Potential Competition and the Prices of Network Goods: Desktop Software

Robert E. Hall
Hoover Institution and Department of Economics, Stanford University

Jimmy Royer
Analysis Group, Inc., and Department of Economics, Université Laval

Marc Van Audenrode
Department of Economics, Université Laval

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Abstract:

Potential competition restrains the prices of an incumbent seller when the incumbent can alter the environment perceived by an entrant in a way that both discourages entry and lowers prices. When the product has network effects, the incumbent can make its product ubiquitous and place the potential entrant at a disadvantage because customers have experience with the incumbent's product. A primary tool for making a product ubiquitous is low pricing. Hence potential competition lowers the prices of network products. We develop a quantitative model for the desktop software business embodying these principles.

This paper grew out of the first author's work on Microsoft issues, first as a consultant to the U.S. Department of Justice in the investigation culminating in the 1995 Consent Decree, then as a neutral commentator, and finally as an expert on damages for Microsoft. We are grateful to Robert Pindyck and Kenneth Judd for guidance and to numerous people at Analysis Group, Inc., especially Bruce Deal, Armando Levy, and David Sosa, for comments and contributions. Appendices and programs relating to this paper are archived at Stanford.edu/ ~rehall

I. Introduction

Does potential competition limit the price of a product? Or does the price of an incumbent remain high until actual entry occurs? Modern competition theory provides a clean answer to these questions. Potential competition disciplines price if the incumbent—acting before entry has occurred—can commit the value of a future state variable. In Michael Spence's [1977] original development of this proposition, the state variable was the capital stock. A firm seeking to prevent the entry of a rival expands its current capital stock so as to lower the price that it would charge in the event it faced a competitor in the next period. As a byproduct, the current price is lower as well. In a more recent version, Drew Fudenberg and Jean Tirole [2000] model the state variable as the installed base of the seller of a product with network effects. A firm seeking to prevent the entry of a rival sets a low current price to make its product ubiquitous and reduce the market available next period to a would-be rival.

We provide an empirical implementation of an extended version of Fudenberg and Tirole's model. We consider desktop software—a leading example of a product with extensive network effects. We distinguish two components of the software—the operating system and the primary user package, the productivity suite. The top seller in this market, by far, is Microsoft. Thus we consider how Microsoft defends Windows and Office from actual rivalry. We portray Microsoft as setting prices below the levels that it would choose if there were no threat of entry, in order to create an environment where entry would be marginally unremunerative. Low prices make Windows and Office ubiquitous and more difficult for a rival to supplant, because of network effects.

Network effects operate across both customers and time. For software with network effects, one customer is more likely to use a product if others are using it. Desktop software users often help each other with problems. They exchange files whose formats are unique to operating systems or application packages. They anticipate changing tasks or jobs so that knowledge gained in one place will be useful in another, if the same software is in use there. Over time, the experience a user gains from working with particular software is a capital asset—it makes the user more productive in future work. We call the critical state variable the experience base rather than the installed base—it is not the physical survival of the product, but the human capital specific to a brand of software that accounts for the network effects that are critical to the influence of potential competition.

Microsoft uses a variety of strategies to create an economic environment that depresses the profit of potential entrants sufficiently to discourage them from entering. In that environment, the revenue that an entrant would earn is too little to compensate for the resources required to build, launch, and support products that would compete with Microsoft's. A primary strategy is setting low prices to generate high volumes of sales and thus build a large experience base. Other strategies, including advertising, also expand the experience base, but do not lower price. Our model takes advertising and other promotional effort into account as endogenous variables. We treat the remainder—including Microsoft's dealings with its customers and rivals—as aspects of the environment that do not automatically respond to other changes in the environment. Our model provides a tool for estimating the effects on prices of changes in those exogenous determinants.

We view Windows and Office as complements. Network effects arise from the use of both products together. In a market with network effects from complementary products, a would-be rival must make a frontal assault on both markets. Where businesses are linked by complementarities and sellers benefit from complementarities by selling in both businesses, the would-be rival would have the best chance of success by entering both businesses simultaneously. In other words, the contingency of greatest risk to Microsoft is that a rival—potentially an existing large, successful software or computer company—would invest several billion dollars coding a new operating system and productivity suite and then spend many billions of dollars more promoting and supporting these products. Although this frontal assault would be expensive, the returns are equally large—the entry scenario discussed later involves a present discounted value of revenue to the hypothetical entrant of many billions of dollars. Accordingly, we concentrate on the case of entry to both the operating system and productivity suite businesses. We believe that other types of entry are of less risk to Microsoft and therefore have a smaller role in constraining the pricing of Microsoft's products. First, entry into operating systems alone suffers the disadvantage that the rival would be depending on revenue from that product alone in competition with Microsoft. The entrant would be sacrificing the benefits of selling the complementary application suite. In addition—and probably more important—there would be little market for a new desktop operating system unless it could run all of the existing popular Windows or Macintosh applications. We understand that achieving this level of compatibility is technically extremely difficult and prohibitively expensive.

A potential rival might consider entry in competition with Office without also offering a new operating system. Such a rival might try to limit development costs by starting with existing products such as WordPerfect, WordPro, or Lotus 1-2-3. Although this mode of entry would be more promising than offering a stand-alone operating system, it too has disadvantages. First, the operating system accounts for more than half total likely desktop software revenue in these businesses, judging by Microsoft's actual revenue from the two products. Second, complementarity works in reverse—applications help sell operating systems. Stand-alone entry in productivity suites fails to capture that benefit. Rather, entry into Windows-compatible suites gives the complementarities to Microsoft rather than to the entrant.

We should also note that business strategies based on niche products are profitable in desktop software. Apple's strategy for the Macintosh operating system falls into that category. Apple's operating system runs on its proprietary hardware. Apple has chosen not to develop an operating system as a separate product in competition with Windows for use on computers made by others. Similarly, Apple has not developed a high-powered applications suite. Apple has chosen against a frontal assault on Microsoft. Microsoft discourages frontal assaults by low pricing, marketing, and other policies.

Instead of losing money on a frontal assault, Apple enjoys a niche among certain types of users. Microsoft provides a productivity suite compatible with Apple's operating system.

Niche strategies have small effects on the pricing of Microsoft's products, so we have omitted them from the model. Given the size of the desktop software business, niche entry could still result in sales of millions of dollars per year. Even so, the possibility of such entry is not the primary concern of firms in Microsoft's position. It would not be economical to depress the prices of its widely used products to deter entry of niche products. The type of entry that Microsoft fears the most—and that therefore constrains its prices—is the frontal assault. Once the rival has made the investments needed to make that assault, Microsoft would suffer a substantial loss of profit. Hence Microsoft will—if it can—alter the economic environment to make those investments unremunerative.

Our model quantifies the relationship between the development costs faced by potential rivals and Microsoft's pricing and experience base. We find that Microsoft's prices for Windows and Office are substantially lower as a result of potential competition.

In addition to setting prices that recognize the effect of potential competition and promotional efforts that reduce the revenue available to a rival, Microsoft has used other practices that have been challenged in court under antitrust law as inappropriate limitations on the opportunities available to an entrant. We do not study the legitimacy of the challenged practices. Our estimate of entry cost includes all the costs that an entrant would encounter, including those of overcoming the challenged practices.

II. Earlier Literature

Bain [1949] first formalized an incumbent's decision to cut its prices to decrease the probability of entry. Thirty years later, Friedman [1979] observed that low prices had a limited commitment value since a credible threat to cut prices *upon entry* may deter entry as effectively and more profitably than a price cut *prior to entry*. Models developed at the same time introduced a credible threat of low prices following entry by incorporating state variables with commitment value such as capacity (Spence [1977, 1979]). Milgrom and Roberts [1982] explained limit pricing as a way for incumbents to hide the potential profitability of entry.

Network externalities have been analyzed in several markets: Gandal [1994] and Brynjolfsson and Kemerer [1996] showed that consumers are willing to pay a substantial premium to purchase spreadsheet software compatible with the dominant standards. Ohashi [2001] demonstrated network effects in VCRs, and Economides and Himmelberg [1995] in fax machines.

Our model examines the limit-pricing behavior of an incumbent in the presence of network externalities. We define a state variable, the experience base, to capture the externalities—a new customer prefers a product with a larger experience base because of easier interaction with existing users and the likelihood of help from them. The experience base plays a role similar to the state variables in other dynamic oligopoly game—capacity, capital investment, sticky prices, adjustment costs, and fixed costs. In our model, the incumbent's experience base deters entry by lowering the prospective sales of a potential entrant.

We calculate the Markov-perfect equilibrium of a dynamic Bertrand differentiated-products duopoly game. A Markov-perfect equilibrium depends only on the payoff-relevant elements of the environment—here the experience bases of the two sellers. We rule out trigger strategies that might sustain something close to the joint monopoly outcome. The equilibrium resembles the familiar one-shot differentiated products Bertrand equilibrium, but differs because of the two players' recognition of the implications for the future of the changes in the experience bases resulting from current play. In a Markov-perfect equilibrium, the players in one period recognize that they will play again in the next period, after their current play has influenced the state variables. The equilibrium is accordingly subgame perfect.

Maskin and Tirole [2001] discuss Markov-perfect equilibria in games with observable actions (as in our framework). They explain the benefits for applied work in restricting the set of equilibria to those that are Markov perfect: First, the Markov-perfect restriction generally much reduces the problem of multiple equilibria. Second, by eliminating other variables, a Markov-perfect specification helps achieve a clear understanding of the role of the key state variables—here, the experience bases. Third, the Markov-perfect setup reduces the number of parameters that need to be estimated. Fourth, the equilibria of these games are easy to calculate. Fifth, a Markov-perfect specification is the simplest one consistent with rationality. Sixth, Markov perfection embodies the principle that players' behavior is the same in strategically equivalent subgames. Seventh, these equilibria are continuous in their determinants—small changes in the state variables lead to small change in the equilibrium.

In an earlier paper, Maskin and Tirole [1998] studied the properties of Markov-perfect equilibria in dynamic oligopoly games in a Cournot framework. Giovannetti [2001] studies the Markov-perfect equilibrium of a dynamic Bertrand game with adoption of technologies. Finally, Chen and Rosenthal [1996], consider the Markov-perfect equilibrium of a dynamic Bertrand game when consumers change their loyalties slowly. All of these papers are purely theoretical.

Our work is similar in method and objective to a large body of empirical work that aims to predict the effects on prices of alterations in the pattern of competition—see, for example, Hausman, Leonard, and Zona [1994] and Froeb, Tschantz, and Crooke [2003]. That research uses the differentiated-products Bertrand model and calibrates a demand system to data from a variety of sources. Most of the research focuses on the effects of mergers.

There is also a large body of literature on the empirical estimation of dynamic oligopoly games. These models—which most often consider Markov-perfect equilibria—have been used to measure the degree of collusion in oligopolies (See Slade [1995] for a review) and sticky prices (Slade [1998]). Empirical estimations of Markov-perfect equilibrium models has been simplified thanks to Hotz and Miller's [1993] result which eliminates the need to solve the dynamic programming problem by backwards induction in empirical estimations.

We combine elements from all of this earlier research—network effects, empirical Bertrand equilibrium, and dynamic duopoly. Our primary focus is on the role of entry costs as determinants of price in a setting of limit pricing. We are not aware of any earlier work in the empirical analysis of competition that combines all of these elements.

III. Framework for Studying Potential Competition

Our model portrays the evolution of the desktop software businesses for many years into the future. Potential entrants and Microsoft use the same logic in thinking through the economics of entry. An entrant projects how, if it builds desktop software that can compete with Microsoft's products, the two sets of products will compete with each other. The demand for each product depends, among other things, on the size of the experience base that customers bring into the period, and the base depends on sales of that seller's software in earlier periods. Microsoft starts off with an advantage from its relatively substantial experience base, whereas an entrant starts without any experience base among potential customers.

We characterize competition between the two sellers according to standard principles. They are Bertrand rivals in two linked product markets. Demand has a dynamic element in both markets: Users gain experience from units sold today that stimulates demand for the product and brand in the future. As a result, both sellers set prices lower than they would otherwise.

Competition between the sellers occurs in subsequent periods according to the same principles. The result is a forecast of sales well into the future. Each seller has to decide how much to shade its prices downward to capture the benefit of the enlarged subsequent experience base a lower price generates. They make this decision so as to maximize the present value of the revenue stream. We consider the Markov-perfect equilibrium where each player in a given period makes the Bertrand assumption about the other player—no price response—in the current period but understands the outcome of the game when played next period and uses that outcome to value the future implications of the prices set today. The model predicts a value for Microsoft's revenue stream and a value for the entrant's stream. These values depend on the size of Microsoft's experience base brought into the first period.

Later in the paper we will show how Microsoft determines the prices of the two products, according to the model. For the purposes of summarizing our analysis of the effects of potential competition, little is lost by considering a combined price. It is the price of one copy of Windows plus the price of Office multiplied by the fraction of Windows purchasers who also purchase Office. Later we will show how the Windows and Office prices are linked. Throughout the paper, we consider the prices that Microsoft receives—the price paid by computer makers for Windows and the price paid by distributors for Office. For the moment, we restrict our attention to stationary prices. When Microsoft holds its price constant in a setting where it faces no actual rivalry, the experience base is equal to the resulting level of sales divided by the rate of depreciation of the experience base. A higher stationary price results in a lower experience base. Further, a lower Microsoft experience base implies a higher present value of revenue for an entrant. Figure 1 shows the resulting relation between Microsoft's stationary price and the present value of the potential entrant's revenue, as calculated from the model with our estimates of its parameters.

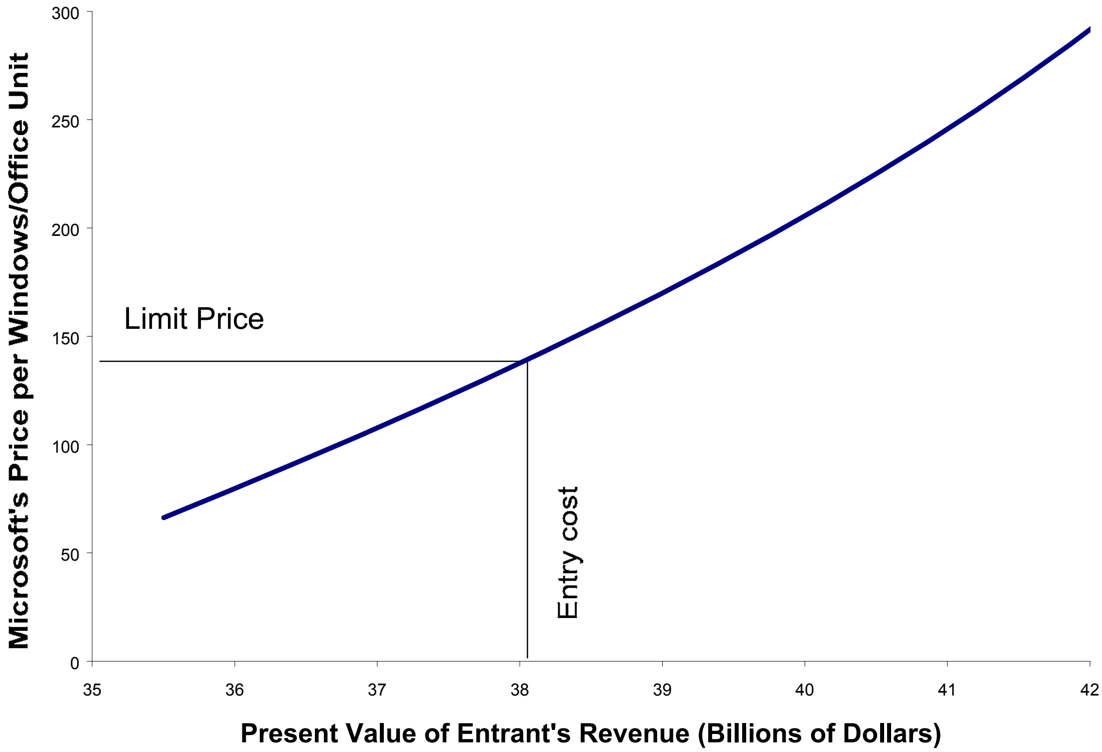

Figure 1. Entrant's Present Value of Revenue as a Function of Microsoft's Stationary Price

Without the discipline of potential competition, Microsoft would set a higher price and earn a higher stream of revenue. Specifically, according to our parameter estimates, the combined price would be $354 and the present value of revenue would be $191 billion. We call this price the *unconstrained price*. We use the relationship shown in Figure 1 to determine the *limit price*—the price that keeps the present value of the entrant's profit just below the entrant's cost. In Figure 1, we take the cost to be $38 billion, which implies that the limit price is $143, approximately the actual price in 2002.

It is possible for the two prices just discussed to have the reverse relationship—that if Microsoft sets the unconstrained price, the resulting revenue for a prospective entrant would not cover the entrant's cost. We call this Case I. Because our model implies an unconstrained price distinctly above the actual price, we conclude that Case I does not apply to Microsoft.

If the unconstrained price would result in entry—as we believe it would—then a further analysis is required to predict the actual outcome in the market. In this circumstance, Microsoft does need to worry about entry and may choose the limit price to discourage the potential entrant. The limit price would result in a high enough experience base to create an environment where the Microsoft products were sufficiently ubiquitous to prevent entry. But it is not certain that Microsoft will adopt the limit price. The last step is to calculate the profits that Microsoft will earn from limit pricing. For this purpose, note that limit pricing will have to be used for each period in the future, as the possibility of entry exists in every future period. We call the repeated use of limit pricing Case II.

Microsoft could pursue another strategy—use unconstrained pricing in the preliminary period, permit entry to occur, and then live with competition in all future periods. We call this Case III. If Case I does not apply, Microsoft will choose whichever of Case II and Case III delivers the higher present value. We infer from the absence of frontal assault on Microsoft's position that its optimal strategy was, in fact, the limit pricing of Case II.

As noted earlier, we will concentrate on the possibility of simultaneous entry of a new software provider into both the operating system and applications businesses. The new seller's level of sales is closely related to the prices that the new seller will command in the two businesses. Given the experience base associated with Microsoft products, the new seller will choose to under-price Microsoft, but will nonetheless divert only a fraction of Microsoft's sales. Figure 2 shows the evolution of the share of operating systems and applications suites. From only approximately 10 percent in the first year, the entrant gradually rises to a 50-percent share. Note that the 50-percent share is not a fixed prediction of the model. As we noted earlier, in a market with network effects, it is likely that the leader will have a high share. The 50-percent limit reflects uncertainty as to whether the entrant or Microsoft would prove to be the ultimate winner.

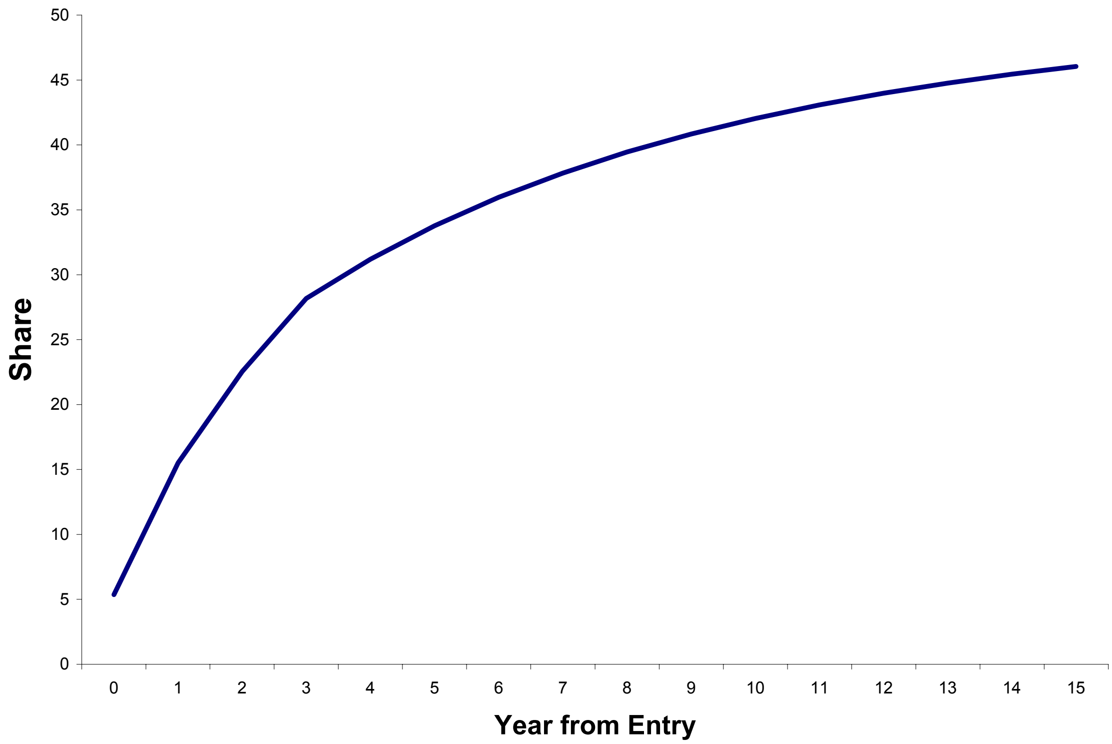

Figure 2. Share of Operating System and Applications Suite Sales Captured by the Hypothetical Entrant

Because of the difficulty of overcoming experience effects and the need for low penetration pricing, the prices set by the entrant are necessarily lower—less than 70 percent during the first year—than Microsoft's prices without entry for both the operating system and the application suite. Figure 3 shows the evolution of the price of the entrant's operating system and applications suite during the first few years of competition compared to Microsoft's price over the same period.

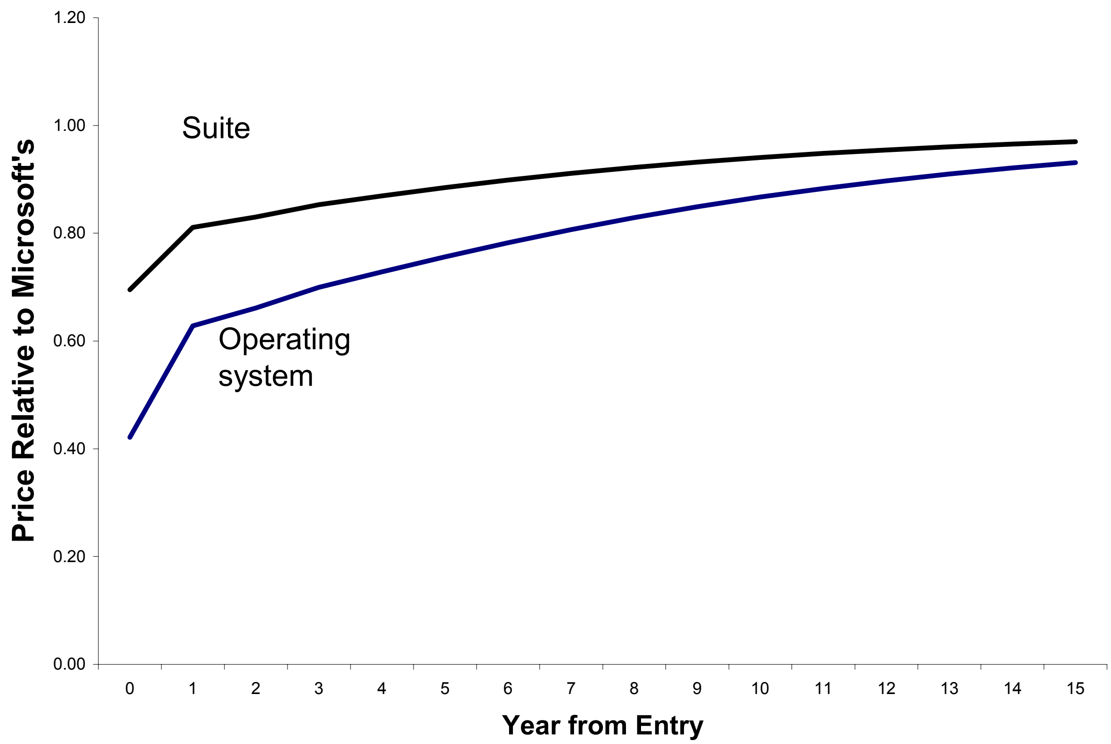

Figure 3. Entrant's Prices Relative to Microsoft's Prices

The present value of the revenue earned by the entrant upon successful entry in both operating system and applications businesses—$38 billion—provides our estimate of the total development, marketing, and support costs of the effort.

Microsoft uses a variety of business strategies to influence the environment perceived by a potential entrant. In addition to our primary focus on low pricing, our model considers one non-price strategy—product promotion—but does not consider adjustments in others, such as product enhancement, made for the purpose of discouraging entry.

Microsoft will not choose constrained pricing if it could earn more profit by setting the unconstrained price during the period before entry could occur and then accepting the consequences of entry afterwards. According to the model, Microsoft earns revenue worth $153 billion in present value if it sets the constrained price to ensure that no entry occurs. On the other hand, if Microsoft decided to accommodate entry and set a price in the period before entry to achieve maximum present value, it would earn somewhat lower revenue worth $148 billion. Thus the model explains why Microsoft has not chosen Case III.

What about Case I? If the actual costs of entry—development, promotion, and continuing support costs—were substantially above $38 billion, we would conclude that Case I applies and Microsoft need not concern itself about the possibility of entry. Although we do not provide the details in this paper, we have examined data on entry costs and concluded that there are in the range of $38 billion, so that entry is a true threat and Case I does not apply. We conclude that Microsoft is in Case II, where it sets a limit price in response to potential competition.

IV. The Model

In period –1, Microsoft is alone in the market. In period 0, a rival will enter if the present value of its revenue exceeds the total of development, promotion, and support costs, $38 billion. Microsoft may act in period –1 to make entry unattractive, by expanding its experience base. The result will be a lower (limit) price in the sense of the modern literature on limit pricing. The duopoly model developed here describes Microsoft's thought process in deciding whether to adopt a limit price, the rival's thought process in deciding whether to enter, and the actual competition that occurs if the rival does enter.

Microsoft sells two complementary products, Windows and Office, and the rival sells imperfect substitutes for both. The demand for product i facing seller j at time t is the product of a brand choice logit function, a new brand factor, and a single-seller demand factor:

$$y_{i,j,t} = \frac{e^{-\theta_1 p_{1,j,t} - \theta_2 p_{2,j,t} + \phi b_{j,t}}}{\sum_k e^{-\theta_1 p_{1,k,t} - \theta_2 p_{2,k,t} + \phi b_{k,t}}} x_{j,t} e^{\mu_i - \lambda_i p_{i,j,t} - \gamma_i p_{3-i,j,t}} \tag{4.1}$$

In the logit for brand choice, $p_{1,j,t}$ is the price of the operating system of seller *j* at time *t* and p_2 is the price of the suite. The parameters θ_1 and θ_2 control the intensity of competition between Windows and the rival operating system and between Office and the rival suite. $b_{j,t}$ is seller *j*'s experience base and the parameter ϕ controls the network effect. The new brand factor, $x_{2,t}$, expresses the disadvantage suffered by an entrant not captured by the other variables. $x_{1,t} = 2 - x_{2,t}$ reflects the fact that the disadvantage suffered by the entrant is reallocated to the incumbent, everything else being equal. In the single seller demand function, μ_i is a scale parameter for the demand for product *i*, λ_i is the semi-elasticity of single-seller demand for product *i*, and γ_i is the cross-price effect from product 3-*i* to product *i*, describing the complementarity.

The experience base depreciates at rate δ —its law of motion is

$$b_{j,t} = (1-\delta)b_{j,t-1} + y_{1,j,t-1} + y_{2,j,t-1}. \tag{4.2}$$

The sellers are Bertrand rivals. We consider the Markov-perfect dynamic equilibrium. Seller *j* chooses $p_{i,j,t}$ to maximize

$$\begin{aligned} & p_{1,j,t} y_{1,j,t} + p_{2,j,t} y_{2,j,t} + \\ & \beta V_{j,t+1}\left((1-\delta)b_{1,j,t} + y_{1,j,t} + y_{2,j,t}, (1-\delta)b_{1,3-j,t} + y_{1,3-j,t} + y_{2,3-j,t}\right) \end{aligned} \tag{4.3}$$

on the hypothesis that the other sellers' prices will not respond. Let $\tilde{p}_{i,j,t}\left(b_{j,t}, b_{3-j,t}\right)$ be the equilibrium prices and $\tilde{y}_{i,j,t}\left(b_{j,t}, b_{3-j,t}\right)$ the equilibrium quantities in the Bertrand game, both functions of the state variables $b_{j,t}$. $V_{j,t}\left(b_{j,t}, b_{3-j,t}\right)$ is the value seller *j* achieves from the game from t onwards and β is the discount factor. Although we cannot provide a formal proof of the uniqueness of the equilibrium, we can show that the approximated value function at time T is strictly increasing in a player's own base and strictly decreasing in the other player's base. Since all the relevant information about past strategies is included in the bases, no two strategies at time T-1 can lead to equal levels of profit at time T. This reasoning can be carried backwards up to period 0 and shows the uniqueness of the equilibrium path. As we noted, however, since this reasoning applies to the approximated value function as opposed to the true (unknown) value function, it cannot amount to a formal proof.

We use standard collocation methods to approximate the value functions with Chebyshev polynomials (Judd [1996, 1998] and Vedenov and Miranda [2001]).[1] We consider an environment that has arbitrary variations over time in all driving forces for $t=-1,\ldots,T$ and is stationary for $t=T+1,\ldots,\infty$. We solve first for the stationary value functions satisfying the stationary Bellman equations,

$$\begin{aligned} V_j^*\left(b_j, b_{3-j}\right) &= \tilde{p}_{1,j}\tilde{y}_{1,j} + \tilde{p}_{2,j}\tilde{y}_{2,j} + \\ &\beta V_j^*\left((1-\delta)b_j + \tilde{y}_{1,j} + \tilde{y}_{2,3-j}, ((1-\delta)b_{3-j} + \tilde{y}_{1,3-j} + \tilde{y}_{2,3-j}\right) \end{aligned} \tag{4.4}$$

where the underlying driving forces are at their stationary values. Although we have never found more than a single stationary equilibrium, we have not been able to demonstrate analytically that the equilibrium is unique.

Second, for the time T and before, when the environment is non-stationary, we take $V_{j,T}=V_j^*$ and iterate backwards according to

$$\begin{aligned} V_{j,t}\left(b_{j,t}, b_{3-j,t}\right) &= \tilde{p}_{1,j,t}\left(b_{j,t}, b_{3-j,t}\right)\tilde{y}_{1,j,t}\left(b_{j,t}, b_{3-j,t}\right) + \tilde{p}_{2,j,t}\left(b_{j,t}, b_{3-j,t}\right)\tilde{y}_{2,j,t}\left(b_{j,t}, b_{3-j,t}\right) + \\ &\beta V_{j,t+1}\left(\left(1-\delta\right)b_{j,t} + \tilde{y}_{1,j,t} + \tilde{y}_{2,j,t}, \left(1-\delta\right)b_{3-j,t} + \tilde{y}_{1,3-j,t} + \tilde{y}_{2,3-j,t}\right) \end{aligned} \tag{4.5}$$

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[1] A computational appendix providing details is available from Stanford.com/~rehall.

As we noted earlier, the equilibrium is unique, so this recursion defines a unique sequence of value functions given a starting $V_{j,T}$.

From the equilibrium price and quantity functions and the law of motion of the bases, we can calculate equilibrium trajectories of any length. With a finite horizon, however distant, these trajectories are unique.

V. Estimation of Parameters

The primary source for the behavioral characteristics of the model is a study of the penetration of a hypothetical new brand of desktop software carried out by John Hauser. Hauser conducted a computer-based study of consumer and business purchasers, gathered responses, and estimated a conjoint model of personal computer software purchase decisions (see Dahan and Hauser [2002] and Toubia, Simester, and Hauser [2003]). Hauser's study asked respondents to consider a hypothetical new operating system-productivity suite combination, with the same general capabilities as Windows and Office. The new software could exchange files with Microsoft software, but was not identical to Microsoft software. The characteristics considered in the study included price, the fraction of other computer users who had already adopted the new software, and the availability of support for the new software. The study also gathered information about the respondent, including experience using personal computers.

Hauser's model estimates the success of the new software in the year of its introduction, showing the share of users who would adopt the software. We calibrated the parameters of our model to replicate the penetration estimated by Hauser's model. The difference between the penetration level for a higher and a lower price reveals the cross-elasticity of demand, a key parameter of our model. In addition, the difference between the share of the new software among less experienced and more experienced users of about 10 percentage points reveals the effect of the experience base on demand for the new software and provides one way to calibrate this parameter.

A. Market Growth

Although growth was substantial in desktop software sales during the 1980s and 1990s, prospective growth has declined in the last few years. We calibrate our model to Microsoft sales data for 2002 and assume that no growth in the market over the next 25 years. Prospective sales depend on the outlook for the personal computer in competition with other methods for carrying out the tasks now assigned to those computers.

B. Cross-Price Responses

To estimate the cross-price response parameter, θ_1 and θ_2, we calibrated the demand function to the results of the conjoint study. Without the (small) price effect from γ_1 and γ_2, the demand function implies the following relation in any given time period between the log of the ratio of the sales and the prices of the two products:

$$\log \frac{y_{i,2}}{y_{i,1}} = k + \theta_1 \left(p_{1,1} - p_{1,2} \right) + \theta_2 \left(p_{2,1} - p_{2,1} \right) + \lambda_i \left(p_{i,2} - p_{i,1} \right), \tag{5.1}$$

where k is a constant for that time period, incorporating the effects of the bases and other factors. The conjoint model aggregates the two products. We approximate the aggregation by taking the equally-weighted average of the two log-differences:

$$\log \frac{y_2}{y_1} = k + \left(\theta_1 + .5\lambda_1\right)\left(p_{1,1} - p_{1,2} \right) + \left(\theta_2 + .5\lambda_2\right)\left(p_{2,1} - p_{2,2} \right), \tag{5.2}$$

We assume that the cross-elasticities of the two products are the same at the observed point, denoted with bars: $\bar{p}_1\left(\theta_1 + .5\lambda_1\right) = \bar{p}_2\left(\theta_2 + .5\lambda_2\right)$. Let $\psi = \frac{\bar{p}_1}{\bar{p}_2}$. Equation (4.2) becomes

$$\log \frac{y_2}{y_1} = k + \left(\theta_1 + .5\lambda_1\right)\left(p_{1,1} - p_{1,2} \right) + \psi \left(\theta_1 + .5\lambda_1\right)\left(p_{2,1} - p_{2,2} \right), \tag{5.3}$$

The conjoint model considers the sum of the prices of the two products: $\tilde{p}_j = p_{1,j} + p_{2,j}$. We interpret the conjoint as implicitly spreading the price differences in proportion to the actual prices: $p_{2,2} - p_{2,1} = \frac{\bar{p}_2}{\bar{p}_1}\left(p_{1,2} - p_{1,1}\right) = \frac{1}{\psi}\left(p_{1,2} - p_{1,1}\right)$. Combining all of this, we get

$$\log \frac{y_2}{y_1} = k + \left(\theta_1 + .5\lambda_1\right) 2 \frac{\psi}{1+\psi}\left(\tilde{p}_1 - \tilde{p}_2\right), \tag{5.4}$$

The regression of the log of relative sales on the price difference multiplied by $2\frac{\psi}{1+\psi}$ in the conjoint results gives a coefficient of 0.0056. Our estimate of λ_1 is 0.0053 (see below), so the resulting implied estimate of θ_1 is 0.003. Our estimate of λ_2 is 0.0035, so the resulting implied estimate of θ_2 is 0.001.

C. Effect of Experience Base

We considered two methods for calibrating the experience effect parameter, ϕ.

1. Differences in choices between experienced and inexperienced respondents

The entrant faces a disadvantage at the outset from Microsoft's base, *b*. As a result, its share is multiplied by the factor

$$s = \frac{1}{1 + e^{\phi b + x}}, \tag{5.5}$$

where *x* accounts for other influences. The derivative of the share with respect to the base is

$$\frac{ds}{db} = -\phi s\left(1 - s\right) \tag{5.6}$$

Let s_X be the share of the entrant among users with experience with the incumbent's software and s_I be the share among users without that experience. Let B denote the upper bound for experience base. Then

$$s = bs_X + (B-b)s_I \tag{5.7}$$

and

$$\frac{ds}{db} = -(s_I - s_X). \tag{5.8}$$

Equating the two derivatives and solving for the coefficient yields:

$$\phi = \frac{s_I - s_X}{s(1-s)}. \tag{5.9}$$

The conjoint study shows that the share of the entrant is about 0.1 higher among inexperienced users relative to experienced users. If the calibration is at the point $s = 0.3$, then $\phi = \frac{.1}{.21}$ or about 0.5.

2. Calibration from Initial Installed Base

The conjoint model implies a relationship between the entrant's market share and its share of the installed base. We use this relationship to estimate ϕ. We use the following specification that is a generalization of the share part of the demand function in the model:

$$z_2 = c\frac{1}{1+e^{\phi(b_1-b_2)}} - \varepsilon \tag{5.10}$$

where b_1 and b_2 are respectively Microsoft's and the entrant's bases; c is a constant; z_2 is the market share obtained by the entrant, and ε is a constant that shifts z_2 to offset the entrant's disadvantage. In one variant, we set ε so that z_2=.5 when the bases are equal Note that this shift also makes z_2 symmetric around the level of equal bases—when the entrant's share is 25 percent, z_2 is close to the value that 1- z_2 would have if the entrant's share were 75 percent.

We fit four different specifications for the share equation. We take the level of the Microsoft base to be given by approximately the steady state level implied by Microsoft sales in 2002. The results of the estimations, performed on 50 observations, with z_2 ranging from 1 percent to 50 percent, are shown in Table 1.

Specification	*Constraints*	*Estimate of* ϕ
1	$c=1$ and $\varepsilon=0$	0.34
2	$\varepsilon=0$	0.25
3	$c=1$ and $\varepsilon=0.102$	0.18
4	$\varepsilon=0.102$	0.20

Table 1. Estimation of ϕ

We adopt $\phi = 0.23$ as our estimate for the results reported in this paper.

D. Depreciation Rate of the Experience Base

To estimate the depreciation rate of the experience base, δ, we associated the duration of experience with the time when a PC remains in service. We estimated the rate of depreciation implicit in data for software sales and the installed base gathered by IDC, a provider of market data on high-technology industries. Worldwide sales and installed base figures from IDC were obtained for MS Word, Excel, and Windows from 1987 to 1998 (www.idctracker.com). We can infer the depreciation in the stock of software in a particular year by adding sales to the installed base at the beginning of the year and comparing that to the reported installed base. The difference is depreciation. From an examination of depreciation rates across years and products, we conclude that depreciation on average is about 0.30. This figure is also supported by data on the effective lifetimes of PCs. New guidelines issued by the Bureau of Economic Analysis suggest a geometric decay rate of just above 0.37. Other recent guidelines suggest a four-year lifecycle for business computers and a longer cycle for home computers. Since the figure we use implies that less than 25 percent of the original base remains after four years, we take these guidelines as confirmatory of the 0.30 value. Thus we adopt $\delta = 0.3$ as our estimate of the depreciation rate of the experience base.

E. Disadvantage of New Seller

Entrants face a disadvantage when entering a new market because of low initial consumer awareness and other aspects of product adoption, as well as the lack of an experience base. In our model, the $x_{j,t}$ parameters capture the disadvantage not attributable to the experience base. When the respondents in Hauser's conjoint study were asked to consider equally functional operating system-productivity suite combinations, the one named Microsoft enjoyed significantly higher market share than the one named Newsoft. We chose $x_{1,1} = 1.74$ and $x_{2,1} = .26$ based on that finding. The entrant's disadvantage declines over time. We project that the disadvantage would disappear after three years (about the half-life of the experience base effect). In periods 2 and 3, we took $x_{1,2} = 1.25$ and $x_{2,2} = .75$, and $x_{1,3} = 1.08$ and $x_{2,3} = .92$, respectively.

F. Demand scale parameters

To estimate the demand scale parameters, we used data on the number of units of software actually sold and their prices supplied by Microsoft. We used sales data to calculate estimated worldwide prices and unit sales of Windows and Office. We estimated worldwide Windows and Office sales for the period January 1, 1995 to June 30, 2001 based on the ratio of worldwide revenues to U.S. revenues for Windows and Office. The resulting estimates are $\mu_1 = 0.65$ and $\mu_2 = 0.10$.

G. Single-Seller Price Response of Demand

For the overall price response of demand for desktop software, we treat the demand for Windows, in the single seller setting, as derived from the demand for PCs. If that demand has the constant-elastic form,

$$A_{PC}\left(p_{PC}\right)^{\varepsilon_{PC}} \tag{5.11}$$

and if the PC industry is competitive with constant marginal cost, apart from Windows, of *c*, then the price is $p_{PC} = c + p_1$ and the derived demand for software is

$$A_{PC}\left(c + p_1\right)^{\varepsilon_{PC}} \tag{5.12}$$

We approximate this function by $e^{\mu_1 - \lambda_1 p_1}$ by equating elasticities:

$$\lambda_1 = \frac{\varepsilon_{PC}}{p_{PC}} \tag{5.13}$$

To estimate the elasticity of demand for personal computers, ε_{PC}, we draw upon a study by Igal Hendel. He estimates a demand system for business purchases of PCs, broken down by models and brands. He reports $\varepsilon_{i,j}$, the elasticity of demand for product *i* with respect to the price of product *j*. The corresponding derivatives are $\frac{\partial D_i}{\partial p_j} = \frac{q_i}{p_j}\varepsilon_{i,j}$. These are approximately symmetric, as required by demand theory (most of the discrepancies appear to come from his rounding of the reported elasticities). Then the overall elasticity of demand is $\frac{\bar{p}}{y}\sum_i \sum_j \frac{\partial D_i}{\partial p_j}$, where $\bar{p}$ is the average price and *y* is total sales in units. The concavity of the profit function implies that this is negative, a property that holds in Hendel's results. The value of the elasticity is -3.6. We do not have any comparable estimates for home purchases, but we believe it is reasonable to use this figure for the home category as well.

We make a further adjustment for upgrades. Approximately 30 percent of Windows units sold are upgrades. A Windows upgrade—for some applications—is an alternative to the purchase of a new PC. Such a PC is purchased, in effect, from the used PC market, in the sense that the alternative would be to sell the PC with the obsolete version of Windows in the used PC market. We take the price of a used PC in this setting to be 25 percent of the price of a new PC. As a result, the demand for upgrades is more price-elastic, because the price of Windows is a larger fraction of the used computer's price. We take the weighted average of the two values of the semi-elasticity, λ, for units of Windows installed on new machines and upgrade units installed on used machines.

Finally, we made the adjustment described above for the effect of promotional effort.

We use the value of λ for Windows, 0.0053, corresponding to an elasticity of 0.34. This is somewhat more elastic demand than is suggested by the logic above. Our choice is influenced by the same factors that result in a value of the elasticity of demand for Office that is somewhat below the value suggested by the data.

Estimates of the price elasticity of demand for productivity suites as a group tend to range from 0.5 to figures above 1. In the framework of this study, the price of Office is held below the single-seller revenue-maximizing price by limit pricing. At the point of single-period revenue maximization, the price elasticity is one. If the elasticity is greater than one, the demand function must become more elastic as price falls. The demand function used in the model has the opposite property—the elasticity is $p_2\lambda_2$, which falls as price falls. Hence it would not be consistent with the model to use an elasticity close to or greater than one.

We adopt $\lambda_2 = 0.0035$ as our estimate of the single-seller price semi-elasticity of demand for Office.

H. Complementarity

Our approach to estimating the two complementarity parameters, γ_1 and γ_1 follows this logic: Microsoft chooses prices to maximize revenue subject to the constraint that the necessary addition to the experience base occur. That constraint is, with superfluous subscripts omitted,

$$y_1 + y_2 = \text{Entry-deterring level of the base} \qquad (5.14)$$

The first-order conditions for the constrained maximization of revenue $p_1 y_1 + p_2 y_2$ are

$$y_1 - \lambda_1 \left(p_1 + \omega \right) y_1 - \gamma_2 \left(p_2 + \omega \right) y_2 = 0 \qquad (5.15)$$

$$y_2 - \lambda_2 (p_2 + \omega) y_2 - \gamma_1 (p_1 + \omega) y_1 = 0 \quad (5.16)$$

Here ω is the Lagrangian multiplier for the constraint. We impose symmetry on the cross price effects: $\gamma_2 = \gamma_1 \frac{y_1}{y_2}$. These equations can be solved for the values of ω, γ_1 , and γ_2 from the observed prices and sales and from the earlier estimated values of λ_1 and λ_2.

The resulting values are $\gamma_1 = 0.00037$ and $\gamma_2 = 0.00075$.

I. Role of Non-Price Demand Shifters

Microsoft uses advertising and other promotional effort, assistance to computer makers, product improvements, and other tools as well as low prices to expand its user base and deter entry. To see how these affect the analysis, consider a single-product version of the demand system and let *X* be spending on these efforts:

$$D(p, X) = e^{\mu - \lambda p} X^{\eta}, \quad (5.17)$$

with $\eta < 1$.

Microsoft solves the problem

$$\max\ py - X \ni e^{\mu - \lambda p} X^{\eta} = y, \quad (5.18)$$

where *y* is the entry-deterring level of sales. The profit-maximizing price is

$$p = \frac{1}{\lambda}\left[\mu + \eta(\log\eta - \log\lambda) - (1-\eta)\log y\right]. \quad (5.19)$$

The decrease in *p* that accompanies an increase in the entry-deterring level of output, *y*, is smaller than in the case where adjustments in *X* are ignored ($\eta = 0$).

The first-order conditions for the maximization imply

$$X = \frac{\eta}{\lambda} y, \quad (5.20)$$

which means that η can be measured from

$$\eta = \lambda \frac{X}{y} = \varepsilon\sigma \ , \tag{5.21}$$

where $\varepsilon = \lambda p$ is the price elasticity of demand and $\sigma = \frac{X}{py}$ is the share of revenue devoted to promotion.

Finally, the elasticity of the entry-deterring price with respect to the entry-deterring output is $\frac{1}{\varepsilon} - \sigma$.

Notice that the multiplicative advertising factor has no effect on the first-order conditions for the Bertrand model, so it is not necessary to carry it through that analysis. Advertising enters the analysis only when Microsoft considers the constrained problem considered in this section.

We inferred the role of promotional spending from Microsoft's actual spending on sales and marketing. On average over the years 1995 through 2002, Microsoft spent 22 percent of its revenue on sales and marketing. The elasticity of the entry-deterring price with respect to the entry-deterring level of sales is the reciprocal of the elasticity of demand less the revenue share of promotional spending.

J. Discount Rate

We take the discount rate to be 15 percent per year in nominal terms. This figure is within the range of Microsoft's typical weighted-average cost of capital from the Capital Asset Pricing Model. Thus we take $\beta = \frac{1}{1.15} = 0.87$.

K. Summary of Parameter Values

Table 2 collects together the entire set of parameters of the model.

Parameters	Interpretation	Values	
		Windows	*Office*
μ_1, μ_2	Demand scale	0.65	0.10
λ_1, λ_2	Single-seller price semi-elasticities	0.0053	0.0035
γ_1, γ_2	Cross-price semi-elasticities	0.00037	0.00075
		Microsoft	*Entrant*
θ_1, θ_2	Cross-seller price semi-elasticities	0.003	0.001
$x_{1,0}, x_{2,0}$	Entrant disadvantage in period 0	1.74	0.26
$x_{1,1}, x_{2,1}$	Entrant disadvantage in period 1	1.25	0.75
$x_{1,2}, x_{2,2}$	Entrant disadvantage in period 2	1.08	0.92
ϕ	Effect of experience base	0.23	
δ	Annual rate of depreciation of experience base	0.3	
β	Discount factor	0.87	
σ	Ratio of promotional spending to revenue	0.22	

Table 2. Summary of Parameter Estimates

VI. Dynamic Duopoly

According to our estimated demand functions, Microsoft's profit-maximizing prices if it faced neither an active rival nor potential competition would be $189 for Windows and $285 for Office. Although the model considers uniform prices for all customers, actual prices are not uniform, so we regard the results from our model as averages of heterogeneous prices. We will compare the model's unconstrained prices to those it predicts when Microsoft uses limit pricing to deter entry and to those it predicts in the case of active rivalry after entry.

Figure 4 shows the prices of Microsoft and a rival in the case where Microsoft starts with a substantial experience base and the rival starts with zero base. Notice that Microsoft sets prices for Windows and Office early in the period of rivalry higher than the constrained levels. The rival is not yet very effective in constraining Microsoft's price through active competition and Microsoft, in this hypothetical situation, has abandoned limit pricing. As the rival builds its experience base, it becomes a more effective restraining force and Microsoft's prices drop below the limit prices.

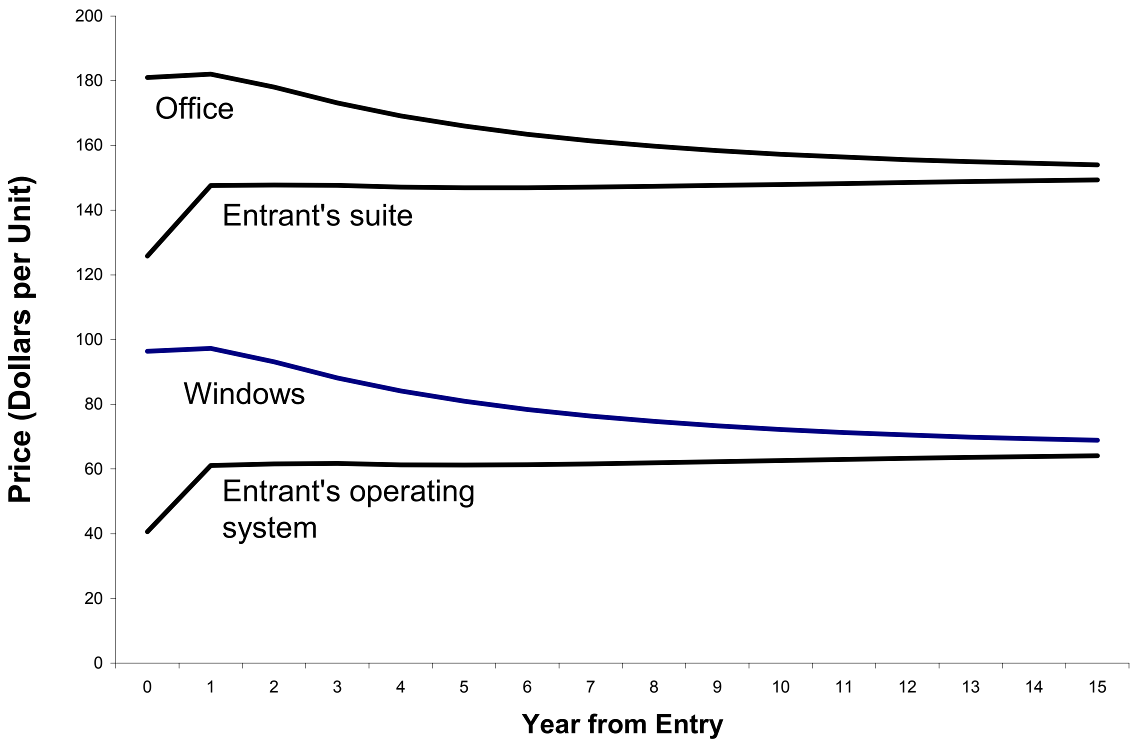

Figure 4. Prices of Microsoft's and the Entrant's Products

Figure 5 shows the key relationships of the model underlying Figure 1—the present value of the entrant's revenue as a function of Microsoft's steady-state price. In the lower graph, the vertical axis is the price of Windows. For each of these prices, there is a corresponding best price for Office—the price that maximizes Microsoft's revenue for a given level of total sales. The combined sales of Windows and Office are shown in the right-hand demand function. The sales, shown on the horizontal axis, are measured as the resulting steady-state experience base, the annual level of sales divided by the rate of depreciation. The upper panel shows the effect of Microsoft's experience base on the present value of a potential entrant's revenue. The limit price corresponds to an experience base just big enough to drive the present value below cost and thus deter entry.

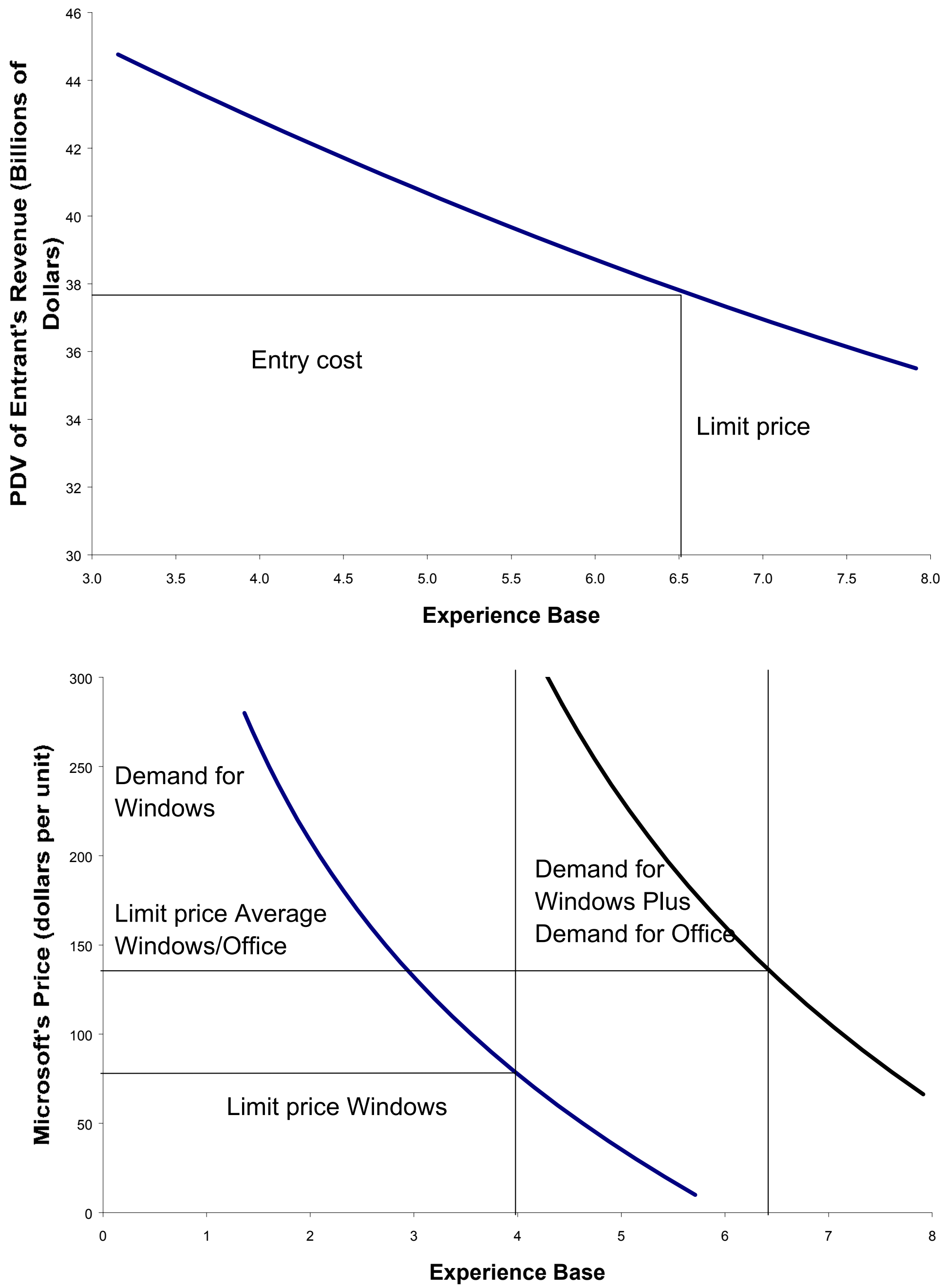

Figure 5. Limit Pricing

We calculate the derivatives of Microsoft's prices with respect to the entry cost. They are $1.27 for Windows and $1.37 for Office for each $100 million of entry cost. The derivative is useful for estimating the effect on Microsoft's prices of changes in entry cost that are not too large. For example, once a potential rival has sunk $100 million in costs, the remaining entry costs are smaller and Microsoft would need to lower its prices by $1.27 and $1.37 to deter the rival from sinking any further costs. In addition, the derivative is useful in estimating the elevation of prices caused by Microsoft's use of business practices that have come under legal challenge.

We interpret the lack of a frontal assault on Microsoft's position in desktop software as reflecting Microsoft's determination that limit pricing is the value-maximizing strategy. Revenue would be lower from a brief period of unconstrained pricing followed by active rivalry. For a sufficiently large reduction in entry cost, the calculation would come out the other way.

VII. Concluding Remarks

An empirical application of the modern theory of limit pricing suggests the power of potential competition in the desktop software market. Despite Microsoft's high shares in the operating system and productivity suite markets, the company's prices are well below the unconstrained single-seller levels. Microsoft has created an environment where entry is unattractive, because the entrant faces the disadvantage of widespread use of and experience with the Microsoft products among its potential customers. One of the ways that Microsoft achieved this outcome was setting prices below the unconstrained level.

This interpretation of Microsoft's position does not rest on any technical superiority of Microsoft's products, although if the products were technically much inferior to those a rival could produce, the cost of deterring entry would exceed the benefit. Thus the view of the competitive process that emerges from our model grants some advantage to being the first seller to sink the costs of developing a new type of product. But it also grants an advantage to a seller with a superior product.

As we have noted throughout this paper, we do not take a position on whether any of Microsoft's practices violate antitrust laws. If Microsoft were prevented from using a practice, and if the removal of the practice lowered the entry cost perceived by a potential rival, then our model predicts that Microsoft would set a lower price, in order to continue to deter entry of all potential rivals.

References

Bain, Joe. 1949. "A Note on Pricing in Monopoly and Oligopoly" *American Economic Review* 58: 211-222.

Brynjolfsson, Erik, and Chris F. Kemerer. 1996 "Network Externalities in Micro-computer Software: An Econometric Analysis of the Spreadsheet Market" *Management Science*.42(12): 1627-1647

Cellini, Roberto and Luca Lambertini. 2002. "Dynamic Oligopoly with Sticky Prices: Closed-Loop, Feedback and Open-Loop Solutions" Mimeo. Universita di Catania.

Chen, Yongmin, and Robert W. Rosenthal. 1996. "Dynamic Duopolies with Slowly Changing Customers Loyalties" *International Journal of Industrial Economics,* 14(3): 269-96.

Dahan, Ely, and John R. Hauser. 2002. "The Virtual Customer" *Journal of Product Innovation Management*, 19(5): 332-354. September.

Driskill, Robert A., and Stephen McCafferty. 1989. "Dynamic Duopoly with Adjustment Costs: A Differential Game Approach" *Journal of Economic Theory* 49: 324-338.

Economides, Nicholas, and Charles Himmelberg. 1995 "Critical Mass and Network Size with application to the US Fax Market." Mimeo. Columbia Business School.

Economides, Nicholas, and Frederick Flyer. 1997 "Compatibility and Market Structure for Network Goods" Mimeo. Stern School of Business.

Friedman, James. 1979. "On Entry Preventing Behavior" in *Applied Game Theory*, S.J Brams *et al*., eds. Vienna: Physica-Verlag.

Froeb, Luke, Steven Tschantz, and Phillip Cook. 2003, "Bertrand Competition with Capacity Constraints: Mergers Among Parking Lots" *Journal of Econometrics* 113(1): 49-67. March.

Fudenberg, Drew, and Jean Tirole. 2000. "Pricing a Network Good to Deter Entry" *Journal of Industrial Economics* 48: 373-390. December.

Gandal, Neil. 1994. "Hedonic Price Indexes for Spreadsheets and an Empirical Test for Network Externalities" *Rand Journal of Economics* 25(1): 160-170.

Giovannetti, Emanuele. 2001 "Perpetual Leapfrogging in Bertrand Duopoly" *International Economic Review* 42(3): 671-96.

Hausman, Jerry A., G. Leonard, and D. Zona. 1994. "Competitive Analysis with Differentiated Products" *Annales d'Economie et de Statistique* 34

Hendel, Igal. 1999. “Estimating Multiple-Discrete Choice Models: An Application to Computerization Returns”, *Review of Economic Studies* 66: 423-446.

Hotz, V. J., and R.A. Miller. 1993. “Conditional-Choice Probabilities and the Estimation of Dynamic Models”, *Review of Economic Studies*, 60, 497-529.

Judd, Kenneth L. 1996. “Cournot vs. Bertrand: A Dynamic Resolution” Mimeo. Stanford University.

_________. 1998. *Numerical Methods in Economics*” Cambridge: MIT Press.

Katz, Michael L., and Carl Shapiro. 1985. “Network Externalities, Competition and Compatibility” *American Economic Review*, 75(3): 424-440.

Maskin, Eric, and Jean Tirole. 1988 “A Theory of Dynamic Oligopoly, I: Overview and Quantity Competition with Large Fixed Costs” *Econometrica,* 56(3): 549-569.

__________________________ 2001 “Markov Perfect Equilibrium I: Observable Actions” *Journal of Economic Theory*, 100, 191-219.

Milgrom, Paul, and D. John Roberts. 1982. “Limit Pricing and Entry under Incomplete Information: An Equilibrium Analysis” *Econometrica* 50: 443-460

Ohashi, Hiroshi. 2001. “The Role of Network Externalities in the U.S. VCR Market, 1978-1986” Mimeo. Faculty of Commerce, University of British Columbia.

Slade, Margaret E. 1995. “Empirical Games: the Oligopoly Case” *Canadian Journal of Economics* 28(2): 368-402

________________ 1998. “Optimal Pricing with Costly Adjustment: Evidence from Retail-Grocery Prices” *Review of Economic Studies* 65: 87-107

Spence, A. Michael. 1977. “Entry, Capacity, Investment, and Oligopolistic Pricing” *Bell Journal of Economics* 8: 534-544.

___________. 1979. “Investment Strategy and Growth in a New Market” *Bell Journal of Economics*, 10(1): 1-19.

Toubia, Olivier, Duncan Simester, and John R. Hauser. 2003. “Polyhedral Methods for Adaptive Choice-based Conjoint Analysis” working paper, Center for Innovation in Product Development, MIT. February.

Vedenov, Dmitry, and Mario J. Miranda. 2001. “Numerical Solutions of Dynamic Oligopoly Games with Capital Investment” *Economic Theory* 18:237-261.