is therefore willing to induce arbitrarily high social costs on business buyers to achieve more market power. This effect of excluding superior technologies through interoperability degradation is the central social loss from such strategies.

The extreme result of this simple example arises because the only effect at work is the market share shifting effect of interoperability degradation. Since in equilibrium each firm extracts the full benefit of its quality improvement, demand for PC operating systems is essentially not affected by reducing interoperability. This will be different if there is genuine product differentiation between server operating systems. We will therefore now turn to a more general model, which we will later estimate.

3.3 General Implications of the Model

We will further below estimate a version of the model in which ε_{ijk} is assumed to be iid with an extreme value distribution. We will allow for more general heterogeneity in the parameter values α, β, γ, and w. We use this model primarily to recover the margins on the PC operating system and the monopolist's server operating system. In particular, we focus on the relative markup derived from equations (4) and (5):

$$\frac{\omega_\Omega - c_\Omega}{\omega - c} = \frac{\frac{q}{q_\Omega}\varepsilon_{\omega_\Omega} - \varepsilon_\omega}{\frac{q_\Omega}{q_{PC}}\varepsilon_\omega^\Omega - \varepsilon_{\omega_\Omega}^\Omega} \tag{10}$$

which is the critical component for assessing the incentives for foreclosure through interoperability degradation. To obtain some insights about the form of heterogeneity that pushes in the direction of interoperability incentives, it is helpful to look more carefully at the exact form the numerator and denominator of this expression take for our specific model of buyer heterogeneity. As we show in Appendix B, the relevant elasticities are given by:

$$\varepsilon_\omega = -\int \frac{q(\alpha,\beta,\gamma,w)}{q} w\alpha s_{00}(\alpha,\beta,\gamma,w)dP(\alpha,\beta,\gamma,w) \tag{11}$$

$$\varepsilon_{\omega_\Omega} = -\frac{q_\Omega}{q}\int \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega} w\alpha s_{00}(\alpha,\beta,\gamma,w)dP(\alpha,\beta,\gamma,w) \tag{12}$$

$$\varepsilon_\omega^\Omega = -\int \frac{q(\alpha,\beta,\gamma,w)}{q} w\alpha s_{00}(\alpha,\beta,\gamma,w)dP(\alpha,\beta,\gamma,w) \tag{13}$$

$$\varepsilon_{\omega_\Omega}^\Omega = -\int \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega} \alpha[1 - s_\Omega(\alpha,\beta,\gamma,w)]dP(\alpha,\beta,\gamma,w) \tag{14}$$

Note that these are the typical elasticities for the logit model, i.e. the parameter of price sensitivity times the market share of the outside good, weighted for each parameter vector by the relative frequency of output demanded. We can determine the sign of ω_Ω by noting that (denoting $dP(\alpha,\beta,\gamma,w)$ as $dP(.)$

for brevity)

$$\frac{q}{q_\Omega}\varepsilon_{\omega\Omega} - \varepsilon_\omega = \int \left[\frac{q(\alpha,\beta,\gamma,w)}{q} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega} \right] [\bar{\varepsilon}_\omega - \varepsilon_\omega(\alpha,\beta,\gamma,w)] \, dP(.) \tag{15}$$

where

$$\bar{\varepsilon}_\omega = \int \varepsilon_\omega(\alpha,\beta,\gamma,w) dP(.)$$

Hence, the price cost margin on servers will be positive if the own price elasticity of the PC operating system, $\varepsilon_\omega(\alpha,\beta,\gamma,w)$, is positively correlated with $\frac{q(\alpha,\beta,\gamma,w)}{q} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}$, i.e. if on average buyers with more elastic demand have higher market share in PC purchases than the monopolist's server purchases. This will happen if firms with more elastic demand (for example firms with higher α) tend to have a higher likelihood of purchasing PCs than they are to purchase servers. This is the general expression of the idea that firms that are more price sensitive have lower valuations for server quality. We would , for example expect that smaller firms would tend to have more price elastic demand for PCs and at the same time value server quality less than larger firms. This seems intuitively plausible and we confirm this in our empirical analysis.

Note that equation (15) will be zero if there is no heterogeneity. When there is no heterogeneity in demand, the monopolist does best by setting the price of the server at marginal cost and extracting all surplus through the PC operating system price. In that case there is no incentive to price discriminate and, hence, no incentive to foreclose competitors in the server market. The greater the price discrimination incentive, the greater the server markup will be.

For ω, the price of PC operating systems, we obtain that it is proportional to:

$$\begin{aligned} \frac{q_\Omega}{q_{PC}}\varepsilon^\Omega_\omega - \varepsilon^\Omega_{\omega_\Omega} &= \int \alpha w s_{00}(\alpha,\beta,\gamma,w) \begin{pmatrix} \frac{M(\alpha,\beta,\gamma,w)-q_\Omega(\alpha,\beta,\gamma,w)}{wM(\alpha,\beta,\gamma,w)-q(\alpha,\beta,\gamma,w)} \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega} \\ +\frac{q_\Omega(\alpha,\beta,\gamma,w)}{q(\alpha,\beta,\gamma,w)} \frac{q(\alpha,\beta,\gamma,w)}{q} \end{pmatrix} dP(.) \\ &\quad -\frac{q_\Omega}{q}\left[\frac{q}{q_\Omega}\varepsilon_{\omega_\Omega} - \varepsilon_\omega\right] \end{aligned} \tag{16}$$

The term in the second line implies that the server margin weighted by the relative quantity of servers to PCs reduces the PC operating system margin. Hence, the complementarity means that whenever there is a positive server margin, the PC operating margin will be smaller than what one would conclude from looking at the PC operating system market alone.

Given estimates for the parameter vector $(\alpha, \beta, \gamma, w)$ and the parameters of the distribution $P(.)$ these expressions can be calculated directly from the estimates. We can therefore infer the margins on the monopolist's operating systems from estimating demand and the our model of the monopolist's optimizing behavior.

4 Estimating PC Demand and Software Margins

4.1 Empirical Framework

We estimate the relevant parameters of our model from data on price, quantities, and characteristics of PCs only. The empirical model of demand is derived from the model of section 3. This model follows the empirical methodology of recent studies on differentiated products. Within each customer segment we employ a random coefficients multinomial logit model with unobserved product characteristics. Individual heterogeneity is modeled through the heterogeneity of the relevant parameters.

For purposes of estimation it is useful to rewrite the conditional indirect utility, $u_{ijk}(\theta)$ in equation (6) as the sum of mean utility and individual specific effects. Denoting the unknown parameter vector as $\theta = (\theta_1, \theta_2, \theta_3, \theta_4)$ we have:

$$u_{ijk}(\theta) = \delta_j(\theta_1) + \eta_{ij}(\theta_2) + \delta_k(\theta_3) + \eta_{ik}(\theta_4) + \epsilon_{ijk}. \tag{17}$$

The first term, δ_j, is the mean utility derived from consuming PC j, which is common to all consumers in each segment. It is given by

$$\delta_j = wx_j\beta - \alpha wp_j + \xi_j, \tag{18}$$

where x_j and β are vectors of the observed product characteristics and the associated taste parameters respectively, α is the mean sensitivity of the brand to the price, p_j of PC j and ξ_j denotes utility derived from characteristics observed by the consumers and the firms, but not the econometrician. Unobserved product characteristics include unquantifiable variables such as firm or brand reputation for reliability, prestige effects or after-sales service quality. Since these characteristics are observed by market participants, they will be correlated with the equilibrium prices making the price coefficient biased towards zero. Instrumental variable techniques can not straighforwardly be applied, given that both p_j and ξ_j enter the market share equation in a nonlinear way. Berry (1994) develops a general method that allows the use of instrumental variables to a large class of discrete choice models.

The second term in equation (17), η_{ij}, represents a deviation from the mean utility. This is individual specific and can be written as

$$\eta_{ij} = \sum_h \sigma_h x_{jh} \nu_{ih} + \sigma_p p_j \nu_{ip} \tag{19}$$

where x_{jh} is the hth characteristic of product j, for $h = 1, ..., H$ and σ_h, σ_p are unknown coefficients. The vector $\nu_i = (\nu_{i1}, ..., \nu_{iH}, \nu_{ip})$ represents each consumer's $H + 1$ idiosyncratic tastes for the H observed characteristics and the associated price. It is drawn from a multivariate normal distribution with zero mean and an identity covariance matrix.[24] Notice that η_{ij} depends on the interaction of consumer specific preferences and product characteristics.

[24] The choice of this distribution is ad hoc. Although the multivariate normal is the most popular choice (e.g. BLP, Nevo, 2000a, 2001), other possibilities have also been explored (e.g., Petrin, 2002). There is no evidence that the choice of this assumption affects the estimated coefficients in any fundamental way.

More precisely, each consumer i derives $(\beta_h + \sigma_h \nu_{ih}) x_h$ utility from every hth product characteristic. Berry, Levinsohn and Pakes (1995) show that allowing for substitution patterns to depend on consumer's heterogeneous tastes (i.e. $\eta_{ij} \neq 0$) is important for realistic demand elasticities.[25] For example, consumers who attach a higher utility to laptop computers would more likely substitute towards other laptops rather than desktops. The notation is symmetric for servers

$$\delta_k = wA_k y_k \gamma - \alpha p_k + \xi_k, \tag{20}$$

and

$$\eta_{ik} = \sum_h \sigma_h x_{kh} \nu_{ih} + \sigma_p p_k \nu_{ip} \tag{21}$$

Finally, ϵ_{ijk} denotes shocks that are identically and independently distributed across products and consumers with a Type I extreme value distribution.[26] The specification of the demand system is completed with the introduction of an "outside good".Customers are allowed to not purchase

[25] When η_{ij} is zero, the only source of heterogeneity among consumers is based on the i.i.d. ϵ_{ij}'s. In terms of elasticities, that implies that all the consumers have the same expected ranking over products. In other words, consumers would substitute more towards the most popular products independently of their characteristics and the characteristics of the products they bought previously.

[26] While this particular assumption facilitates estimation by insuring nonzero purchase probabilities and smooth derivatives for the market share equation, it has recently been criticized. Petrin (2002), for example, shows that welfare changes from the introduction of new products are overstated due to the presence of this idiosyncatic error term. Alternative models, like the probit model of Goolsbee and Petrin (2004), are prohibited for the current application given the large number of products in each period. Finally, recent work by Berry and Pakes (2002) and Bajari and Benkard (2004) that remove the logit error entirely, although promising, is still under development.

any of the PCs offered by these firms. Otherwise, a uniform price increase would not change the quantities purchased. The indirect utility of the outside option is

$$u_{i0} = \xi_0 + \sigma_0 \nu_{i0} + \epsilon_{i0}. \tag{22}$$

where the price of the outside good is normalized to zero. Since relative levels of utility cannot be identified, the mean utility of one good has to be normalized to zero. As is customary, we normalize ξ_0 to zero. The term ν_{i0} accounts for the outside alternatives' unobserved variance. It implies that a random coefficient exists on the constant term for the inside goods' utility.

Each consumer is assumed to purchase one good per period[27] from the available choice set, which provides him with the highest utility. Given the assumption on the distribution of ϵ_{ijk}, the probability that consumer i purchases PC j is given by the multinomial logit choice probability (McFadden, 1973)

$$s_{ij} = \sum_{k=0}^{K} \frac{e^{\delta_j + \delta_k + \xi_{jk} + \eta_{ij} + \eta_{ik}}}{1 + \sum_{l=1}^{J} \sum_{k=0}^{K} e^{\delta_j + \delta_k + \xi_{jk} + \eta_{ij} + \eta_{ik}}} \tag{23}$$

Data constraints mean that we cannot identify the full model. First, we do not know the proportions of server of brand k being used by customers

[27] Although this assumption seems reasonable for home or small business users, it might not be applicable to the large business segment. Hendel (1999), for example, observes PC purchases of large firms and models explicitly the choice of multiple products. However, without more dissagregated information his techniques cannot be applied to the current data. Hence, if this phenomenon is widespread this model can be seen as a first approximation to the true choice model.

who purchased brand j of PCs[28]. Second, we do not have data that breaks down server purchases into larger firms relative to smaller firms so η_{ik} cannot be allowed to vary by group. In other work we allow random coefficients on servers. Given these data constraints, consider estimation of the simpler model where we abstract from the server random coefficients and unobserved PC/server hardware interactions ($\eta_{ik} = \xi_{jk} = 0$).

In this case we can write:

$$s_{ij} = \sum_{k=0}^{K} \frac{e^{\delta_j+\delta_k++\eta_{ij}}}{1+\sum_{j=1}^{J}\sum_{k=0}^{K} e^{\delta_j+\delta_k+\eta_{ij}}} = e^{\delta_j+\eta_{ij}} \sum_{k=0}^{K} \frac{e^{\delta_k}}{1+\sum_{j=1}^{J}\sum_{k=0}^{K} e^{\delta_j+\delta_k+\eta_{ij}}} \tag{24}$$

Reintroducing notation for customer groups n and markets t and taking logs we obtain:

$$\ln(s_{ij}/s_{00})_t^n = \delta_{jt}^n + \eta_{ijt} + \ln\left[\sum_{k=0}^{K}\left(e^{\delta_k}\right)_t^n\right] \tag{25}$$

Notice that the final term in equation (25) varies across markets and groups but not by brand of PC. Consequently we can estimate this equation consistently by including a full set of group n specific time dummies (τ_t^n) in the PC demand equations. The PC demand system can be estimated consistently without explicitly including server characteristics

Market shares for each product, s_j, are obtained by aggregating over consumers and their vectors of unobservable tastes. This integral is solved

[28]We have access to some of this information from other daatsources that we plan to use in future work.

numerically via aggregation by simulation, using a technique introduced by Pakes (1986).Our estimation strategy closely follows Berry (1994) and Berry, Levinsohn and Pakes (1995). In essence, the algorithm minimizes a nonlinear GMM function that is the product of instrumental variables and a structural error term. This error term, defined as the unobserved product characteristics, ξ_j, is obtained through the inversion of the market share equations after aggregating appropriately the individual consumer's preferences. Standard errors corrected for heteroskedasticity are calculated taking into consideration the additional variance introduced by the simulation. More details on the estimation techniques are given in Appendix A.

4.2 Identification and instrumental variables

Identification of the population moment condition, detailed in Appendix A, is based on an assumption and a vector of instrumental variables. We assume that the unobserved product level errors are uncorrelated with the observed product characteristics. In other words, that the location of products in the characteristics space is exogenous.[29] This is actually close to reality since most R&D and most components built in PCs are produced by other firms, not the PC manufacturers.

With respect to the instrumental variables, we experimented with various types of instruments that have been suggested in recent literature. First, in

[29] Endogenizing the firm's decision of which products to produce conditional on its beliefs about what other firms will produce and the state of future demand in a multidimensional differentiated products oligopoly is still an open research question and beyond the scope of this paper.

the spirit of the studies by Hausman, Leonard and Zona (1994), Hausman (1996), Nevo (2000a, 2001) and Hausman and Leonard (2002) we used prices of the same PC models in Canada[30] as instruments for the US prices. Their proximity and close trade relationships, implies that Canadian PC prices have the same cost components as US PC prices and only demand factors would be different[31].

The second set of instruments directly follows the Berry, Levinsohn and Pakes (1995) approach. They used the sum of the same observed characteristics of own-firm products and that of competing firms. Given the previous exogeneity assumption, characteristics of other products will be correlated with price, since the markup for each model will depend on the distance from its nearest competitors. These instruments have been used successfully to study many industries. We modify the previous instruments in the spirit of Bresnahan, Stern and Trajtenberg (1997). They used as instruments functions of the observed characteristics, segmented according to their proposed clustering of the PC market during the late 1980s. Our modification is simpler and closer to the competitive environment during the late 1990s: we calculate the sum of the observed characteristics of products offered by

[30]Given that we examine only these top nine manufacturers, we were able to match each model with the same model sold in Canada over the same period. The dataset on the Canadian models and prices is also from IDC. These prices were also deflated using the Canadian price index.

[31]Moreover, such an instrument could be partially immune to the Bresnahan (1996) critique, since aggregate shocks (such as a national advertising campaigns) that affect the US demand would be uncorrelated with the Canadian demand. The disadvantage of this instrument, however, is the small cross-sectional variation (i.e. only one instrument for each price).

each firm and its rivals, conditional on the form factor of each computer. The intuition underlying this modification is that the price of a desktop PC would be more constrained by the proximity of other desktops rather than a laptop, given their fundamental differences in functionality and technical characteristics.

4.3 Data and Estimation

Quarterly data on quantities and prices between 1995Q1 and 2001Q2 was taken from the personal computer tracker (PC Quarterly Tracker), an industry census conducted by International Data Corporation's (IDC). The PC Tracker gathers information from the major vendors, component manufacturers and various channel distributors.[32] It is one of the best available datasources for the PC industry.[33] We concentrate on the top nine producers in the US market to match each observation with more detailed product characteristics.[34] The unit of observation is defined as a manufacturer (e.g. Dell), brand (e.g. Optiplex), form factor (e.g. desktop), processor type (e.g. Pentium II), processor speed (e.g. 266 MHZ) combination. More detailed information on data sources and construction can be found in Appendix C.

In the personal computer market, manufacturers reach customers via four

[32] IDC claims that it covers more than 80% of the US market.

[33] Various datasets from IDC have been used both in economics (Foncel and Ivaldi, 2001; Van Reenen, 2004; Pakes, 2003; Genakos, 2004) and in management (Bayus, 1998; Bayus and Putsis, 1999, 2001).

[34] These manufacturers are: Acer, Compaq, Dell, Gateway, Hewlett-Packard, IBM, NEC, Sony and Toshiba. Apple was excluded due to the fact that we were unable to match more detail characteristics in the way its processors were recorded by IDC.

channels: retail stores, distributors (working with small resellers), integrated resellers and direct distribution. Given that the data is transaction rather than list prices, we implicitly assume that manufacturers set prices and that retailers act as neutral pass-through intermediaries or that they are charging constant margins. In other words, we do not model the potential strategic role of retailers, as it has been emphasized recently in the empirical economics and marketing literature.[35] Assuming no significant market power on the part of PC retailers is close to the market reality for two reasons: first, because of the fast pace of innovation and shortening of product life cycles, and second, because of the multiplicity of competing sales channels. This assumption is consistent with various industry reports[36], which indicate that computer retailers operate on very thin margins. [37]

This dataset also provides unique information on the PC buyers identity at an aggregate level, distinguishing among the following segments: large, medium and small business, small office, government, education and home.[38] Hence, in our analysis we estimate the demand model both for the whole

[35] For example, Goldberg and Verboven (2001), Sudhir (2001), Berto Villas Boas (2004), Villas-Boas and Zhao (2004) and Bonnet, Dubois and Simioni (2005) attempt to estimate retailer's strategic behavior.

[36] "The death of the reseller", *Business Week*, February 4, 1999.

[37] It is also supported by the price protection strategy followed by most PC manufacturers: if the price of a computer fell while it was in the distribution channel, the manufacturer would reimburse the reseller accordingly. See, Jan Rivkin and Michael Porter, "Matching Dell", HBS Case 9-799-158, p.7.

[38] According to IDC definitions a Small Office is a non-residential business site with less than 10 employees. Similarly, Small Business is a business site with 10 to 99 employees, Medium Business with 100 to 499 employees and a Large Business with 500 or more employees. The Home segment includes all the home purchases, regardless of usage (home office, work-at-home or consumer applications).

market and for each of the three following segments: home, small business (including the small business, small office and medium business segments)[39] and large business. These three segments account for the majority (average 89%) of all PC sales. The largest is the home segment (37%), followed by the small business (34%) and then the large business (17%).

Despite the large number of small producers, the PC industry is rather concentrated with the top five firms accounting for the 52% and the top ten firms for the 72% of the aggregate sales. Appendix Table 1 presents the average percentage shares of the nine firms included in our sample. They account for the 65% of total sales, with 60% and 65% for the home and small business segment, while they reach 80% in the large business segment.

Appendix Tables A2 through A5 provide sales weighted means of the variables that are used in the specifications below, both for the overall market and different segments. These variables include quantity (in units of 1,000), price (in $1,000 units), "benchmark"[40] (in units of 1,000), RAM (in units of 100MB), monitor size and dummies for the CD-ROM (1 if standard, 0 otherwise), internet (1 if modem or ethernet included as standard, 0 otherwise) and desktop (1 if desktop, 0 if portable). The variable choice is based on two

[39] We calculated aggregate elasticities for each of these segments based on IV logit regressions. Small office, small business and medium business have very similar elasticities and for that reason, we combine them in a single segment. We also experimented separating the medium business segment from the combined small office-small business segment. Results from either the IV logit or the random coefficients model confirmed their similarity. Analogous views for the market segmentation are also expressed by industry leaders like M. Dell, CEO of Dell (Magetra, 1998).

[40] This variable is a combination of the type and speed of each processor. See Appendix C for more details. Bajari and Benkard (2002) were the first to use this variable.

criteria: first, to capture technological innovation (i.e. the "benchmark" and RAM) and trends in related markets (i.e. the modem/ethernet for internet and CD-ROM for multimedia). Second, to be relevant both for the overall market and for the three individual segments.

These tables reveal the remarkable pace of innovation and competition in this industry. The number of products rises from 88 in 1995Q1 to 277 in 2001Q2, along an upward trend. The core computer characteristics have improved dramatically exhibiting average quarterly growth of 13% ("benchmark" memory) and 11% (RAM). New components at the start of the sample period, such as the CD-ROM and internet peripherals, that are installed in 68% and 51% of new PCs respectively, diffuse quickly and are virtually standard by the end of the sample period. Even more spectacularly, this fast technological progress is accompanied by rapidly falling prices. In real terms, the sales-weighted average price of PCs fell by 45% in the late 1990s.[41] This combination of forces allowed portable computers to become affordable for more consumers, which can be seen by the negative trend of the desktop market share. Finally, the tables reveal some interesting differences among the various segments. Large businesses, for example, buy more expensive PCs on average, with better core characteristics and a stronger preference for portable computers. They are slightly behind, however, in adopting pe-

[41] There is an extensive empirical literature using hedonic regressions that documents the dramatic declines in the quality adjusted price of personal computers. See, for example, Dulberger (1989), Gordon (1989), Triplett (1989), Berndt, Griliches and Rappaport (1995) and Pakes (2003).

ripherals.

4.4 Main results

We turn now on the demand estimates from the simple logit model and the random coefficients logit model for the overall market and each consumer segment separately, before discussing their implications in terms of the theoretical model.

The simple logit model (i.e. $\eta_{ijt} = 0$) is used in order to examine the importance of instrumenting the price and to test the different sets of instrumental variables discussed in the previous section. Table 1 reports the results obtained from regressing $\ln(s_j) - \ln(s_0)$ on prices, characteristics and a full set of time effects (by quarter). Columns 1 and 2 report OLS results. While including firm fixed effects in column (2) an improvement on column (1) as both the price coefficient and the model fit increase, the majority of products are predicted to have inelastic demands (88.4% for column (1) and 58.4% for column (2)), which is clearly unsatisfactory.

To correct for the endogeneity of price, we experiment with different instrumental variables in the last three columns. In column (3), we use Canadian prices of the same models. The price coefficient increases in absolute magnitude, as expected, but almost a quarter of all the products still have inelastic demand. There is also a perverse negative coefficient on RAM (implying that, ceteris paribus, consumers prefer lower to higher RAM) and a surprising positive desktop dummy coefficient (implying that, ceteris paribus, consumers prefer a desktop to a laptop). Moreover, the Hansen-Sargan overidentification test is rejected, suggesting that the identifying assumptions are not valid.

In column (4) of Table 1 we include "other characteristics" as suggested by Berry et al (1995) in conjunction with Canadian prices. Both the price coefficient and the proportion of inelastic demands remain largely unaffected, however. The diagnostics still reject the validity of the instruments

When we use only "other characteristics" instruments in column (5), the coefficient on price rises significantly (leaving no products with inelastic demands). Moreover, the test of overidentification restrictions cannot be rejected at the 1% level of significance, suggesting that the instruments are valid. All other coefficients are statistically significant with their expected signs, in contrast to previous columns RAM is now positive and significant as we would expect. These results suggest that Canadian prices cannot be taken as exogenous, perhaps because of common cross border demand shocks due to advertising campaigns. Consequently we keep to the modified "other characteristics" instrument set in the final column in the rest of the tables.

Other things to note in column (5) is that the "benchmark" is valued more highly than RAM and the CD-ROM availability more highly than internet peripherals. The desktop dummy indicates that consumers attach greater value to laptop computers. The only surprising result is the small negative coefficient for monitor size.[42] Finally, the processor generation dum-

[42]This most likely stems from the introduction of more advanced and thinner monitors

mies[43] indicate that each new CPU generation contributes significantly over the fourth generation, with the sixth generation contributing most. This is probably due to the significant improvements to PC hardware and software during the sixth generation and the relatively short period since the introduction of the seventh generation (the first model appears in 2000Q1)[44].

Table 2 reports results from the random coefficient model pooling across all segments. Column (1) replicates column (5) from the previous table to ease comparison. Due to the difficulty of the full model estimation, a parsimonious list of random coefficients has been selected. As Bresnahan, Stern and Trajtenberg (1997) suggested, because of the modularity of personal computers and the ease with which consumers can re-configure their machines, not all characteristics carry the same weight. For example, consumers might choose a computer that does not have a modem or a CD-ROM as standard not because they do not value it, but simply because they can buy it afterwards and possibly arbitrage any price differences. To the extent that this re-configuration can be easily done, we would not be able to capture consumers heterogeneous preferences along these dimensions. Hence, we focus here on random coefficients for the "benchmark" and desktop vari-

of the same size in the last 2-3 years of the data. These are not recorded separately.

[43] In dynamic markets with frequent changes in the processor's underlying technology, such as the PC market, competition among products of the same CPU generation differs significantly from competition with products of other generations. Applications of this idea in a standard hedonic framework can be found in Pakes (2003) and Chwelos, Berndt and Cockburn (2004), where they use indicator variables for CPU generations to estimate "piece-wise" stable coefficients for the PC characteristics.

[44] Similar results regarding the instrumental variable validity hold for each of the three market segments, but for brevity are not reported here.

ables. These are essential characteristics for every computer and cannot be altered as easily as other core characteristics (such as RAM or hard disk) or peripherals (such as the modem or CD-ROM).

Full model results are in column (2) of Table 2. The random coefficients are identified by observing multiple markets with different distributions of the observed characteristics. For the whole market, three out of four coefficients have z-statistics greater than one. Moreover, each characteristic is estimated to have a significantly positive effect either on the mean or standard deviation of the taste distribution. The magnitudes of the standard deviations relative to their means suggest that there is significant heterogeneity on price and on the preferences for desktop computers. Most of the remaining coefficients retain their signs and significance, as in the IV regressions.

The advantage of using the random coefficients model stems from the more realistic substitution patterns among PCs, which is important for the aggregate elasticities simulation. One way to test the overall model implications is to compare the estimated percentage profit margins with observed values. Most of these multiproduct firms do not report separate accounting measures for their PC operations. Even if they did, however, accounting estimates of profit margins are known to be problematic.[45] For that reason, we rely on two surveys from the Financial Times that put gross profit margins of the top PC manufacturers at 20% in 1996 and 10% in 1998.[46] Table

[45] See, for example, Fisher and McGowan (1983).

[46] "When profits switch off-line from performance: Despite record sales, PC manufacturers are struggling on slim margins", *Financial Times* (10/2/1996). "The world PC

A6 summarizes the estimated PC hardware markups and margins for the different models.[47] Markups derived from the OLS regression are too high and imply that most brands have negative marginal costs. Results from the IV regression still predict an average markup of 21 percent, which reaches 33 percent at the 90th percentile. However, profit margins are more realistic in the random coefficients model. The median is 13.4 percent ranging well within the reported values from 10.36 in the 10th percentile to 18.75 in the 90th percentile.[48]

Table 3 reports the analysis broken down by segment and is our key set of results. The first three rows contain results for the home segment, the next three for the small business segment and the final three for the large business segment. Turning to the home segment first, a qualitatively similar pattern of results emerges to that for the whole market. The coefficient on price is biased towards zero in OLS (column 1) compared to the IV logit in column 2 by a large factor. This is true across all three segments. There is also evidence in columns 3, 6 and 9 of random coefficients for price and key

market: Big name suppliers tighten their grip", *Financial Times* (4/3/1998).

[47] These quantities are calculated based on the assumption that there exist a pure strategy Bertrand-Nash equilibrium in prices. For more details see Genakos (2004).

[48] It is worth noting that our estimates fall between the other two papers that estimate a structural demand model for the PC industry. Foncel and Ivaldi (2005), using quarterly data from IDC (without the additional product characteristics on RAM, benchmark, etc. that we matcehd in manually) for the home segment from various industrialized countries during the period 1995-1999, estimate a nested logit model and report a mean margin of 2.7% for the US in 1999. Goeree (2004) using quarterly data from Gartner for the US home segment between 1996-1998 reports a median margin of 19% from her preferred model. Based on our estimates, the mean and median margins for the home segment are 12.6 and 11.5 percent respectively.

characteristics that are significantly different from zero, leading Wald tests to reject OLS and IV logit regressions in favour of the more flexible model.

There is substantial variation in the estimated coefficients between the three segments. Businesses seem to consistently have price coefficients closer to zero (i.e. less elastic demands) than households and small businesses, whatever estimation method is used. The degree of heterogeneity in the price coefficient also seems greater among large businesses (1.79) than small businesses (1.04) and households (0.88). Furthermore, businesses seem to place a higher mean valuation on quality than do households (e.g. in the random coefficients specification the mean value of "benchmark" is over 2 for large and small businesses and under 1.4 for households).

The differences among the segments, however, become more meaningful, when looking at the aggregate demand elasticities. Using the standard method of simulating a 1% increase in the price of all models, we calculate aggregate elasticities for the whole market and the three segments in Table 4. The upper and lower panels present the mean elasticities from the IV logit and random coefficients model respectively. Demand is overall more inelastic based on the random coefficients model results. This is due to random coefficients' more flexible substitution patterns both for the inside products and the outside good. A very consistent pattern of results emerges from both methods, however: the home segment has the most elastic demand and the large business segment the least elastic. For the random coefficients model the ratio of the home segment elasticity to the large business elasticity difference is about 1.8 to 1, whereas for the IV logit it is 2.5 to 1. The small business' elasticity falls between the large business and the home segment.

As we argued earlier, this heterogeneity implies that a price discriminating monopolist would have strong incentives to charge higher prices to the larger firms because they have more inelastic demand. We show in the next section that the implied relative margins from these elasticities suggests that server OS mark-ups are substantially higher than PC OS mark-ups.

5 Estimating the relative output effect and the implications for Foreclosure Incentives

5.1 The Econometric Approach

In order to empirically estimate the relative output effect, $-\frac{\left.\frac{dq(\mathbf{p}_j,\mathbf{p}_k,a)}{da}\right|_{\omega,\omega_\Omega}}{\left.\frac{dq_\Omega(\mathbf{p}_j,\mathbf{p}_k,a)}{da}\right|_{\omega,\omega_\Omega}}$, we resort to a method that makes as little assumptions as possible about the maximization behavior of rivals to Microsoft in the server market. In essence, we estimate the residual demand functions for Microsoft's PC operating system demand q and server operating system demand q_Ω. This means that we are looking at the demands when all other players in the market are setting their equilibrium prices. This residual demand function will depend on the characteristics of PCs that are sold, as well as the PC operating system, the characteristics of Microsoft and non-Microsoft servers. We consider a "reduced form" estimation of PC and server quantities, as well as on the operating system prices of Microsoft ω and ω_Ω. Note that the derivatives of residual demand with respect to interoperability a corresponds precisely to the derivatives we need to calculate the relative output effect.

One might then worry that changes in interoperability are fairly infrequent and hard to observe. However, given the assumption that server characteristics enter the indirect utility function linearly, the ratio of the derivatives is the same for any common marginal change in a given quality characteristics of rival servers. We can therefore exploit the quality variation in rival servers to identify the relative output effect. A last complication that arises is that the number of observations to identify the relevant parameters is much lower than for our demand estimation, because we cannot exploit any cross-sectional variation in our data. For that reason we construct quality indices for rival servers, Microsoft servers, and PCs in order to reduce the number of parameters to be estimated. We thus obtain estimating equations:

$$q_t = \lambda_1^{PC} I(\overline{y}_{kt,k\in\Omega}) + \lambda_2^{PC} I(\overline{y}_{kt,k\notin\Omega}) + \lambda_3^{PC}\omega_{\Omega t} + \lambda_4^{PC}\omega_t + \lambda_5^{PC} I(\overline{x}_t) + \varsigma_t^{PC} \quad (26)$$

$$q_{\Omega_t} = \lambda_1^{\Omega} I(\overline{y}_{kt,k\in\Omega}) + \lambda_2^{\Omega} I(\overline{y}_{kt,k\notin\Omega}) + \lambda_3^{\Omega}\omega_{\Omega t} + \lambda_4^{\Omega}\omega_t + \lambda_5^{\Omega} I(\overline{x}_t) + \varsigma_t^{\Omega} \quad (27)$$

where $I(\overline{y}_{kt,k\in\Omega})$ is an index of quality of servers running Microsoft server OS, $I(\overline{y}_{kt,k\notin\Omega})$ is an index of quality of servers running non-Microsoft servers OS, and $I(\overline{x})$ is an index of PC quality. Since ω_t and $\omega_{\Omega t}$ are essentially unobservable, we replace them with the implied values from equations(4) and (5) evaluated at our estimated demand parameters[49].

Given that variation in any quality characteristic will generate the same ratio of quantity changes, this will be true for variation in a quality index as well. We can therefore identify the relative output effect from the coefficients on the rival server quality index, λ_2^{Ω} and λ_2^{PC}. Hence, we estimate the relative effect of interoperability as:

$$-\frac{\left.\widehat{\frac{dq(\mathbf{p}_j,\mathbf{p}_k,a)}{da}}\right|_{\omega,\omega_\Omega}}{\left.\frac{dq_\Omega(\mathbf{p}_j,\mathbf{p}_k,a)}{da}\right|_{\omega,\omega_\Omega}} = -\frac{\widehat{\lambda_2^{PC}}}{\widehat{\lambda_2^{\Omega}}} \tag{28}$$

5.2 Data

In order to estimate the relative output effect we need data on server characteristics that was not needed for the estimation of the relative margins. This server data comes from IDC's Quarterly Server Tracker. It is built in a similar way to the PC Tracker (see Van Reenen, 2004 for more details)[50]. As with the PC tracker, information on characteristics is limited in the original IDC database so we merged in characteristics data (memory, speed, hard disk size, etc.) from a variety of other datasources. As with the PC industry there have been tremendous falls in quality adjusted prices over time for this industry.

[49] For PC OS we also experimented with using the quality adjusted price index of White et al (2004).

[50] IDC's Quarterly Server Tracker is available only from 1996Q1 ro 2001Q1, a slightly shorter time series than the PC Tracker.

5.3 Estimation Results

The results for our residual demand estimations are presented in Table 5. The first column reports a regression of the quantity of Microsoft server operating systems sold against non-Microsoft server quality (as proxied by server memory[51]), Microsoft server quality, PC quality[52], Microsoft server OS prices and the PC Windows OS price (see equation (26)). The signs of the coefficients are in line with expectations. Non-Microsoft server quality is negatively correlated with Microsoft sales and Microsoft server quality is positively correlated with Microsoft server sales. Both of these effects are significant at the 10% level. PC quality is significantly associated with higher Microsoft sales at the 5% level as we would expect from complementarity. Similarly, Microsoft server prices have a negative association with Microsoft server quantity sold, as do PC OS prices. The second column of Table 5 implements equation (27) and reports the results from a regression of PC quantities against the same variables in column (1). The pattern of the coefficients are similar to column (1) although the non-Microsoft server quality is much smaller in magnitude and statistically insignificantly different from zero. This is important as it suggests that the relative interoperability effect is small implying that there is little cost of lost PC sales from a strategy of interoperability degradation.

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[51] This was found to be the most important characteristic in the analysis of server demand in Van Reenen (2004). We experimented with other measures of server quality such as speed, but these did not give any significant extra explanatory power in the regressions.

[52] We build a quality index of PCs based on our estimates of Table 3 following Nevo (2003).

The last two columns implement an IV strategy using lagged values of the suspected endogenous variables as instruments[53]. The standard errors rise, but the pattern of coefficients is very similar to those in the first two columns. We also experimented with some other specifications such as including a trend or polynomials in time, but these were insignificantly different from zero.

5.4 Implications for the model

We use the set of parameter estimates from our model combined with empirical data to examine whether the interoperability condition holds. Recall that the condition for there to exist an incentive for degrade interoperability was given in equation (1) and is re-written below for convenience.

$$\frac{\omega_\Omega - c_\Omega}{\omega_{OS} - c_{OS}} > -\frac{\left.\frac{dq(\mathbf{p}_j,\mathbf{p}_k,a)}{da}\right|_{\omega,\omega_\Omega}}{\left.\frac{dq_\Omega(\mathbf{p}_j,\mathbf{p}_k,a)}{da}\right|_{\omega,\omega_\Omega}}$$

Intuitively, degrading interoperability increases Microsoft server sales but reduces PC sales. The benefit of doing this will depend on the size of the server margin relative to the PC margin (the "relative mark up" on the left hand side of (1)). Other things equal the larger the server OS margin $(\omega_\Omega - c_\Omega)$ relative to the PC OS margin $(\omega_{OS} - c_{OS})$ the greater the incentive to degrade. On the other hand, there is a cost as the monopolist must take into account the size of the change in demand from reducing interoperability (a down).

[53] Serial correlation would invalidate the use of these instruments, but there is no evidence of serial corretion conditional on the covariates (see base of columns 1 and 2).

We use the common w and two group case (large and small firms). The formula for the relative mark-up is given in equation (10) and the formula for the relative effect of interoperability is given in equation (28). It is clear from Figure 2 that the mark-up for server OS is much greater than that for the PC OS. This is consistent with several other pieces of data that suggest much higher margins on server OS than PC OSs[54].

Figure 2 also shows that the relative mark-up is far higher than the relative output effect of interoperability. This strongly suggests that there have been incentives for Microsoft to degrade interoperability. The fact that the relative output effect of interoperability has fallen over time (as Microsoft's share of the server market has risen) suggests that these incentives have grown stronger over time as the cost of degrading interoperability has fallen.

6 Conclusions

In this paper we examine the incentives for a monopolist to degrade interoperability in order to monopolize a complementary market. This is the main concern in the European Commissions 2004 Decision against Microsoft. The incentive to reduce rival quality in a secondary market comes from the desire to more effectively extract rents from the primary market that are limited *inter alia* by the inability to perfectly price discriminate. We have detailed a general model of heterogeneous demand in a logit framework (encompassing

[54] IDC (1999) estimate server OS prices were in the area of \$700 to \$800 in 1999. This compares to a PC OS price of around \$60. The implied relative mark-up of 12 to 13 is similar to that derived in Figure 1.

Berry et al, 1995, for example) and consider in detail a simplified version of this general model designed to capture the essential features of the empirical application (for PCs and servers). We derived the conditions under which a monopolist would have incentives to degrade interoperability and showed that these conditions are open to econometric investigation.

We implemented our method in the PC OS by estimating demand parameters using several methods including Berry et al (1995) allowing for different customer segments. We found that the ranking of the demand elasticities for the three segments (large firms had the lowest sensitivity to price, and households the greatest sensitivity). Using estimates from this model we showed that there did appear to be strong incentives for Microsoft to decrease interoperability, and that these incentives have grown stronger over time. In our view, the combination of theory with strong micro-foundations and detailed demand estimation is the correct way to confront complex issues of market abuse and should be used more often.

There are limitations over what we have done and many areas for improvement. First, our model is entirely static, whereas it is likely that dynamic incentives are also important in leveraging. Appendix E has some indications of such a dynamic model and demonstrates that our findings of leverage incentives are reinforced in this dynamic setting. An important challenge is how to effectively confront such theoretical models with econometric evidence. Second, data limitations prevented us from fully exploiting the server information, but there are many ways that this could be used more efficiently (see Davis et al, In Process), especially if we have more detailed micro-information on the demand for different types of servers. Finally, the full structure of the random coefficients approach is only partially exploited in our theoretical framework. Although we have gone some of the way in the direction of endogenising characteristic choice (interoperability decisions) there is still a long way to climb.

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Appendices

A Appendix: Estimation Details

The estimation strategy closely follows Berry (1994) and Berry, Levinsohn and Pakes (1995). The error term is defined as the unobserved product characteristics, ξ_j, that enter the mean utility. In order to compute these unobserved characteristics, we solve for the mean utility levels, δ_j, by solving the implicit system of equations

$$s\left(x_j, p_j, \delta_j; \theta_2\right) = S \tag{29}$$

where $s(\cdot)$ is the vector of the calculated market shares and S is the vector of the observed market shares. Essentially, this finds the vector δ_j, given the nonlinear parameters θ_2, that matches the predicted to the observed market shares. Berry (1994) shows that this vector exists and is unique under mild regularity conditions on the distribution of consumer tastes and in this model it is numerically calculated using BLP's contraction mapping algorithm. Once this inversion has been computed, the error term is calculated as $\xi_j = \delta_j\left(x, p, S; \theta_2\right) - \left(x_j\beta + \alpha p_j\right)$.

Given a set of instruments, $Z = [z_1, ..., z_M]$, a population moment condition can be written as $E[Z'\xi(\theta^*)] = 0$, where $\xi(\theta^*)$ is the above defined structural error term evaluated at the true value parameters. Then, following Hansen (1982), an optimal GMM estimator takes the form

$$\widehat{\theta} = \arg\min_{\theta} \widehat{\xi}(\theta)' Z A^{-1} Z' \widehat{\xi}(\theta), \tag{30}$$

where $\widehat{\xi}(\cdot)$ is the sample analog to $\xi\left(\cdot\right)$ and A is a consistent estimate of the $E\left[Z'\xi\xi'Z\right]$.

The intuition behind this procedure is straightforward. The structural residuals were defined above as the difference between the mean utility and the one predicted by the linear parameters, $\theta_1 = (\alpha, \beta)$. The purpose of the GMM estimator is simply to minimize the distance between these two predictions. At the true parameter value θ^*, the population moment condition is equal to zero, so the estimates would set the sample analog of the moments, i.e. $Z'\widehat{\xi}$, equal to zero. If there are more independent moment equations than parameters, we can not set all the sample analogs exactly to zero, but as close to zero as possible. By using the inverse of the variance-covariance matrix of the moments, we give less weight to those moments that have the higher variance. The weight matrix is calculated using the usual two step procedure, starting with an initial matrix given by $Z'Z$. The minimization of the GMM function was performed using both the Nelder-Mead nonderivative search method and the faster Quasi-Newton gradient method based on an analytic gradient. For more details see the appendix in Nevo (2000b).

Finally, using the results in Berry, Linton and Pakes (2004), we computed the predicted market shares using a smooth simulator and a large number of simulation draws (more than ten times larger than the average number of products in the sample) to obtain consistent and asymptotically normal estimators for the parameters. We compute standard errors for the estimates using the asymptotic variance of $\sqrt{n}\left(\widehat{\theta}-\theta^*\right)$ given by

$$\left(\Gamma'\Gamma\right)^{-1}\Gamma'\left(\sum_{i=1}^{3}V_i\right)\Gamma\left(\Gamma'\Gamma\right)^{-1} \tag{31}$$

where Γ is the gradient of the moments with respect to the parameters, evaluated at the true parameter values and approximated by its sampling analog. There are three possible sources of variance: the process generating the product characteristics, V_1, the consumer sampling process, V_2, and the simulation process, V_3. The first component is given by the variance of the moment conditions and approximated using its sampling analog. Given that the sample size is taken to be the household population of the US, the contribution of the second component is assumed to be negligible. Moreover, to account for the variance introduced by the simulation, we calculated the third component by bootstrapping fifty times the moment conditions to obtain an estimate of their variance across different sets of simulation draws. Due to the fact that firm and processor generation specific dummy variables are included in the estimation and also there is a high turnover of products (see also Pakes, 2003, p. 1586), we do not aggregate over moment restrictions for models across any dimension.

B Appendix: Details of derivations

Individual specific Elastcicities

$$\begin{aligned}\varepsilon_{\omega}(\alpha,\beta,\gamma,w) &= \frac{1}{q(\alpha,\beta,\gamma,w)}wM(\alpha,\beta,\gamma,w)\frac{\partial\sum_{j=1}^{J}\sum_{k=0}^{K}s_{jk}(\alpha,\beta,\gamma,w)}{\partial\omega}\\ &= \frac{1}{q(\alpha,\beta,\gamma,w)}wM(\alpha,\beta,\gamma,w)\frac{\partial}{\partial\omega}\left[\frac{\sum_{j=1}^{J}\sum_{k=0}^{K}e^{\delta_j+\delta_k+\delta_{jk}}}{1+\sum_{j=1}^{J}\sum_{k=0}^{K}e^{\delta_j+\delta_k+\delta_{jk}}}\right]\\ &= -w\alpha s_{oo}(\alpha,\beta,\gamma,w)\end{aligned} \tag{32}$$

and

$$\begin{aligned}
\varepsilon_{\omega_\Omega}(\alpha,\beta,\gamma,w) &= \frac{1}{q(\alpha,\beta,\gamma,w)} wM(\alpha,\beta,\gamma,w) \frac{\partial \sum_{j=1}^{J}\sum_{k=0}^{K} s_{jk}(\alpha,\beta,\gamma,w)}{\partial \omega_\Omega} \\
&= \frac{1}{q(\alpha,\beta,\gamma,w)} wM(\alpha,\beta,\gamma,w) \frac{\partial}{\partial \omega_\Omega} \left[\frac{\sum_{j=1}^{J}\sum_{k=0}^{K} e^{\delta_j+\delta_k+\delta_{jk}}}{1+\sum_{j=1}^{J}\sum_{k=0}^{K} e^{\delta_j+\delta_k+\delta_{jk}}} \right] \\
&= -w\alpha s_{00}(\alpha,\beta,\gamma,w) \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q(\alpha,\beta,\gamma,w)} \qquad (33)
\end{aligned}$$

$$\begin{aligned}
\varepsilon_{\omega}^{\Omega}(\alpha,\beta,\gamma,w) &= \frac{1}{q_\Omega(\alpha,\beta,\gamma,w)} M(\alpha,\beta,\gamma,w) \frac{\partial \sum_{j=1}^{J}\sum_{k\in\Omega} s_{jk}(\alpha,\beta,\gamma,w)}{\partial \omega_\Omega} \\
&= \frac{1}{q_\Omega(\alpha,\beta,\gamma,w)} M(\alpha,\beta,\gamma,w) \frac{\partial}{\partial \omega} \left[\frac{\sum_{j=1}^{J}\sum_{k\in\Omega} e^{\delta_j+\delta_k+\delta_{jk}}}{1+\sum_{j=1}^{J}\sum_{k=0}^{K} e^{\delta_j+\delta_k+\delta_{jk}}} \right] \\
&= -w\alpha s_{00}(\alpha,\beta,\gamma,w) \qquad (34)
\end{aligned}$$

$$\begin{aligned}
\varepsilon_{\omega_\Omega}^{\Omega}(\alpha,\beta,\gamma,w) &= \frac{1}{q_\Omega(\alpha,\beta,\gamma,w)} M(\alpha,\beta,\gamma,w) \frac{\partial \sum_{j=1}^{J}\sum_{k\in\Omega} s_{jk}(\alpha,\beta,\gamma,w)}{\partial \omega_\Omega} \\
&= \frac{1}{q_\Omega(\alpha,\beta,\gamma,w)} M(\alpha,\beta,\gamma,w) \frac{\partial}{\partial \omega_\Omega} \left[\frac{\sum_{j=1}^{J}\sum_{k\in\Omega} e^{\delta_j+\delta_k+\delta_{jk}}}{1+\sum_{j=1}^{J}\sum_{k=0}^{K} e^{\delta_j+\delta_k+\delta_{jk}}} \right] \\
&= -\alpha\left(1 - \frac{\sum_{j=1}^{J}\sum_{k\in\Omega} e^{\delta_j+\delta_k+\delta_{jk}}}{1+\sum_{j=1}^{J}\sum_{k=0}^{K} e^{\delta_j+\delta_k+\delta_{jk}}}\right) \\
&= -\alpha \sum_{k\notin\Omega} s_k(\alpha,\beta,\gamma,w) \qquad (35)
\end{aligned}$$

To generate the aggregate elasticities we simply need to add up the frequency weighted individual elasticities:

$$\begin{aligned}
\varepsilon_\omega &= \int \frac{q(\alpha,\beta,\gamma,w)}{q} \varepsilon_\omega(\alpha,\beta,\gamma,w) dP(\alpha,\beta,\gamma,w) \\
&= -\int \frac{q(\alpha,\beta,\gamma,w)}{q} w\alpha s_{00}(\alpha,\beta,\gamma,w) dP(\alpha,\beta,\gamma,w) \qquad (36)
\end{aligned}$$

$$
\begin{aligned}
\varepsilon_{\omega_\Omega} &= \int \frac{q(\alpha,\beta,\gamma,w)}{q} \varepsilon_{\omega_\Omega}(\alpha,\beta,\gamma,w) dP(\alpha,\beta,\gamma,w) \\
&= -\int \frac{q(\alpha,\beta,\gamma,w)}{q} w\alpha s_{00}(\alpha,\beta,\gamma,w) \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q(\alpha,\beta,\gamma,w)} dP(\alpha,\beta,\gamma,w) \\
&= -\frac{q_\Omega}{q} \int \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega} w\alpha s_{00}(\alpha,\beta,\gamma,w) dP(\alpha,\beta,\gamma,w) \qquad (37)
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon_\omega^\Omega &= \int \frac{q(\alpha,\beta,\gamma,w)}{q} \varepsilon_\omega^\Omega(\alpha,\beta,\gamma,w) dP(\alpha,\beta,\gamma,w) \\
&= -\int \frac{q(\alpha,\beta,\gamma,w)}{q} w\alpha s_{00}(\alpha,\beta,\gamma,w) dP(\alpha,\beta,\gamma,w) \qquad (38)
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon_{\omega_\Omega}^\Omega &= \int \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega} \varepsilon_{\omega_\Omega}^\Omega(\alpha,\beta,\gamma,w) dP(\alpha,\beta,\gamma,w) \\
&= -\int \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega} \alpha[1 - s_\Omega(\alpha,\beta,\gamma,w)] dP(\alpha,\beta,\gamma,w) \qquad (39)
\end{aligned}
$$

We can then determine the sign of ω_Ω and ω_{OS} by noting that (denoting $dP(\alpha,\beta,\gamma,w)$ as $dP(.)$ for brevity)

$$
\begin{aligned}
\frac{q}{q_\Omega}\varepsilon_{\omega_\Omega} - \varepsilon_{\omega_{OS}} &= \int \left[\frac{q(\alpha,\beta,\gamma,w)}{q} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}\right] \left[w\alpha s_{oo}(\alpha,\beta,\gamma,w)\right] dP(.) \\
&= -\int \left[\frac{q(\alpha,\beta,\gamma,w)}{q} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}\right] \left[\varepsilon_\omega(\alpha,\beta,\gamma,w)\right] dP(.) \\
&= \int \left[\frac{q(\alpha,\beta,\gamma,w)}{q} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}\right] \left[\bar{\varepsilon}_\omega - \varepsilon_\omega(\alpha,\beta,\gamma,w)\right] dP(.) \qquad (40)
\end{aligned}
$$

where the last equality comes from subtracting $-\int \left[\frac{q(\alpha,\beta,\gamma,w)}{q} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}\right] \bar{\varepsilon}_\omega dP(.) = 0$ from the second line where

$$
\bar{\varepsilon}_\omega = \int \varepsilon_\omega(\alpha,\beta,\gamma,w) dP(.)
$$

For ω, the price of PC operating systems we obtain that it is proportional to:

$$
\begin{aligned}
\frac{q_\Omega}{q}\varepsilon^{\Omega}_{\omega} - \varepsilon^{\Omega}_{\omega_\Omega} &= \int \alpha w s_{00}(\alpha,\beta,\gamma,w) \begin{pmatrix} \frac{M(\alpha,\beta,\gamma,w)-q_\Omega(\alpha,\beta,\gamma,w)}{wM(\alpha,\beta,\gamma,w)-q(\alpha,\beta,\gamma,w)} \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega} \\ +\frac{q_\Omega(\alpha,\beta,\gamma,w)}{q(\alpha,\beta,\gamma,w)} \frac{q(\alpha,\beta,\gamma,w)}{q} \end{pmatrix} dP(.) \\
&\quad -\frac{q_\Omega}{q} \int \alpha w s_{00}(\alpha,\beta,\gamma,w) \left[\frac{q(\alpha,\beta,\gamma,w)}{q} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega} \right] dP(.)
\end{aligned} \tag{41}
$$

C Appendix: Data Construction

As noted in the Data section, quarterly data on quantities and prices[55] between 1995Q1 and 2001Q2 was taken from the PC Tracker census conducted by International Data Corporation's (IDC). The available dataset provided disaggregation by manufacturer, brand name, form factor,[56] chip type (e.g. 5th Generation) and processor speed bandwidth (e.g. 200-300 MHz). However, during the late nineties, there was a surge in the number and variety of new processors, with Intel trying to achieve greater market segmentation by selling a broader range of vertically differentiated processors. At the same time the rise of the internet and the proliferation of the multimedia meant that PCs were differentiated in a variety of dimensions that would be essential to control for. For that purpose we concentrated on the US market and focused on the top nine manufacturers, who represented the majority of sales and for whom reliable additional information could be collected.

Therefore, we matched each observation in the IDC dataset with more detailed product characteristics from various PC magazines.[57] In order to be consistent with the IDC definition of price, we assign the characteristics of the median model per IDC observation if more than two models were available. The justification for this choice is that we preferred to keep the transaction prices of IDC, rather than substitute them with the list prices published in the magazines. An alternative approach followed by Pakes (2003) would be to list all the available products by IDC observation with their prices taken from the magazines and their sales computed by splitting the IDC quantity

[55] Prices are defined by IDC as "the average end-user (street) price paid for a typical system configured with chassis, motherboard, memory, storage, video display and any other components that are part of an "average" configuration for the specific model, vendor, channel or segment". Prices were deflated using the Consumer Price Index from the Bureau of Labor Statistics.

[56] Form factor means whether the PC is a desktop, notebook or ultra portable. The last two categories were merged into one.

[57] The characteristics data was taken from PC magazines (PC Magazine, PC Week, PC World, Computer Retail Week, Byte.com, Computer User, NetworkWorld, Computer World, Computer Reseller News, InfoWorld, Edge: Work-Group Computing Report, Computer Shopper) and Datasources.

equally among the observations. Although, clearly, both approaches adopt some ad hoc assumptions, qualitatively the results would probably be the same. Both list and transaction prices experienced a dramatic fall over this period and the increase in the number and variety of PCs offered would have been even more amplified with the latter approach. Finally, instead of using the seventeen processor type dummies and the speed of each chip as separate characteristics, we merge them using CPU "benchmarks"[58] for each computer. Our final unit of observation is defined as a manufacturer (e.g. Dell), brand (e.g. Optiplex), form factor (e.g. desktop), processor type (e.g. Pentium II), processor speed (e.g. 266 MHZ) combination with additional information on other characteristics such as the RAM, hard disk, modem/ethernet, CD-ROM and monitor size.

Small businesses are those employing less than 400 employees and large businesses are all those private sector organizations employing more than 400 employees. We drop the government and education sectors from the analysis.

The potential market size for the Home segment is assumed to be the number of US households (taken from the Current Population Survey), whereas for the Small and Large business is the total number of employees as reported in the Statistics of US Businesses. We performed various robustness checks by reducing the market sizes or by fitting different diffusion curves (see Genakos, 2004). None of the results change in any fundamental way.

D Appendix: Matching results with the model

To implement the simulation described in Figure 1 we draw on parameters estimated form the econometrics, the model and data. We use estimates from various datasources in addition to the parameter estimates. We use estimates for the total numbers of PCs by customer type are from the IDC PC Tracker and the total server numbers are from the IDC Quarterly Server Tracker. The potential market is fixed by the total number of workers in the US working in small firms (under 400 employees) in the small business segment or in large firms (over 400 employees). We use the Harte Hanks Survey of firms to estimate the proportion of all Microsoft servers used by small businesses and the proportion of businesses who have PCs but no servers. The average PC to server ratio (w) is fixed at the aggregate ratio of PCs in the business sector to servers.

Note that we consider only small firms and large firms and assume that Microsoft can perfectly price discriminate between the home and business segments. Although Microsoft does charge a higher price for the Home and Professional editions of XP, it is unlikely that this is perfect price discrimi-

[58] CPU benchmarks were obtained from *The CPU Scorecard* (www.cpuscorecard.com). They are essentially numbers assigned to each processor-speed combination based on technical and performance characteristics.

nation due to some arbitrage. If we allowed for some restraint on price discrimination between home and business segments then this would obviously increase Microsoft's incentives to degrade interoperability as there would be even more unexploited rents from the PC operating system.

E Appendix: The long run anti-competitive effects of interoperability degradation

Even when the one monopoly profit theory holds in the short run it is now well recognized that in a world with incomplete contracts there can be important incentives for exclusionary conduct like the degradation of interoperability because of their impact on long run market power. This is similar to Bernheim and Whinston's paper on exclusive dealing which makes the basic mechanism that generates incentives for exclusionary conduct particularly transparent. The important contribution their paper is precisely in making the mechanism transparent. The fact that they look at exclusivity clauses in contracts as one particular exclusionary strategy and that they use an exit mechanism to increase the market power of the firm using the exclusionary strategy in the future are secondary modelling issues. The basic mechanism unveiled is applicable to any strategy with short run exclusionary effects and any mechanism by which the long run competitiveness of the firm that suffers the exclusionary practice is reduced.

In the economic literature exclusionary effects, be they complete through exit or partial through a reduction of the competitiveness of the rival, always rely on two ingredients. First, there has to be some (potentially costly) activity that could potentially directly shift market share to the firm that is trying to generate an exclusionary effect. Secondly, this shift in market share somehow has to reduce the ability of a rival to compete in the future. We will now show that it is a simple exercise to translate these mechanisms into a formal model that is driven by the particular conditions in the software industry.

E.1 A Model of long run exclusion based on applications network effects.

We will simplify the model above a little to have the simplest one monopoly profit model imaginable, but extend it by allowing other complementary products offered by third parties: server specific applications. All buyers have the same value for the overall product: $v + a_i f(n_i)$, where v is the intrinsic value of the PC OS, a_i is the quality parameter for the server OS interoperating with the PC OS. $f(n_i)$ scales this quality by the number of applications n_i that are available, where we assume that $f(0) = 1$. We assume that $f(n)$ is increasing, strictly concave and the Inada conditions hold. The interaction with server quality parameter a_i indicates a complementarity between server functionality and applications. We also assume that there are no customers that only want the PC OS.

We now look at a dynamic game. In the first stage the PC OS monopolist that also owns the server OS 1 can decide to degrade interoperability with server OS 2. Then both firms compete for customers that will use the operating systems for two periods. In the third stage independent outside companies decide whether or not to invest in developing an applications software for one or the other server OS. Then server operating systems are improved through an exogenous (stochastic) process. We assume that any quality increase in the server OS will be available at no cost to customers who have already bought the software through an upgrade to the old server OS.[59] In the fourth stage the PC OS monopolist and its rival in the server OS market again market their products to a new generation of demand. Finally, in stage 5, applications developers market their applications by setting prices to the final customers.

The last stage of this game can be trivially solved by noting that every application software developer can extract the marginal benefit of his software from a buyer for whose server OS he has written the software. This follows because all buyers who own a given system in the last period will have the same preferences. Hence, the outcome is the same whether we have uniform pricing or buyer specific pricing. Hence, $p_{n_i} = a_i f'(n_i)$ will be the price an applications developer can obtain for each copy in the last period market.

In the fourth stage of the game, the sellers of operating systems face two different customer groups. There is a group that has already purchased an operating system. We assume for simplicity that they will be out of the market. Then there is a new group of customers that newly enter the market (either a new generation or people who were not active as buyers in the previous period because of existing equipment whose equipment has now fully depreciated). Let $\theta_i a_{i1}$ be the server OS quality level achieved by stage 4, where $\theta_i \geq 1$ represents the exogenous quality improvement of the server since stage 2 and a_{i1} the initial quality level. The equilibrium at this stage can then be derived by exactly the same arguments as in section 2 of this paper. We obtain:

Lemma 4 *Let $A_i(\theta_i, n_i) = \theta_i a_i \left[f(n_i) - f'(n_i)n_i\right]$, then: (i) If $A_1(\theta_1, n_1) > A_2(\theta_2, n_2)$, then the PC OS monopolists makes all sales in period 4 of both the PC OS and the server OS extracting the whole value $v + A_1(\theta_1, n_1)$ from the consumer. (ii) If $A_1(\theta_1, n_1) < A_2(\theta_2, n_2)$, then in an equilibrium that does not involve strictly dominated strategies, the PC Os monopolist extracts*

[59] This assumption is inessential for our results but simplifies notation. The assumption also means we do not have to separately look at cases of uniform prices of application software across generations or price discrimination. Again such distinction would make no difference for the qualitative results.

a rent of $v + A_1(\theta_1, n_1)$ *from each customer, sets server price* $p_1 = 0$*, and firm* 2 *sells the server OS at price* $A_2(\theta_2, n_2) - A_1(\theta_1, n_1)$*.*

Proof. Note that given n_1 applications are being developed for server OS 1 and n_2 applications for server OS 2, buyers anticipate buying all of these applications at a total expense of $\theta_i a_i f'(n_i) n_i$. Hence, their willingness to pay for the bundle i is given by $v + \theta_i a_i \left[f(n_i) - f'(n_i)n_i\right]$. Then the whole problem is just like the one in the first section only with $\theta_i a_i \left[f(n_i) - f'(n_i)n_i\right]$ replacing the quality parameter of the particular server. The result then follows. ■

A central ingredient in this model is stage 3 at which applications developers have to decide whether to invest into developing an applications software and for which of the server OSs they want to develop the software. We normalize the size of the total population of each generation to a mass of 1. Let s_{it} be the (expected) market share of server OS i in generation t. We assume that applications developers are monopolistically competitive so that they do not perceive an impact of their investment on the total number of applications written for each server OS. The cost of developing an applications software is F. Hence, a software developer will have an incentive to invest in an application for server OS i if and only if:

$$E_{n_i, a_i}\left\{p_{n_i}(a_i) x_i\right\} \geq F$$

where x_i is the number of applications sold. With a continuum of potential applications developers and letting s_{i1}be the first period market share, the equilibrium condition becomes

$$\left(s_{i1} E\{\theta_i\} + \int_1^\infty \int_{\hat{\theta}_i}^\infty \theta_i dG(\theta_i) dG(\theta_j)\right) a_i f'(n_i^*) = F \tag{42}$$

where $\hat{\theta}_i = \max\{1, \theta_j \frac{a_j\left[f(n_j^*) - f'(n_j^*)n_j^*\right]}{a_i\left[f(n_i^*) - f'(n_i^*)n_i^8\right]}\}$. Note that the left hand side of (42) becomes arbitrarily large as $n_i \to 0$. Furthermore, as $n_i \to \infty$, $f'(n_i) \to 0$ and, since the expression in brackets cannot exceed $(s_{i1} + 1) E\{\theta_i\}$, the left hand side converges to zero. Hence, there exists a solution n_i^* to this equation. Note that on the left hand side of these equations an increase the number of applications written for a specific server OS generates two countervailing effects on the marginal returns of further investments into applications for that server. First there is the direct marginal benefit effect. This is always negative. The second comes in through a network effect. More applications increase the probability that the server type for which the software was written will be the one that is sold in period 4. Now note that at an equilibrium the marginal direct effect must always outweigh the marginal network effect of entry because otherwise a marginal firm could enter and generate strictly positive profits. Hence, we have:

$$\left(s_{i1}E\{\theta_i\} + \int_1^\infty \int_{\hat{\theta}_i}^\infty \theta_i dG(\theta_i)dG(\theta_j)\right)\frac{f''(n_i^*)}{f'(n_i^*)} + \frac{\partial \hat{\theta}_i}{\partial n_i}\int_1^\infty \hat{\theta}_i g(\hat{\theta}_i)dG(\theta_j) < 0$$

at an optimal entry decision given n_j^*. We will assume for the sake of technical simplicity that there exists only a single n_i^* for any given n_j^* that satisfies the equation above. From this we can now directly sign the changes in incentives that result from changes in the parameters applications developers face:

Lemma 5 *The number of applications for server i increases in s_{i1} and a_i and decreasing in n_j^* and a_j.*

Proof. Let $L(n_i^*, v)$ be the left hand side of the free entry condition above and v one of the parameters. Then comparative statics with respect to a variable v are given by:

$$\frac{dn_i^*}{dv} = -\frac{L_v}{L_{n_i^*}},$$

where $L_{n_i^*} < 0$ by the second equilibrium condition. Then the result follows from the fact that $L_{s_{i1}} > 0, L_{a_i} > 0$, $L_{n_j^*} < 0$ and $L_{a_j} < 0$. ■

A higher market share in the first period implies that there is a higher customer base when the applications have been written. This is a direct effect of first period purchases on second period demand for applications. The other comparative statics effects are mediated through the impact on second period server sales. Essentially, increasing the relative quality of one server OS will increase the marginal benefit from writing for that server OS because it becomes more likely to be adopted by the new generation. This relative quality increase can come first because an earlier quality advantage may make it more likely that quality is also better in the future and, secondly, that more applications will also increase the probability that the product is adopted, leading to a positive feedback (network effect) on the incentives for developing applications. Indeed, these comparative statics carry over to the equilibrium behavior.

Proposition 6 *In the best and worst equilibrium from the point of view of firm i, n_i^* increases and n_j^* decreases as s_i and a_i increase and as a_j decreases.*

Proof. Equilibrium conditions are the same as in a two player game in which player i maximizes payoffs

$$\int_0^{n_i^*}\left[\left(s_{i1}E\{\theta_i\} + \int_1^\infty \int_{\hat{\theta}_i}^\infty \theta_i dG(\theta_i)dG(\theta_j)\right)a_i f'(n_i) - F\right]dn_i$$

over n_i^*. This game is supermodular in $(n_i^*, -n_j^*)$ and has positive first differences in (n_i^*, s_i), (n_i^*, a_i) and $(n_i^*, -a_j)$ as well as in $-n_j^*$ and these three parameters. Hence, by Milgrom and Roberts (1991) the claimed comparative statics properties follow. ■

While there may be multiple equilibria, the set of equilibrium outcomes systematically moves with first period market share and first period quality. The first one is the most fundamental effect, since it occurs because operating systems are a durable good that will generate a stock of demand for complements in the future (see Kühn and Padilla 1996 for a basic discussion of the demand creating role of durables for complementary goods in the future). The second effect comes about because of any effects of quality provided to the first generation on quality provided to the next generation. If this relationship were completely random there would be no such effect. If the state of technology determines to some degree how likely the possibility of overtaking the rival in quality is, then first period quality differences will be amplified through the third period applications development decisions.

It may be argued that any quality degradation initially could be reversed later on, so that interoperability decisions would have no systematic direct effect on third period applications investment decision. Even then the indirect effect through the established market share of a server OS i initially will have a systematic effect. For this reason our results will not be affected if we would allow the period 1 decision of the PC OS monopolist to be reversed before stage 3.

We are now in a position to analyze competition between the suppliers of server OSs for the first generation of customers. Customers will be forward looking and anticipate the development of applications in the future. Hence, their value of purchasing the PC OS together with a server OS from firm i is given by:

$$2v + a_i[1 + E\{\theta_i\}[f(n_i^*) - f'(n_i^*)n_i^*]] - w - p_i$$

Note that n_i^* will depend not only on a_i and a_j, but also on s_i, the market share a buyer expects server OS i to have in the market in his own generation. This implies that there is a network effect among buyers of the same generations. A buyer of server OS i wants other buyers to purchase that server OS as well because this improves the provision of applications software in the future.

Define $\Psi_i(s_1) = a_i[1 + E\{\theta_i\}[f(n_i^*(s_1) - f'(n_i^*(s_1)n_i^*(s_1)]]$. First generation Customers will purchase from firm i, if

$$2v + \Psi_i(s_1(p_i, p_j)) - p_i > 2v + \Psi_j(s_1(p_i, p_j)) - p_j$$

and

$$2v + \Psi_i(s_1(p_i, p_j)) - p_i \geq w$$

where $s_1(p_i, p_j)$ is the market share of firm 1 if server prices p_i and p_j are charged. Clearly, the coordination issue between buyers complicates the analysis here, because a price cut may induce a switch away from the price cutting firm if buyers expect other buyers to switch away as well.

To analyze this game we also need to specify the precise payoffs of the firms. The payoff of the PC OS monopolist is given by:

$$w + s_1 p_1 + v + E_{\theta_1}\{A_1(\theta_1, n_1^*(s_1))\}$$

The firm gets w from all buyers in the first period and p_1 from those that purchase its server OS. Furthermore, we have shown in Lemma 1 that its profits from the second generation of consumers is $v + E_{\theta_i}\{A_1(\theta_1, n_1^*(s_1))\}$. Hence the PC OS monopolist gains both from first generation customers from increased market share in the standard way, but also benefits because his expected profits are rising in the number of second period customers. The payoffs of firm 2 are given by:

$$(1 - s_1)p_2 + E_{\theta_1,\theta_2}\{\max\{A_2(\theta_2, n_2^*(s_1)) - A_1(\theta_1, n_1^*(s_1)), 0\}\}$$

Again, winning market share today leads to higher profits from first generation customers but also allows a larger extraction of rents from second period customers as well. The following Proposition repeats the basic results of the simple model of section 2:

Proposition 7 *(i) Suppose $\Psi_1(1) > \Psi_2(1)$, then in any equilibrium in which all first generation customers purchase from the same firm, $p_1^* \leq \Psi_1(1) - \Psi_1(1)$, and firm 1's equilibrium profits are $3v + \Psi_1(1) + E_{\theta_1}\{A_1(\theta_1, n_1^*(1))\}$. (ii) Suppose $\Psi_2(1) > \Psi_1(1)$, then in any equilibrium in which all first generation customers purchase from the same firm, $p_2^* = \Psi_2(1) - \Psi_1(1)$, and firm 1's equilibrium profits are given by $3v + \Psi_1(1) + E_{\theta_1}\{A_1(\theta_1, n_1^*(0))\}$.*

Proof. Consider an equilibrium in which all first generation customers buy from one of the two firms and let $\Psi_i(1) - \Psi_j(1) > 0$. Suppose firm j makes the sales at a price $p_j \geq 0$. Then firm i could lower the price to $p_j + \Psi_i(1) - \Psi_j(1) - \varepsilon > 0$ and obtain a strict profit in the first period and also increase its second period profit. Hence, firm i makes the sale. Since $p_j \geq 0$, it can make the sale at any price $p_i \leq \Psi_i(1) - \Psi_j(1)$. If $i = 2$ the firm will charge at least $\Psi_i(1) - \Psi_j(1)$ in equilibrium. If $i = 1$ it could charge a price below $\Psi_1(1) - \Psi_1(1)$ and increase the whole sale price w to make up the difference. Suppose firm i would charge more than $\Psi_i(1) - \Psi_j(1)$. Then firm j could induce all customers to switch at a price $p_j > 0$, contradicting the claim that this is an equilibrium. Existence of such an equilibrium is also straightforward to see. ■

This proposition is entirely analogous to the equilibrium characterization result in section 2. Relative to the first generation of consumers the PC OS monopolist can extract the same surplus independently of whether his server OS is purchased or not. However, his extraction possibilities relative to the second generation depend on his market share in the first generation market.[60] Hence, if the PC OS monopolist looses the first stage competition, his profits will be strictly lower, than when he wins it. It should be noted that it is possible to have some other equilibria in this model in which the two firms share the market. However, any such equilibria would be sustained by beliefs that a price cut by a firm would induce customers to switch away from that firm. Such switch would be made credible for each customer by the quality enhancing effect of the switch of others. Such equilibria rely on a perverse coordination effect where, locally, firms face upward sloping residual demands at equilibrium. We believe for practical purposes it is safe to assume that firms expect residual demand for a product never to decrease if the price for that product falls. Then the equilibria we have characterized here are the only equilibria in this market.

E.2 The incentive to degrade interoperability

It is now easy to see that degradation of interoperability can be a profitable strategy for the monopolist. This works through two channels. First, if the degradation of interoperability in stage 1 is permanent and reduces the quality of the rival's product in the future this will shift investment in applications software away from firm 2 and two firm 1. This could also happen if the reduction in interoperability reduces the likelihood that firm 2 will produce an overtaking innovation in stage 4. As far as information about existing technology increases the ability to innovate further, this is a realistic issue in this market. Secondly, the PC OS monopolist also has an incentive to degrade interoperability when its rival has a better server product in terms of the expected net present value to buyers. By degrading interoperability the monopolist can inefficiently switch the choices of the first generation. The incentive to do this comes from the ability to extract more surplus from second generation buyers in the future. We will discuss in the next section, that this is precisely the type of mechanism that Bernheim and Whinston employ in their exclusive dealing paper.

Proposition 8 *The PC OS monopolist has strict incentives to degrade interoperability with the server OS of firm* 2. *If second period quality is not*

[60] This result depends on the assumption that firms cannot set negative prices. If arbitrarily negative prices could be set the bidding process would bring the prices of firm 1 down to its opportunity costs of loosing business in the second generation market and a neutrality result would occur. However, this is would be a highly questionable model given that at negative prices everyone would want to buy the OS even if it is not used.Furthermore, many slight variations of the model will make the PC monopolist care about his margin in the server OS market (as for example in our model that demonstrated the short run effect or in a model with some product differenbtiation) and the qualitative results of such extensions are better captured in the model with the assumption that price cannot become negative.

directly affected by current restrictions on interoperability, reductions in interoperability will still be profitable if firm 2 is more efficient and the reduction in interoperability is large enough.

Proof. The profits of firm 1 in this market are given by $\Pi_1(a_2) = 3v + \Psi_1(1) + E_{\theta_1}\{A_1(\theta_1, n_1^*(s_1))\}$. Let a_2^u be the undegraded quality level and a_2^d be the quality level after degradation of interoperability. Clearly,

$$\begin{aligned}\Pi_1(a_2^u) - \Pi_1(a_2^d) &= -\int_{a_2^d}^{a_2^u} \frac{d\Psi_1(1)}{da_2} da_2 - E_{\theta_1}\{\int_{a_2^d}^{a_2^u} \frac{\partial A_1(\theta_1, n_1^*(s_1))}{\partial n_1^*} \frac{\partial n_1^*(s_1)}{\partial a_2} da_2 \\ &\quad + \left[E_{\theta_1}\{A_1(\theta_1, n_1^*(a_2^d, 1))\} - E_{\theta_1}\{A_1(\theta_1, n_1^*(a_2^d, s_i))\}\right]\end{aligned}$$

where the first line of the right hand side is the effect that comes from the degradation of future quality of the rival through current reduction in interoperability, keeping the initial market share constant. The second line is the impact of a change in current quality of the rival through current reductions in interoperability. This effect is clearly zero if the PC OS monopolist was already making all the sales of the server OS. However, if the rival were to sell the server OS in an equilibrium without quality degradation, the PC OS monopolist always has the choice of reducing interoperability so much that using the rival server Os is useful. This will clearly increase second period profits by increasing the ability to extract rents from second period customers. It has no costs in terms of first period sales, on the contrary, if the current quality degradation also lowers future quality of the rival server OS this effect will be reinforced. ■

It should be stressed that we started from a one period model in which the one monopoly profit theory holds. As soon as in a two period framework it is not possible to extract all the benefits firm 1 could get as a monopolist without competition, there is an incentive to degrade the rival's server OS quality in order to achieve extraction possibilities in the last period. The way first period market shares matter for second period profit extraction possibilities is through the well recognized applications network externality present in markets for operating systems. Any artificially generated shift in first period market share is translated into greater relative investments in applications for the PC OS monopolist's server OS. This same effect could equally be generated through increasing the cost of the rival, because it simply works through the resulting market share effect. Similarly, this effect will work if it is sufficiently costly to counteract rivals sabotage through interoperability decisions, so that it is unprofitable to overcome the quality degradation induced by degraded interoperability. These are results that should be regarded as very robust and are fully in line with recent work on exclusionary strategies by Bernheim and Whinston (1998), Rey, Tirole, and Seabright (2001), Cremer, Rey, and Tirole (2000), and Carlton and Waldman (2000).

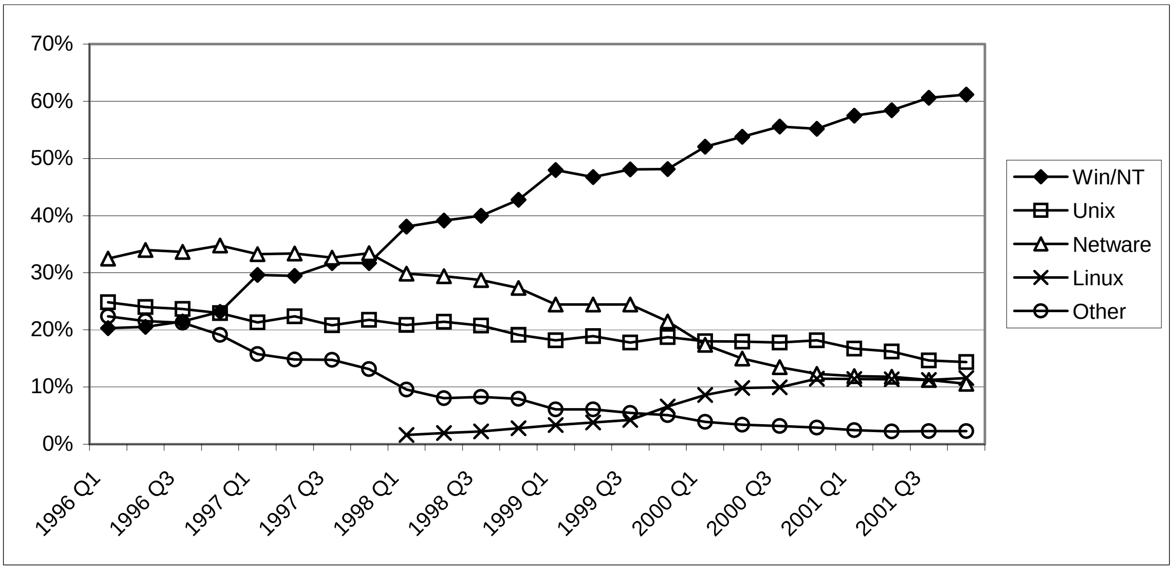
E.3 An extension covering broader claims

The model we have developed above has much broader interpretations than the literal interpretation given in the model exposition section. First, the modelling of interoperability degradation as a direct reduction in the quality of the rival server OS is just for modelling convenience: it makes the verbal discussion more transparent because we only have to talk about the different server OSs and their qualities and not of the "qualities of the PC OS/server OS bundles". In reality Microsoft does, of course, not degrade the quality of the rival server OS. Instead it degrades the quality of its own PC OS whenever that PC OS interoperates with a Microsoft server. The model should make clear that such a distinction is only semantic. All that matters for the arguments in our models is that, by reducing interoperability, the overall quality of the PC OS/rival server OS system is reduced. We could formulate this explicitly, but mathematically the two models would be identical. Quite generally, this is an access problem to the functionalities of the PC OS and the models show that discriminatory access quality degradation is a real possibility in such markets.

This discussion should also make clear that our choice of letting the applications network effect run through server applications is an arbitrary one. In particular, the story of defensive leveraging against rival server OSes becoming a substitute for future editions of the Microsoft PC OS is covered by this analysis. All we need is that there is an interaction term between interconnection (i.e. server quality) and the value of applications run on either the server or the PC. In this slight modification of the model, applications producers would decide to either write applications to run on the Microsoft PC OS or as thin client applications on the rival server OS. Just as Netscape combined with Java could be used as an alternative platform for applications software writers, a server OS could be used as a platform for applications that only require minimal functionality on the PC desktop. It should be clear to the reader that the model could simply be reinterpreted in that way given that the a_i term can be treated as the quality of a specific bundle solution regardless of where applications are run. However, it should be pointed out that there is an additional effect that strengthens the argument even more. When applications are written to the server OS as thin client applications, customers have no need of upgrading the PC OS. Hence, there is the additional effect that such applications development will reduce the demand for PC OSs in the future, creating additional incentives for early exclusion of rival server OSs. Foreclosure via exclusive dealing arrangements is the most appropriate analogy for understanding the foreclosure effects of degraded interoperability.

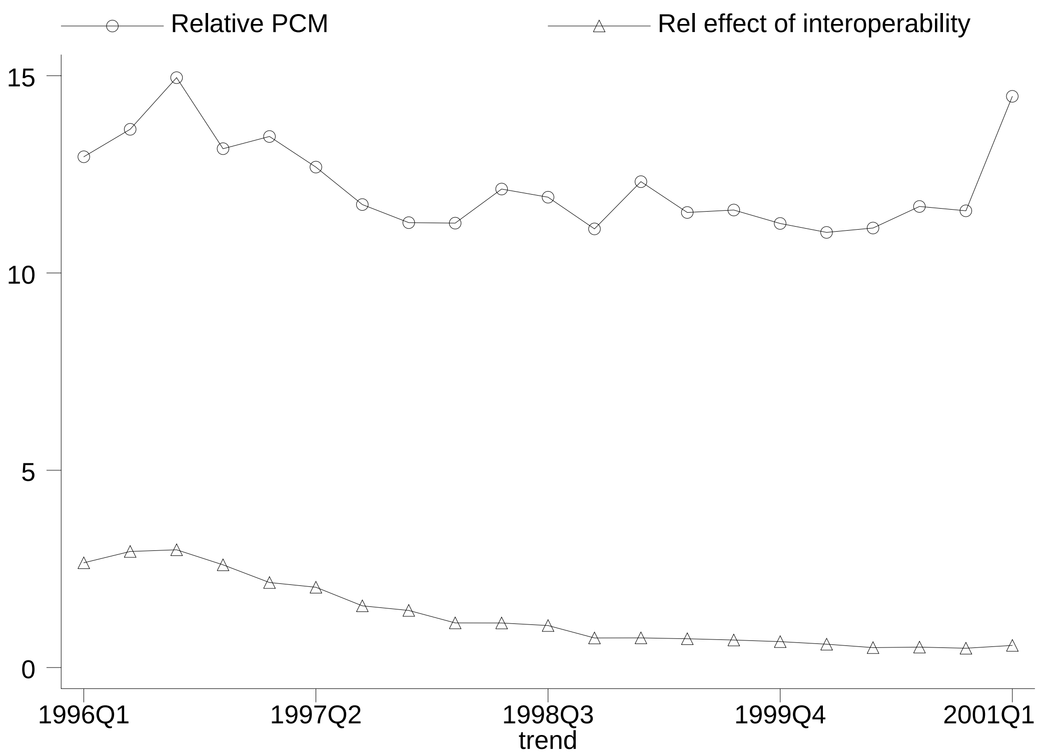
Figure 1: Evolution of market shares for software vendors (units)

Unit shares of the total server market



Source: IDC Quarterly Tracker Survey, World Market

Figure 2: Relative Mark-up and Relative Output Effect (of Interoperability)



Notes: This is taken from the estimated parameters in Tables 3 and 5 and the empirical data on prices and quantities in the US economy (See Appendix D)

Table 1
Results from Logit Demand for PCs in all segments[a]

	OLS	OLS	IV	IV	IV
Variables	(1)	(2)	(3)	(4)	(5)
Price	-0.328**	-0.475**	-0.686**	-0.696**	-2.737**
	(0.030)	(0.031)	(0.048)	(0.048)	(0.505)
Constant	-9.225**	-9.494**	-8.895**	-8.865**	-3.080**
	(0.177)	(0.187)	(0.220)	(0.221)	(1.456)
Benchmark	0.316**	0.323**	0.443**	0.449**	1.612**
	(0.088)	(0.084)	(0.086)	(0.086)	(0.308)
RAM	-0.346**	-0.307**	-0.158*	-0.151*	1.285**
	(0.090)	(0.089)	(0.095)	(0.095)	(0.377)
CD-ROM	0.091**	0.135**	0.150*	0.150*	0.295**
	(0.076)	(0.077)	(0.079)	(0.079)	(0.120)
Internet	0.216*	0.337*	0.320**	0.319**	0.155*
	(0.058)	(0.055)	(0.055)	(0.055)	(0.088)
Monitor Size	-0.016**	-0.017**	-0.020**	-0.020**	-0.052**
	(0.005)	(0.005)	(0.005)	(0.005)	(0.010)
Desktop	0.615**	0.569**	0.412**	0.404**	-1.121**
	(0.057)	(0.056)	(0.062)	(0.062)	(0.384)
5th Generation	0.360**	0.329**	0.381**	0.384**	0.891**
	(0.111)	(0.117)	(0.122)	(0.122)	(0.222)
6th Generation	0.256*	0.275*	0.469**	0.478**	2.352**
	(0.149)	(0.150)	(0.156)	(0.156)	(0.512)
7th Generation	0.998**	0.974**	1.050**	1.054**	1.791**
	(0.263)	(0.262)	(0.262)	(0.262)	(0.442)
Firm Dummies	no	yes	yes	yes	yes
Adjusted R^2	0.130	0.229	- -		
Hansen-Sargan Test of Over Identification (critical value)[b]				63.61 (20.09)	18.064 (18.47)
1st Stage R^2			0.46	0.46	0.01
1st Stage F-test			4043.8	452.68	5.02
Instruments:[c]	No	No	Yes	Yes	Yes
Canada prices			X	X	
Other characteristics				X	X
Own price elasticity					
Mean	-0.68	-0.99	-1.43	-1.45	-5.69
Standard	0.29	0.42	0.61	0.62	2.42
Median	-0.64	-0.92	-1.33	-1.35	-5.32
% of inelastic demands	88.44	58.38	23.79	22.74	0

[a] Dependent variable is $\ln(S_{jt})$-$\ln(S_{0t})$. Based on 4,767 observations across all segments (home, small and large business). All regressions include time dummy variables. Asymptotically robust standard errors are reported in parentheses.
* Z-statistic>1.
** Z-statistic>2.
[b] Hansen-Sargan test of over identification for the IV regressions with the 1% critical values in parentheses.
[c] Canada prices are the prices of the same models in Canada; Other characteristics are the sums of the values of the same characteristics of other products offered by the same firm, the sums of values of the same characteristics of all products offered by other firms, the number of products belonging to the same firm and the number of products of other firms: all these are split by form factor (laptop vs. desktop).

Table 2
Results from the random coefficients model in all segments[a]

	IV[b]	Random coefficient[c]
Variables	(1)	(2)
Means		
Price	-2.737**	-5.942**
	(0.505)	(1.386)
Constant	-3.080**	-1.240
	(1.456)	(4.190)
Benchmark	1.612**	2.594**
	(0.308)	(0.967)
RAM	1.285**	1.710**
	(0.377)	(0.732)
CD-ROM	0.295**	0.323**
	(0.120)	(0.156)
Internet	0.155*	0.110*
	(0.088)	(0.112)
Monitor Size	-0.052**	-0.062**
	(0.010)	(0.023)
Desktop	-1.121**	-5.142*
	(0.384)	(3.990)
5th Generation	0.891**	1.352**
	(0.222)	(0.339)
6th Generation	2.352**	3.837**
	(0.512)	(0.907)
7th Generation	1.791**	2.252**
	(0.442)	(0.735)
Standard Deviations		
Price		1.260**
		(0.604)
Constant		2.503*
		(2.143)
Benchmark		0.130
		(3.122)
Desktop		3.878*
		(2.954)
GMM Objective (df)		3.52 (3)

[a] Based on 4,767 observations for the whole market. All regressions include firm and time dummy variables. Asymptotically robust s.e. are reported in parentheses.
* Z-statistic>1.
** Z-statistic>2.
[b] This is the same as column (7) in Table 1
[c] Parameters estimated via the two-step GMM algorithm described in the estimation section. The standard errors reported take into account the variance introduced through the simulation by bootstrapping the relevant component of the variance in the moment conditions.

Table 3
Results of the demand estimation for the different segments

	Home Segment			Small Business Segment			Large Business Segment		
	OLS	IV	Random Coefficients	OLS	IV	Random Coefficients	OLS	IV	Random Coefficients
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Means									
Price	-0.761**	-5.069**	-6.410**	-0.360**	-3.090**	-5.831**	-0.299**	-1.578**	-5.771**
	(0.071)	(0.534)	(1.123)	(0.033)	(0.498)	(2.002)	(0.034)	(0.313)	(1.566)
Constant	-10.638**	1.284	1.284	-8.557**	-0.707	1.138	-9.561**	-5.826**	-6.008
	(0.327)	(1.529)	(1.944)	(0.199)	(1.469)	(4.001)	(0.202)	(0.939)	(6.654)
Benchmark	0.271**	2.732**	1.372	0.257**	1.707**	2.714**	0.376**	1.118**	2.263**
	(0.130)	(0.346)	(1.523)	(0.095)	(0.294)	(0.781)	(0.097)	(0.213)	(0.799)
RAM	-0.075	0.833**	0.755**	-0.341**	1.469**	2.083**	-0.425**	0.482*	0.615*
	(0.156)	(0.255)	(0.270)	(0.091)	(0.392)	(0.696)	(0.093)	(0.254)	(0.387)
CD-ROM	0.038	0.456**	0.377*	0.266**	0.285**	0.234*	0.284**	0.345**	0.340**
	(0.136)	(0.184)	(0.214)	(0.076)	(0.127)	(0.170)	(0.080)	(0.100)	(0.128)
Internet[a]	1.200**	0.829**	0.761**	0.138**	0.957**	1.314**	0.081*	0.316**	0.365**
	(0.079)	(0.120)	(0.125)	(0.065)	(0.195)	(0.386)	(0.070)	(0.102)	(0.182)
Monitor Size	-0.014*	0.022*	0.026**	-0.027**	-0.069**	-0.085**	-0.058**	-0.079**	-0.082**
	(0.008)	(0.013)	(0.013)	(0.007)	(0.012)	(0.019)	(0.007)	(0.009)	(0.018)
Desktop	1.303**	-2.568**	-7.115*	0.241**	-1.963**	-8.568*	0.399**	-0.532**	-2.597*
	(0.101)	(0.493)	(4.159)	(0.058)	(0.407)	(5.587)	(0.064)	(0.233)	(1.500)
5^{th} Generation	0.341*	1.663**	1.808**	0.370**	1.047**	1.510**	0.294**	0.633**	1.207**
	(0.184)	(0.321)	(0.418)	(0.118)	(0.250)	(0.481)	(0.121)	(0.182)	(0.424)
6^{th} Generation	0.760**	4.689**	5.101**	0.305**	2.809**	4.433**	0.036	1.224**	2.673**
	(0.238)	(0.589)	(0.745)	(0.154)	(0.523)	(1.418)	(0.162)	(0.342)	(0.899)
7^{th} Generation	1.788**	3.533**	3.609**	0.576**	1.902**	2.511**	0.019	0.576*	1.025**
	(0.363)	(0.614)	(0.648)	(0.279)	(0.499)	(0.863)	(0.291)	(0.361)	(0.511)
Standard Deviations									
Price			0.882**			1.042*			1.792**
			(0.444)			(0.609)			(0.712)
Constant			0.759			2.377			4.399*
			(1.179)			(2.652)			(3.810)
Benchmark			1.377**			0.051			0.102
			(0.647)			(1.885)			(5.285)
Desktop			4.374*			5.370*			2.555*
			(2.327)			(4.003)			(2.043)

Notes: All regressions include firm and time dummy variables. Asymptotically robust s.e. are reported in parentheses. * Z-statistic>1. ** Z-statistic>2. Parameters for the random coefficients are estimated via the two-step GMM algorithm described in the estimation section and the standard errors reported take into account the variance introduced by simulation.
[a] Internet dummy equals one if the PC includes as standard a modem for the home segment or an ethernet card for the Small and Large business segment.

Table 4
Estimated Mean Aggregate Elasticities

	All Segments	Home Segment	Small Business Segment	Large Business Segment
IV Logit	(1)	(2)	(3)	(4)
1995-2001	4.95	7.94	5.93	3.17
Random Coefficient Logit				
1995-2001	3.94	4.70	4.17	2.62

Notes: Aggregate demand elasticity is calculated as the percentage change in total market share from a one percent increase in the price of all products in the market. Results for the overall market and each segment separately are based on the estimated coefficients in Tables 2 and 3.

Table 5:
"Reduced form" Estimation of the impact of interoperability on server and PC quantities

	(1)	(2)	(3)	(4)
Dependent variable:	Ln(Windows Servers)	Ln(PC)	Ln(Windows Servers)	Ln(PC)
Estimation method:	OLS	OLS	IV	IV
Non-Microsoft server quality	-0.148*	0.003	-0.155**	-0.012
	(0.080)	(0.047)	(0.060)	(0.115)
Microsoft server quality	0.175*	0.130*	0.101	0.087
	(0.109)	(0.071)	(0.119)	(0.070)
PC quality	0.290**	0.098**	0.357**	0.232*
	(0.052)	(0.033)	(0.132)	(0.145)
PC OS price	-0.275	-1.244**	-0.271	-2.202
	(0.546)	(0.345)	(1.650)	(1.766)
Microsoft Server OS price	-1.266**	-0.127	-1.073	0.785
	(0.340)	(0.127)	(0.804)	(0.962)
LM test of Autocorrelation (p-value)	0.360	0.342		
R^2	0.932	0.990		

Notes
These are aggregate time series regressions. Robust standard errors in parentheses. IV uses lagged values of PC quality, PC OS price and Microsoft server OS price as instruments. Server quality assumed exogenous.

Appendix Table A1: Sample Market Coverage

Firm	Average Percentage Unit Share			
	Whole Market	Home Segment	Small Segment	Large Segment
Acer	3.31	2.16	5.32	2.89
Compaq	14.75	13.67	13.02	20.51
Dell	12.65	3.96	15.81	22.71
Gateway	7.61	10.52	5.28	3.92
Hewlett-Packard	7.46	9.25	5.84	9.40
IBM	7.37	4.51	9.49	10.80
NEC	7.18	12.98	4.07	3.29
Sony	0.74	1.23	0.67	0.18
Toshiba	3.60	1.46	5.04	5.89
Overall	64.66	59.74	64.53	79.58

Notes: Numbers shown are average firm market shares for the period 1995Q1-2001Q2 in the overall market and in each segment separately.

Table A2
Descriptive Statistics for the whole market

Period	No. of models	Quantity	Price	Benchmark	RAM	CD-ROM	Internet	Monitor size	Desktop
1995Q1	88	28.701	2.410	0.140	0.103	0.678	0.513	12.050	0.815
1995Q2	106	23.083	2.370	0.155	0.114	0.690	0.516	11.636	0.799
1995Q3	112	27.673	2.222	0.176	0.130	0.784	0.578	12.390	0.839
1995Q4	118	31.433	2.208	0.192	0.133	0.796	0.597	12.212	0.834
1996Q1	127	25.287	2.285	0.221	0.142	0.847	0.604	12.376	0.813
1996Q2	125	26.559	2.264	0.237	0.150	0.879	0.617	12.367	0.791
1996Q3	124	32.358	2.260	0.264	0.158	0.931	0.665	12.930	0.786
1996Q4	143	31.272	2.108	0.293	0.177	0.933	0.670	13.421	0.780
1997Q1	160	24.719	2.116	0.363	0.219	0.931	0.643	12.169	0.773
1997Q2	195	20.984	2.038	0.413	0.245	0.943	0.659	12.069	0.781
1997Q3	222	22.629	1.998	0.476	0.277	0.977	0.711	11.336	0.792
1997Q4	241	22.572	1.912	0.525	0.313	0.962	0.731	11.672	0.816
1998Q1	245	19.502	1.939	0.609	0.375	0.941	0.783	12.189	0.817
1998Q2	253	18.217	1.903	0.708	0.434	0.961	0.749	12.414	0.795
1998Q3	250	22.883	1.801	0.792	0.489	0.968	0.770	12.898	0.802
1998Q4	182	36.279	1.758	0.915	0.600	0.939	0.845	13.313	0.808
1999Q1	156	37.409	1.674	1.051	0.724	0.944	0.812	15.058	0.811
1999Q2	156	39.256	1.607	1.119	0.771	0.931	0.835	15.822	0.790
1999Q3	136	48.581	1.536	1.259	0.857	0.941	0.889	16.083	0.791
1999Q4	149	48.340	1.465	1.447	0.946	0.944	0.879	15.980	0.795
2000Q1	203	33.184	1.411	1.753	0.958	0.982	0.869	14.060	0.797
2000Q2	226	28.448	1.437	1.933	1.018	0.977	0.855	14.234	0.753
2000Q3	237	32.061	1.381	1.995	1.016	0.978	0.875	14.267	0.752
2000Q4	287	26.080	1.337	2.171	1.056	0.978	0.887	14.868	0.775
2001Q1	249	24.715	1.324	2.390	1.103	0.980	0.871	15.069	0.765
2001Q2	277	19.326	1.331	2.725	1.231	0.975	0.886	15.225	0.730
ALL	4767	27.804	1.752	1.114	0.624	0.934	0.777	13.706	0.789

Note: All the entries in the last seven columns are sales weighted means.

Table A3
Descriptive Statistics for the Home Segment

Period	No. of models	Quantity	Price	Benchmark	RAM	CD-ROM	Modem	Monitor size	Desktop
1995Q1	67	16.206	2.065	0.147	0.105	0.735	0.673	14.139	0.917
1995Q2	78	11.614	1.992	0.161	0.113	0.765	0.681	13.995	0.891
1995Q3	85	15.477	1.916	0.181	0.129	0.859	0.767	14.263	0.927
1995Q4	87	19.069	1.929	0.197	0.134	0.867	0.787	14.196	0.926
1996Q1	76	16.962	2.032	0.223	0.147	0.928	0.842	14.689	0.946
1996Q2	82	12.720	1.996	0.231	0.148	0.929	0.808	14.545	0.920
1996Q3	83	18.474	2.036	0.264	0.160	0.974	0.856	14.635	0.924
1996Q4	92	19.611	1.729	0.291	0.174	0.988	0.892	15.040	0.955
1997Q1	101	15.157	1.747	0.364	0.228	0.986	0.875	12.607	0.956
1997Q2	125	10.517	1.641	0.393	0.238	0.991	0.900	13.265	0.944
1997Q3	141	12.655	1.665	0.460	0.263	0.998	0.919	11.561	0.950
1997Q4	153	13.882	1.663	0.521	0.306	0.997	0.908	12.971	0.967
1998Q1	150	11.551	1.730	0.620	0.366	0.999	0.901	13.852	0.965
1998Q2	163	8.674	1.702	0.731	0.443	0.999	0.867	13.703	0.961
1998Q3	167	11.356	1.660	0.824	0.514	0.999	0.873	13.423	0.955
1998Q4	134	18.841	1.575	0.933	0.623	0.998	0.849	13.132	0.930
1999Q1	117	19.906	1.485	1.030	0.798	0.983	0.888	15.059	0.922
1999Q2	119	17.462	1.395	1.125	0.886	0.941	0.914	15.538	0.887
1999Q3	107	23.779	1.325	1.243	0.940	0.924	0.949	16.041	0.904
1999Q4	114	29.071	1.278	1.425	0.978	0.923	0.914	16.231	0.902
2000Q1	167	19.321	1.229	1.755	0.876	0.988	0.874	14.147	0.900
2000Q2	169	14.631	1.226	1.891	0.938	0.981	0.860	14.674	0.857
2000Q3	179	17.442	1.151	1.906	0.904	0.976	0.878	14.701	0.863
2000Q4	199	16.198	1.112	2.112	0.988	0.973	0.861	15.688	0.886
2001Q1	167	13.873	1.097	2.361	1.059	0.971	0.806	16.739	0.874
2001Q2	195	9.285	1.122	2.727	1.221	0.959	0.798	16.799	0.828
ALL	3317	15.494	1.504	1.118	0.627	0.957	0.863	14.602	0.913

Note: All the entries in the last seven columns are sales weighted means.

Table A4
Descriptive Statistics for the Small Business Segment

Period	No. of models	Quantity	Price	Benchmark	RAM	CD-ROM	Ethernet	Monitor size	Desktop
1995Q1	88	11.010	2.576	0.135	0.100	0.643	0.085	10.737	0.754
1995Q2	106	9.487	2.528	0.151	0.112	0.655	0.109	10.592	0.755
1995Q3	112	10.543	2.400	0.172	0.128	0.741	0.115	11.312	0.783
1995Q4	118	11.642	2.398	0.190	0.132	0.752	0.112	10.948	0.770
1996Q1	127	9.864	2.389	0.218	0.139	0.789	0.131	11.060	0.736
1996Q2	123	11.960	2.345	0.240	0.151	0.852	0.196	11.524	0.746
1996Q3	119	13.389	2.374	0.263	0.157	0.905	0.204	12.125	0.714
1996Q4	137	12.787	2.328	0.294	0.179	0.899	0.167	12.577	0.678
1997Q1	153	9.844	2.312	0.361	0.214	0.898	0.068	12.072	0.669
1997Q2	189	9.076	2.203	0.422	0.248	0.922	0.108	11.685	0.711
1997Q3	214	9.235	2.143	0.482	0.282	0.966	0.158	11.326	0.709
1997Q4	229	9.013	2.049	0.527	0.315	0.946	0.197	10.971	0.726
1998Q1	231	8.185	2.031	0.598	0.375	0.918	0.319	11.454	0.739
1998Q2	242	8.268	1.975	0.698	0.429	0.949	0.296	11.926	0.730
1998Q3	242	10.091	1.864	0.776	0.473	0.956	0.349	12.783	0.721
1998Q4	172	15.181	1.856	0.897	0.581	0.913	0.335	13.412	0.722
1999Q1	154	13.706	1.791	1.062	0.677	0.922	0.321	15.011	0.727
1999Q2	153	15.047	1.723	1.109	0.719	0.926	0.329	15.840	0.721
1999Q3	136	17.252	1.672	1.263	0.811	0.950	0.297	16.033	0.704
1999Q4	146	15.667	1.628	1.452	0.904	0.952	0.308	15.771	0.686
2000Q1	200	10.536	1.571	1.722	1.008	0.986	0.323	14.325	0.683
2000Q2	223	10.480	1.559	1.929	1.051	0.977	0.367	14.291	0.667
2000Q3	233	11.496	1.535	2.040	1.086	0.980	0.390	14.354	0.657
2000Q4	281	9.058	1.476	2.223	1.106	0.978	0.380	14.783	0.682
2001Q1	241	9.045	1.436	2.399	1.137	0.980	0.415	14.757	0.681
2001Q2	267	7.782	1.415	2.720	1.225	0.974	0.489	14.762	0.644
ALL	4636	10.737	1.902	1.077	0.604	0.918	0.277	13.279	0.707

Note: All the entries in the last seven columns are sales weighted means.

Table A5
Descriptive Statistics for the Large Business Segment

Period	No. of models	Quantity	Price	Benchmark	RAM	CD-ROM	Ethernet	Monitor size	Desktop
1995Q1	74	6.365	2.839	0.133	0.105	0.616	0.127	9.936	0.708
1995Q2	88	6.083	2.697	0.152	0.117	0.626	0.150	9.605	0.726
1995Q3	93	6.484	2.541	0.172	0.133	0.705	0.155	10.416	0.757
1995Q4	98	6.901	2.510	0.187	0.132	0.712	0.154	9.915	0.735
1996Q1	104	6.439	2.550	0.221	0.138	0.799	0.187	10.388	0.703
1996Q2	103	7.823	2.437	0.240	0.151	0.863	0.254	11.089	0.706
1996Q3	99	8.946	2.441	0.266	0.157	0.905	0.279	11.426	0.674
1996Q4	114	8.034	2.437	0.294	0.178	0.889	0.236	11.845	0.628
1997Q1	129	7.116	2.409	0.363	0.213	0.896	0.091	11.596	0.637
1997Q2	156	6.807	2.255	0.424	0.248	0.919	0.127	11.209	0.692
1997Q3	181	6.979	2.210	0.489	0.287	0.963	0.177	11.035	0.698
1997Q4	193	6.486	2.123	0.531	0.321	0.931	0.217	10.626	0.709
1998Q1	204	5.660	2.101	0.609	0.388	0.892	0.378	10.898	0.723
1998Q2	219	5.453	2.019	0.695	0.430	0.936	0.335	11.705	0.708
1998Q3	215	6.428	1.885	0.775	0.483	0.947	0.417	12.382	0.734
1998Q4	143	10.259	1.896	0.914	0.595	0.884	0.453	13.447	0.749
1999Q1	131	10.657	1.810	1.069	0.670	0.914	0.436	15.128	0.755
1999Q2	124	14.063	1.705	1.124	0.701	0.926	0.454	16.137	0.763
1999Q3	113	15.190	1.663	1.279	0.796	0.955	0.446	16.213	0.741
1999Q4	122	13.124	1.619	1.487	0.938	0.973	0.401	15.757	0.727
2000Q1	152	9.228	1.592	1.792	1.073	0.963	0.384	13.461	0.731
2000Q2	179	9.047	1.585	2.001	1.091	0.972	0.418	13.481	0.719
2000Q3	194	9.266	1.554	2.085	1.109	0.977	0.440	13.385	0.703
2000Q4	233	7.366	1.555	2.206	1.110	0.986	0.513	13.453	0.707
2001Q1	197	8.413	1.493	2.417	1.120	0.993	0.517	13.143	0.721
2001Q2	222	6.598	1.472	2.730	1.252	0.995	0.623	13.936	0.732
ALL	3880	8.085	1.919	1.165	0.651	0.920	0.363	12.917	0.718

Note: All the entries in the last seven columns are sales weighted means.

Table A6
Estimated PC Hardware Markups and Margins for the whole market (1995Q1-2001Q2)

	OLS Logit	Instrumental Variable Logit		Random Coefficient Logit	
Statistic	(1)	(2)	(3)	(4)	(5)
Median	2113.20	366.38	18.86%	250.38	13.39%
Mean	2114.30	366.56	20.95%	269.59	14.11%
10%	2109.40	365.70	11.61%	201.91	10.36%
90%	2121.80	367.86	33.24%	355.46	18.75%
Standard Deviation	4.64	0.80	9.39%	85.80	3.89%

Notes: Columns (1), (2) and (4) give the estimated markups from the various estimations over the whole sample (4,767 observations). Columns (3) and (5) give the margins, defined as markups divided by observed prices. Both Markups and margins are calculated assuming a Bertrand-Nash equilibrium in prices. All prices have been deflated using the CPI.