Regulation and performance of communication and information networks

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INTRODUCTION

This study examines a monopolist of a base good that benefits from a complementary good provided by either it or another firm. Use of the complementary good requires the base good, but not the reverse. The model assesses and calibrates the extent of the positive influence on the base good profits that is created by the existence of the two sources (internal or external) of the complementary good. An equivalence between a model of a base and complementary good, and a reduced-form model of the base good where network effects are assumed in the utility function as a surrogate for the presence of direct network effects (i.e., a consumer's utility directly increases in the number of users) or indirect network effects (i.e., arising from increased variety of complementary goods produced by other firms) is established. This allows us to examine the pricing of the complementary good under different market structures and in the context of the effect of other complementary goods via the network effects. Additionally, the study assesses and calibrates the influence of the intensity of network effects and quality improvements in the complementary good on profits from the base good. Also evaluated is the incentive that a monopolist has to improve the quality of the base good rather than that of a complementary good that it produces.

The model has implications for the base good monopolist's trade off in improving the quality of its own complementary good versus subsidizing increases in other network effects. The monopolist could subsidize increases in other network effects by, e.g., taking actions to increase sales of the base good thereby increasing consumers' utility directly (direct network effects) or facilitating or subsidizing increased variety of other complementary goods available (indirect network effects). The base good monopolist prefers that an independent firm offer an additional complementary good rather than improve the quality of an extant complementary good by the same amount as the quality offered by the new good, assuming the costs of the two are the same. This results from the complementary goods firm's incentive to restrict output more at higher quality levels, limiting the increase in base good sales via sales of the complementary good. Importantly, the base good monopolist gains more from adding an complementary good to its portfolio of products than increasing the quality of an existing portfolio product by the same quality as that of the new good if the costs of doing so are the same. The effect is stronger than if an independent firm produces the complementary good. This is because adding a complementary good increases sale of the base good because of the complementarities, but an increase in the quality of the complementary good does not affect sales of the base good because the monopolist can fully adjust the price of the complementary good to capture profits from its increased quality.

The model also has implications for the base good monopolist's incentives to invest in improving the base and complementary goods under different market structures and in making them compatible. An independent base good monopolist has a greater incentive to invest in improving the quality of the base good (at the margin) than a joint monopolist who produces both the base and complementary good. Improvements in the base good increase its price and therefore the effective price to use the complementary good. A producer of both internalizes this and has less incentive to improve the base good, while an independent monopolist does not. Conversely, a monopolist who produces both the base and complementary goods has a greater incentive to improve the complementary good (on the margin) than an independent firm would have to improve it. Improvements in the complementary good's quality increase sales of the base good, which the joint monopolist internalizes but the independent firm does not. Finally, if a single firm owns both the base and complementary goods it has a greater incentive to make them compatible than if separate firms offered the two products because increasing compatibility improves sales of both. The base good benefits directly from a more compatible product and the complementary good benefits indirectly because it requires purchase of the base good. A joint monopolist internalizes this feedback while independent firms do not.

Based on these results, a possible explanation of the fact that Microsoft Office is significantly more expensive than Microsoft Windows is discussed. Microsoft has approximately the same market share (over 90 per cent) in the market for operating systems for personal computers as in the market for 'Office applications' (a bundle of word processing, spreadsheet, presentation and database software). However, Microsoft charges a price for its Windows operating system that is significantly lower than the price of its office suite. Although the model does not address the level of prices for Windows and

Office, it can explain this difference in relative prices for Windows and Office. A joint monopolist, such as Microsoft, has two price instruments, the base good and complementary good price. It is optimal to keep the operating system price low even if Office is quite valuable because some users buy Windows for use with other complementary goods. Raising the price of Office but keeping the price of Windows low allows the joint monopolist to capture some of the value provided by Office while not pricing users of other goods complementary to Windows out of the market.

The model of a base and a complementary good is similar to models of 'mix and match,' where consumers assemble systems in fixed proportions, but differs from typical assumptions in these models because the base good in the model is valuable without use of the complementary good. In mix and match models typically neither good is valuable without the other. Mix and match models originated from Matutes and Regibeau (1988) and Economides (1989).[1, 2]

The reduced-form model of the base good in which network effects are summarized by a term that influences utility positively and is increasing in sales, derives from Katz and Shapiro (1985) and Farrell and Saloner (1986). The network effects summarized in the utility function can result from either direct or indirect network effects. In the former case, a consumer benefits directly from the number of individuals adopting the base good (e.g., because there is a larger network to exchange files with) while in the latter case a consumer benefits indirectly from the number of individuals adopting the base good through the increased availability of software variety. Both of these effects are summarized by a term in consumers' utility functions, which is increasing in total sales of the base good.[3]

There has been little attempt to calibrate the size of the network effect used in reduced-form models. Exceptions are Economides (1996b) and Clements (2004). Economides (1996b) calibrates the size of the network effect in the context of measuring the incentive of a patent-holding monopolist who also sells a complementary good to invite competitors in the complementary goods market so as to maximize the network effects. Clements (2004) evaluates the effect of the strength of network effects, degree of compatibility and the density of consumers in the market on standardization under oligopolistic competition. The objective of these papers is different from our objective of providing an equivalence of these modelling approaches and evaluating the incentives of the base good provider to innovate, promote other complementary products and set compatibility standards.

The rest of this chapter starts by setting up the basic framework of the research. The five models used are then developed and discussed. These models differ in the way that network effects and inherent product quality are modelled. The equilibria of these models is then considered. A discussion of the incentives to invest in quality in either the base good or the complementary good in different ownership structures and under different intensities of network effects follows and compatibility decisions made by the base good monopolist are examined. Next, there is a discussion of the explanation of Microsoft's relative pricing provided by the analysis. To conclude, the results are compared with the empirical literature on network effects.

BASIC FRAMEWORK

Assume that consumers are differentiated by their preferences for quality of the base good (B) and quality of the complementary good (C). The second good requires the first good to provide positive utility.[4] For example, think of the Windows operating system as the base good, and an office suite (such as Microsoft Office) as the complementary good, not necessarily produced by the same company. Let the marginal utility of quality of the base good be θ and the marginal utility of quality of the complementary good be ϕ. The pair (θ, ϕ) defines a consumer type. Also, assume that both θ and ϕ are distributed independently and uniformly on [0, 1].

Assumed network effects could be direct effects that result from a consumer's utility directly increasing in the number of other users of the base good or indirect effects that result from other complementary goods whose existence positively influences consumers' willingness to pay for the base good via economies of scale in production. Assume for this study the latter case that the positive consumption effects between the base good and the complementary goods reinforce each other. These effects are summarized by adding a term proportional to sales of the base good in the utility function of a typical consumer.

When consuming one unit of the base good and possibly one unit of the complementary good, consumer (θ, ϕ) receive utility

$$U = \theta q_B - p_B + \alpha x_B + \delta V ,$$

where q_B is the quality of the base good, p_B is the price of the base good, V is the utility from the consumption of the complementary good, x_B is the sales of the base good, α measures the intensity of the network effects and δ is an indicator variable taking the value one if the complementary good is bought and zero otherwise. Thus, network effects arising out of direct or indirect network effects are summarized by an additive term in the utility function proportional to sales.[5] Consumers not purchasing receive zero utility. The utility from the consumption of the complementary good is

$$V = \varphi q_C - p_C ,$$

where q_C is the quality of the complementary good and p_C is the price of the complementary good.

The first model has a base good monopolist in a market where network effects are summarized in the utility function of consumers as proportional to sales. The second model has two monopolists (independent firms), one for the base good and one for the complementary good, and assumes no network effects. The third model adds network effects to the independent firms in Model 2. The fourth model has a single monopolist (joint monopolist) producing both the base and the complementary good. The fifth model adds network effects to the joint monopolist considered in Model 4.

MODELS

Model 1: Single Good Monopolist in a Market with Network Effects

First consider a model of a single good monopolist selling the base good with network effects arising from direct or indirect effects due to the presence of other complementary goods produced with increasing returns to scale. In this case, $\delta = 0$ and consumer θ who buys one unit of the base good of quality q_B at price p_B receives utility of

$$U = \theta q_B - p_B + \alpha x_B , \tag{7.1}$$

where $\alpha > 0$ measures the intensity of the network effect (marginal utility of network expansion). All consumers of type $\theta > \theta_B$ buy the good, where the marginal consumer is

$$\theta_B = \frac{(p_B - \alpha x_B)}{q_B} . \tag{7.2}$$

Sales are

$$x_B = (1 - \theta_B) = 1 - \frac{(p_B - \alpha x_B)}{q_B} . \tag{7.3}$$

Inverting the demand gives

$$x_B = \frac{(q_B - p_B)}{(q_B - \alpha)}, \; \Pi_B = p_B x_B = \frac{p_B(q_B - p_B)}{(q_B - \alpha)}.\text{[6]} \tag{7.4}$$

Assuming zero costs, maximizing profits implies:[7]

$$p_B{}^* = \frac{q_B}{2}, \; x_B{}^* = \frac{q_B}{2(q_B - \alpha)} \text{ and } \Pi_B^* = \frac{q_B^2}{4(q_B - \alpha)}.\text{[8]} \tag{7.5}$$

In the case of no network effects, i.e., when $\alpha = 0$, the demand without network effects is a pivot of the demand with network effects through the point $(0, q_B)$. It is well known that such pivots of linear demands lead to the same monopoly price. Thus, the equilibrium price is unaffected by network effects, while sales and profits are higher with them. Using the subscript 0 for the variables with no networks effects $(\alpha = 0)$, gives

$$x_B^* = x_{B0}\left[\frac{q_B}{(q_B - \alpha)}\right]; \; p_B^* = p_{B0}, \text{ and } \Pi_B^* = \Pi_{B0}\left[\frac{q_B}{(q_B - \alpha)}\right]. \tag{7.6}$$

Model 2: Independent Firms without Network Effects

This model considers two independent monopolists, one for the base good and another for the complementary good, and no network effects are allowed. Comparing the equilibrium of Model 2 to that of Model 1, enables calibration of the intensity of network effects necessary to generate base good profits equivalent to those generated by sales of a complementary good.

There are two groups of purchasers to consider (see Figure 7.1). First, consumers of type $\theta > \theta_B$, $\phi < \phi_{B,BU}$ buy the base good only, where θ_B is the marginal consumer indifferent between buying the base good and buying nothing, i.e.

$$\theta_B = p_B / q_B, \tag{7.7}$$

and $\phi_{B,BU}$ is the marginal consumer indifferent between buying only the base good and buying both the base and complementary goods, i.e.

$$\varphi_{B,BU} = p_C / q_C. \tag{7.8}$$

Second, consumers of types $\varphi > \varphi_{B,BU}$, $\theta > \theta_B$, as well as of types $\varphi > \varphi_{BU}(\theta)$, $\theta < \theta_B$, buy both, where $\varphi_{BU}(\theta)$ is the marginal consumer of

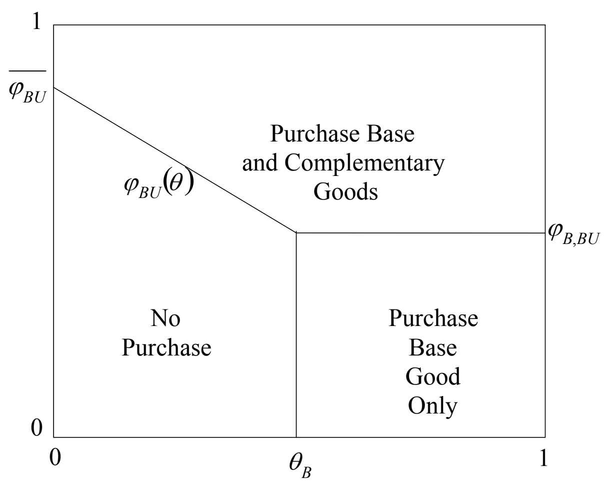

Figure 7.1

type θ indifferent between buying both goods and buying nothing, i.e.

$$\varphi_{BU}(\theta) = (p_B + p_C - \theta q_B)/q_C \ . \tag{7.9}$$

The profits for the base good monopolist are

$$\Pi_B = \left[(1-\theta_B)\varphi_{B,BU} + \left(1-\varphi_{B,BU} - (\overline{\varphi_{BU}} - \varphi_{B,BU}\right)/2\right] p_B \, , \tag{7.10}$$

where $\overline{\varphi_{BU}} = (p_B + p_C)/q_C$ is the consumer of type $\theta = 0$ who is indifferent between buying both goods and nothing. The profits for the complementary good monopolist are

$$\Pi_C = \left[(1-\varphi_{B,BU}) - (\overline{\varphi_{BU}} - \varphi_{B,BU})\theta_B/2\right] p_C \, . \tag{7.11}$$

At the Nash equilibrium in a price-setting game, the first-order conditions for the two monopolists are

$$p_B(3p_B + 4p_C) - 2q_B q_C = 0 \text{ and } p_B^2 - 2q_B(q_C - 2p_C) = 0 \, . \tag{7.12}$$

Since the first-order conditions are nonlinear they are solved numerically to find the equilibrium.[9] The analysis restricts $q_C \geq q_B$ since only interior solutions only and for $q_C > q_B$, $\overline{\varphi_{BU}} > 1$ are considered.[10]

Model 3: Independent Firms with Network Effects

In Model 3, we incorporate network effects arising from direct consumption externalities or other complementary goods into Model 2. The utility function of consumers (eq. 8.1) now has a positive α capturing the network effects. The same regions of consumer types buy as in Model 2, but some margins now depend on α . We use superscript n to denote the presence of network effects

$$\theta_B^n = (p_B - \alpha x_B)/q_B \, , \, \varphi_{B,BU}^n = \varphi_{B,BU} \, , \tag{7.13}$$

$$\varphi_{BU}^n = (p_B + p_C - \theta q_B - \alpha x_B)/q_C , \; \overline{\varphi_{BU}^n} = (p_B + p_C - \alpha x_B)/q_C \; . \tag{7.14}$$

Demand for the base good is given by solving for x_B in

$$x_B = 1 - \theta_B^n(x_B) + \left[1 - \left(\overline{\varphi_{BU}^n}(x_B) - \varphi_{B,BU}^n(x_B)\right)\theta_B^n / 2\right]. \tag{7.15}$$

Since θ_B^n and φ_{BU}^n are both linear functions of x_B , this is a quadratic equation. Using the positive root, x_B^* , that solves this equation, the profit function for the base good monopolist is

$$\Pi_B^n = \left[\left(1 - \theta_B^n(x_B^*)\right)\varphi_{B,BU}^n + \left(1 - \varphi_{B,BU}^n - 1/2\left(\overline{\varphi_{BU}^n}(x_B^*) - \varphi_{B,BU}^n\right)\theta_B^n(x_B^*)\right)\right] p_B \tag{7.16}$$

and for the complementary good monopolist is

$$\Pi_C^n = \left[(1 - \varphi_{B.BU}^n) - 1/2\left(\overline{\varphi_{BU}^n}(x_B^*) - \varphi_{B,BU}^n\right)\theta_B^n(x_B^*)\right] p_C \tag{7.17}$$

The first-order conditions for the two firms are nonlinear functions of the prices and so are solved numerically.[11]

Model 4: Joint Monopolist without Network Effects

In Model 4, the joint monopolist sells both the base and complementary goods. The marginal consumers are defined in the same manner as in Model 2, and the profit function for the joint monopolist is

$$\begin{aligned}\Pi_B + \Pi_C &= (1-\theta_B)\varphi_{B,BU}\, p_B \\ &\quad + \left(1-\varphi_{B,BU} - 1/2\left(\overline{\varphi_{BU}} - \varphi_{B,BU}\right)\theta_B\right)(p_B + p_C)\end{aligned} \tag{7.18}$$

The joint monopolist chooses both prices to maximize its profits. The first-order conditions are

$$3p_B(p_B+2p_C) - 2q_Bq_C = 0 \text{ and } 3p_B^2 - 2q_B(q_C - 2p_C) = 0\,. \tag{7.19}$$

These can be solved to get the equilibrium prices, quantities, and profits:

$$p_B = \frac{2q_B}{3},\ p_C = \frac{q_C}{2} - \frac{q_B}{3}\,, \tag{7.20}$$

$$x_B = 1 - \frac{p_B(p_B+2p_C)}{(2q_Bq_C)} \text{ and } x_C = 1 - \frac{(p_B^2 + 2p_Cq_B)}{(2q_Bq_C)}\,.\text{[12]} \tag{7.21}$$

Notice that the price of the base good is independent of the quality of the complementary good. This is true for general demand functions, since the marginal revenue of the joint monopolist from sales of the base good is independent of the quality and price of the complementary good, at the optimal complementary good price. To see this, consider general demand functions for the base and complementary goods, $D_B(p_B)$ and $D_C(p_B+p_C)$ respectively. Then profits are:

$$\Pi_B = p_B\left[D_B(p_B) + D_C(p_B+p_C)\right] \text{ and } \Pi_C = p_C D_C(p_B+p_C)\,, \tag{7.22}$$

and joint profits are $\Pi = \Pi_B + \Pi_C$ so that the first-order conditions are (where primes denote derivatives):

$$\begin{gathered} D_B + p_B D_B' + D_C + (p_B+p_C)D_C' = 0\,, \\ D_C + (p_B+p_C)D_C' = 0\,. \end{gathered} \tag{7.23}$$

These conditions imply that $D_B(p_B) + p_B D'_B(p_B) = 0$. Therefore, for the joint monopolist the choice of price for the base good is independent of the choice of price and quality of the complementary good.

The joint monopolist completely internalizes in the complementary good price any changes in the quality of the complementary good, and therefore the price of the basic good remains unaffected by such quality changes.[13] In the analysis only positive prices are considered for the complementary good and therefore restrict $q_C > 2q_B / 3$.[14]

Model 5: Joint Monopolist with Network Effects

Model 5 incorporates network effects for the base good into Model 4. The marginal consumers are defined in the same manner as in Model 3 and the profit function for the joint monopolist is

$$\begin{aligned} &\Pi_B^n + \Pi_C^n = \left(1 - \theta_B^n\left(x_B^*\right)\right)\varphi_{B,BU}^n p_B \\ &+\left(1 - \varphi_{B,BU}^n - \frac{1}{2}\left(\overline{\phi_{BU}^n}\left(x_B^*\right) - \varphi_{B,BU}^n\right)\theta_B^n\left(x_B^*\right)\right)\left(p_B + p_C\right). \end{aligned} \tag{7.24}$$

The first-order conditions for the firm are nonlinear functions of the prices and are solved numerically.[15]

EQUIVALENCE RESULTS

In this section, the size of network effects necessary to achieve the same base good profits as those arising from sales of the complementary good are calibrated. This is possible since the models explicitly allow for positive effects of the complementary good sales as well as models that allow for network effects that are summarized in the utility function. Thus, establishing equivalence between the network effects (defined as added profits to a base good monopolist) created by the presence of a complementary good and those summarized in the utility function is done for the various industry structures and for quality levels. This equivalence is used in base good profits to analyse the incentive of the base good monopolist to offer its own complementary good, improve the quality of a complementary good that it offers, and subsidize an independent firm so that it offers or increases the quality of a complementary good it provides.

The focus is on a particular type of equivalence, in base good profits, because the primary interest is in the incentives of the base good monopolist. This equivalence, of course, does not ensure that consumer welfare is equated. Doing so requires determining how to weight the utility of consumers with high versus low valuations of base and complementary goods since purchasing patterns vary across different equilibria. In addition, profits could not be equilibrated at the same time as consumer welfare. One could also calibrate equivalence in total profits across both firms. However, this is an inappropriate comparison to make when comparing models with and without network effects. Similarly, calibrating the equivalence in total (base and complementary good) profits for the base good monopolist is inappropriate when comparing models in which the base good firm controls the complementary good to those in which it does not. Accordingly, the focus is on equivalence in base good profits as the goal is to evaluate the incentives of the base good monopolist.[16]

An important property of all the models is scalability. It is easy to check that the equilibrium sales x_B and x_C are unaffected by a common scaling (up or down) of q_B, q_C, and α by the same coefficient $\lambda > 0$. Additionally, the equilibrium prices p_B and p_C are proportional to the common scaling factor λ of q_B, q_C, and α, and therefore their ratio (p_C / p_B) is unaffected by scaling. It follows that equilibrium profits are also proportional in the scaling factor λ. Thus, all variables are scaled (normalized) in terms of the quality of the base good q_B, defining the normalized quality of the complementary good as $\tilde{q}_C = q_C / q_B$, the normalized α or normalized network effects as $\tilde{\alpha} = \alpha / q_B$, the normalized prices of the goods as $\tilde{p}_B = p_B / q_B$, $\tilde{p}_C = p_C / q_B$, the normalized relative price of the complementary good in relation to the base good as $\tilde{R}_{CB} = \tilde{p}_C / \tilde{p}_B = p_C / p_B$, the normalized base good profits as $\tilde{\Pi}_B = \Pi_B / q_B$, and the normalized complementary good profits as $\tilde{\Pi}_C = \Pi_C / q_B$. All normalized variables remain unaffected by the common scaling of q_B, q_C, and α. Below, are reported results for all models in terms of normalized variables.

Equivalence of Network and Complementary Good Effects Produced by an Independent Firm

The demonstration begins with a model of two independent monopolists, one producing the base good and another producing a complementary good (Model 2). This situation is compared with a model of a single base good monopolist with network effects summarized in their utility function (Model 1). Equivalence between the two models is established by equating the normalized base good equilibrium profits. An independent firm selling the complementary good results in increased sales of the base good. The equivalence finds the network effects (αx) in the utility of individual consumers, where $\tilde{\alpha}$ measures the intensity of the network effect necessary to equate base good profits.

Table 7.1 Independent firms: Equivalence of quality and network effects

Normalized Complementary Good Quality $(\tilde{q}_C = q_C / q_B)$	Normalized Relative Complementary Good Price $(\tilde{R}_{CB} = p_C / p_B)$	Normalized Base Good Profits $(\tilde{\Pi}_B = \tilde{\Pi}_B / q_B)$	Normalized Equivalent α $(\tilde{\alpha} = \alpha / q_B)$
1	0.7071	0.3431	0.2714
2	1.2291	0.4003	0.3755
3	1.7375	0.4273	0.4149
5	2.7441	0.4532	0.4484
10	5.2481	0.4755	0.4743

Notes: (a) in this and all subsequent tables, results are to 4 d.p. unless otherwise noted. (b) these are equilibrium prices under presence of the complementary good but no network effects.

Table 7.1 shows the normalized network effects, $\tilde{\alpha}$, required to obtain equivalent normalized base good profits in the absence of the complementary good. For example, line three of the table indicates that a base good monopolist in the absence of a complementary good but with an $\tilde{\alpha}$ of 0.4149 earns the same normalized base good profits as a base good monopolist with an $\tilde{\alpha}$ of zero in the presence of an independent monopolist producing a complementary good of normalized quality $\tilde{q}_C = 3$. In this and all following analyses $q_C \geq q_B$ is chosen to ensure an interior solution for the independent firms market structure and to ensure a positive price for the complementary good in the joint monopolist market structure as described earlier.

Equivalence of Network and Complementary Effect Good Produced by a Joint Monopolist

The base good sales of the joint monopolist increase when it also sells the complementary good. Normalized network effects, $\tilde{\alpha}$, are required to obtain equivalent normalized base good profits by a monopolist providing only the base good. The results are summarized in Table 7.2. This is equivalent to Table 7.1 but for a joint monopolist rather than for two independent firms. For example, line three of the table indicates that a monopolist producing a base good in the absence of a complementary good with an $\tilde{\alpha}$ of 0.4375 earns the same normalized base good profits as a monopolist selling a base and a complementary good of normalized quality $\tilde{q}_C = 3$ with an $\tilde{\alpha}$ of zero. The results in Table 7.2 are presented in numerical form for easy

Table 7.2 Joint monopolist: Equivalence of quality and network effects

Normalized Complementary Good Quality $\left(\tilde{q}_C = q_C / q_B\right)$	Normalized Relative Complementary Good Price $\left(\tilde{R}_{CB} = p_C / p_B\right)$	Normalized Base Good Profits $\left(\tilde{\Pi}_B = \tilde{\Pi}_B / q_B\right)$	Normalized Equivalent α $\left(\tilde{\alpha} = \alpha / q_B\right)$
1	0.2500	0.4444	0.4375
2	1.0000	0.4444	0.4375
3	1.7500	0.4444	0.4375
5	3.2500	0.4444	0.4375
10	7.0000	0.4444	0.4375

Note: These are equilibrium prices under presence of complementary good but no network effects.

comparisons with other tables. They can also be presented in algebraic form using equations (7.20) and (7.21) as: $\tilde{R}_{CB} = 3\tilde{q}_C / 4 - 1/2$ and $\tilde{\Pi}_B = 4/9$. Equating $\tilde{\Pi}_B$ to the normalized base good profits from Model 1 (single good monopolist with network effects) gives (from equation 8.5) the equivalent $\tilde{\alpha}$ of $\tilde{\alpha} = 7/16$.

Comparing Table 7.1 and Table 7.2, we observe that, while normalized base good profits are sensitive to the normalized quality of the complementary good for the independent monopolist, they are not for the joint monopolist. For the joint monopolist, all the variation in the normalized quality of the complementary good is reflected in the normalized complementary good price and the normalized base good price is unaffected (i.e., $\tilde{p}_B = 2/3$ while $\tilde{p}_C = (\tilde{q}_C / 2) - 1/3$).[17] This follows from the fact that the joint monopolist is able to adjust the price of the complementary good to fully reflect its adjustment in quality. Since it has both price instruments available, the joint monopolist can adjust the complementary good price so that the margin for consumers buying only the base good (the θ_B margin in Figure 7.1) is not distorted by the change in complementary good quality. The joint monopolist does not want to alter the base good price because consumers who buy only the base good may be priced out of the market since they do not benefit from complementary good quality improvements. In contrast, the independent monopolist of the base good, in a Nash equilibrium framework, changes its price in the direction of changes in the quality of the complementary good. Thus, base good prices and profits are sensitive to quality changes of the complementary good when independent firms produce the two goods separately but not when the same firm produces them. As a result, the strength of the network effects (as measured by the $\tilde{\alpha}$ needed to equate the normalized base good profits) is not sensitive to changes in the normalized quality for the joint monopolist but is for the equilibrium of independent firms.[18]

Table 7.1 and Table 7.2 are used to assess the base good monopolist's incentive to invest in improving the quality of the complementary good when it owns the complementary good versus when an independent firm owns it. Microsoft in effect subsidizes compatible applications that it does not sell by including in Windows various functions that are useful to applications developers and which applications developers would have to develop by themselves if they were not available in Windows.[19] As noted, the base good monopolist does not benefit (in terms of base good profits) from improvements in the complementary good quality when it owns both products, but does when an independent firm controls the complementary good. Therefore, the base good monopolist has a greater incentive to invest in improving the complementary good when an independent firm controls it. Of course, as a joint monopolist, there might be separate incentives provided by the complementary good profits that it would benefit from.

Equivalence of Low-Quality Good with Network Effects and a High-Quality Good for an Independent Firm

Next the effect of increasing the normalized quality of the complementary good when independent firms produce the base and complementary goods is analysed. An increase in the degree of normalized network effects equivalent to an increase in the normalized quality of the complementary good is found. In particular, increases in the normalized quality of the complementary good in Model 2 are compared to an increase in normalized network effects (an increase in $\tilde{\alpha}$ from 0) in Model 3 with a fixed normalized quality of $\tilde{q}_C = 1$. In Table 7.3, e.g., line three considers a base good monopolist in the presence of an independent complementary good monopolist with normalized relative quality $\tilde{q}_C = 1$. If the normalized quality of the complementary good is increased to $\tilde{q}_C = 5$ this is equivalent (in normalized base good profits) to increasing $\tilde{\alpha}$ from zero to 0.2792.

These results can be used to assess the incentive of the base good monopolist to subsidize an increase in the quality of an independent firm's complementary good versus subsidizing an additional complementary good offered by an independent firm. As shown, an independent monopolist who produces the base good has normalized profits of $1/4$ when there is no complementary good and no network effects (Model 1). So an independent monopolist producing a base good in the absence of a complementary good and with no network effects earns normalized base good profits of 0.25. From row one of Table 7.1 a base good monopolist in the presence of an independent complementary good monopolist offering normalized

Table 7.3 Equivalence of quality increase and network effect, independent firms

Increase in Normalized Complementary Good Quality $\left(\tilde{q}_C = q_C / q_B\right)$	Normalized Relative of Complementary Good Price (High Quality) $\left(\tilde{R}_{CB} = p_C / p_B\right)$	Normalized Base Good Profits (High Quality) $\left(\tilde{\Pi}_B = \tilde{\Pi}_B / q_B\right)$	Equivalent Increase in Normalized α $\left(\tilde{\alpha} = \alpha / q_B\right)$
$1 \to 2$	1.2291	0.4003	0.1591
$1 \to 3$	1.7375	0.4273	0.2230
$1 \to 5$	2.7441	0.4532	0.2792
$1 \to 10$	5.2481	0.4755	0.3242

Notes: These are equilibrium prices and profits under the higher normalized complementary good quality.

complementary good quality $\tilde{q}_C = 1$ earns base good profits of 0.3431. Thus, adding one complementary good of quality $\tilde{q}_C = 1$ increases normalized base good profits by approximately 0.0931. This is larger than the normalized base good profits increase precipitated by a normalized quality increase from $\tilde{q}_C = 1$ to 2 in the complementary good (which, by comparing the base good profits in row one of Table 7.3 to base good profits in row one of Table 7.1, is approximately 0.0572).

Thus, a monopolist of the base good prefers that the independent firm add a complementary good of normalized quality 1 rather than increase the normalized quality of a complementary good from 1 to 2 if the costs of both changes are the same. Adding a complementary good expands the market for the base good more than an equivalent increase in the normalized quality of the complementary good increases the market for the base good because the elasticity of demand for the complementary good is declining in its quality so that the producer of the complementary good restricts output more per incremental increase in quality as the quality rises. This can be seen by computing the elasticity of demand for the complementary good from (7.11), which yields $-p_C / (q_C - p_C - 0.5\theta_B p_B)$.[20] Demand for the complementary good becomes more inelastic at higher quality levels because the market becomes saturated. Thus at increasingly higher quality levels of the complementary good, the complementary good firm restricts output more and the base good monopolist benefits less from market expansion of the base good. The complementary goods firm does not internalize the profits from the market expansion of the base good and at increasingly higher quality levels the market for the complementary good becomes saturated (the marginal consumer approaches $\theta = 0$) so it is optimal to raise price and limit output. This would imply that Microsoft prefers to subsidize a greater number of applications that are independent goods with respect to each other (neither substitutes nor complements to each other) but are complementary goods to its Windows operating system (base good) rather than a few such applications of higher quality.

Equivalence of a Low-Quality Good with Network Effects and a High-Quality Good for a Joint Monopolist

Next, the effect of increasing the normalized quality of the complementary good when a joint monopolist produces the base and complementary goods is analysed. Increases in the normalized quality in Model 4 are compared to increases in normalized network effects (an increase in $\tilde{\alpha}$, starting from 0) in Model 5 with fixed normalized quality equal to $\tilde{q}_C = 1$. The results are reported in Table 7.4. For example, row three of Table 7.4 considers a joint monopolist producing base and complementary goods of normalized quality $\tilde{q}_C = 1$. If the normalized quality of the complementary good is increased to $\tilde{q}_C = 5$ no increase in $\tilde{\alpha}$ is required to maintain the same normalized base good profits. The base good profits are invariant to the complementary good quality. As noted earlier, the joint monopolist can adjust the price of the complementary good to fully reflect changes in its quality so it does not need to change the base good price. The zero $\tilde{\alpha}$ increases in Table 7.4 mean that the joint monopolist does not get any benefits in its normalized base good profits from increases in the normalized quality of the complementary good that it produces.

Comparing Table 7.3 and Table 7.4, we observe that normalized profits for the base good are sensitive to improvements in the normalized quality of the complementary good for the independent firms but not for the joint monopolist. As discussed earlier, this follows from the fact that the joint monopolist is able to adjust the price of the complementary good to fully reflect its change in quality. In contrast, the independent monopolist of the base good, at the Nash equilibrium, changes its price in the direction of changes in the quality of the complementary good. Thus, to improve base good profits the joint monopolist should subsidize independent complementary goods but not its own, whilst an independent firm producing the base good benefits from both.

Table 7.2 and Table 7.4 can also be used to assess the incentive of the joint monopolist to invest in increasing the quality of its complementary good versus adding a complementary good. From Model 1 a monopolist producing only a base good and with no network effects earns normalized base good profits of $1/4$. So a monopolist producing a base good in the absence of a complementary good and with no network effects earns normalized base good profits of 0.25. From row one (Table 7.2) a joint monopolist offering a

Table 7.4 Equivalence of quality increases and network effects, joint monopolist

Increase in Normalized Complementary Good Quality $\left(\tilde{q}_C = q_C / q_B\right)$	Normalized Relative Complementary Good Price (High Quality) $\left(\tilde{R}_{CB} = p_C / p_B\right)$	Normalized Base Good Profits (High Quality) $\left(\tilde{\Pi}_B = \tilde{\Pi}_B / q_B\right)$	Equivalent Increase in Normalized α $\left(\tilde{\alpha} = \alpha / q_B\right)$
$1 \to 2$	1.0000	0.4444	0.0000
$1 \to 3$	1.7500	0.4444	0.0000
$1 \to 5$	3.2500	0.4444	0.0000
$1 \to 10$	7.0000	0.4444	0.0000

Notes: (a) these are equilibrium prices and profits under the higher normalized complementary good quality. (b) increase is from zero.

base good along with a complementary good of normalized quality $\tilde{q}_C = 1$ earns normalized base good profits of $4/9$. Thus, adding one complementary good of normalized quality $\tilde{q}_C = 1$ increases normalized base good profits by $7/36$. From row one of Table 7.4, increasing the normalized quality level of the complementary good has no effect on normalized base good profits, because the joint monopolist has both price instruments available and can adjust the complementary good price optimally without distorting the margin for consumers buying only the base good. This implies that the joint monopolist has an incentive to add a complementary good of minimal quality but not invest in its improvement based on its effect on base good profits only.[21]

EFFECT OF QUALITY LEVEL AND NETWORK EFFECTS ON PROFITS

An important question frequently posed in the network effects literature concerns the incentive to improve the quality of products and how this is affected by the presence of complementary goods and network effects. In this section the incentive for firms to invest in quality at the margin under different market structures (joint monopoly versus independent firms) and different levels of network effects are assessed. Although not explicitly modelled an investment stage can assess the incentives to invest at the margin by considering the marginal effects of quality improvements on base good profits.

First, the effect on profits of quality changes in the base and complementary goods in the presence of varying levels of network effects is assessed. Also contrasted are the effects of quality changes when independent firms produce the two products to those when a joint monopolist produces both.

Next, consider the effect of changes in base good quality on the normalized base good profits of the base good monopolist with an independent monopolist providing a complementary good. The results on $d\tilde{\Pi}_B / dq_B$ are reported in column 1 of Table 7.5 for different combinations of normalized network effects and normalized complementary good quality levels.[22]

Second, the effect of changes in the complementary good quality on the normalized base good profits of the base good monopolist with an independent monopolist providing a complementary good is assessed. The results on $d\tilde{\Pi}_B / dq_C$ are reported in column 2 of Table 7.5.

Third, the effect of changes in the base good quality on the normalized complementary good profits of the complementary good monopolist with an independent monopolist providing the base good is assessed. The results on $d\tilde{\Pi}_C / dq_B$ are reported in column 3 of Table 7.5.

Fourth, the effect of changes in the complementary good quality on the normalized complementary good profits of the complementary good monopolist with an independent monopolist providing the base good is assessed. The results on $d\tilde{\Pi}_C / dq_C$ are reported in column 4 of Table 7.5.

Fifth, the effect of changes in base good quality on the normalized base good profits (Column 5) and normalized complementary good profits (Column 7) of the joint monopolist is examined. The total effect of the change in base good quality on the joint monopolist is the sum of the two columns.

Sixth, the effect of changes in complementary good quality on the normalized base good profits (Column 6) and normalized complementary good profits (Column 8) of the joint monopolist is considered. Again, the total effect of the change in the complementary good quality on the joint monopolist is the sum of the two columns.

Each row of Table 7.5 provides the effects at a given combination of normalized network effects and normalized quality levels. For example, row two shows that for an $\tilde{\alpha}$ of zero and $\tilde{q}_C = 2$, a marginal increase in base good quality increases the normalized profits of the independent base good monopolist by 0.3270, decreases the normalized profits of the independent complementary good monopolist by 0.0571, increases the joint monopolist's normalized base good profits by 0.4444 and decreases the joint monopolist's normalized complementary good profits by -0.1482. At the same level of normalized network effects and quality levels, a marginal increase in complementary good quality increases the normalized profits of the independent base good monopolist by 0.0366, normalized profits of the independent complementary good monopolist by 0.2194, increases the joint monopolist's normalized complementary good profits by 0.2593 and does not affect the joint monopolist's normalized base good profits.

Note that increasing the quality of the base good decreases normalized profits for the complementary good ($d\tilde{\Pi}_C / dq_B < 0$), when independent monopolists produce the two goods. Since the base good is required for consumers to value the complementary good, an increase in the base good's quality increases price sufficiently that the complementary good firm's profits are squeezed. Conversely, $d\tilde{\Pi}_B / dq_C > 0$ when an independent monopolist produces the second good. Improving the complementary good increases complementary good consumers' willingness to pay for the base good, which complementary good consumers must purchase, thus allowing the base good monopolist to increase the price of the base good. Because of the increased base good price, the monopolist loses some sales to base-good-only consumers, but not enough to offset the increased revenues from complementary good consumers.

For the joint monopolist, $d\tilde{\Pi}_C / dq_B$ is also negative because the joint monopolist finds it optimal to raise the price of the base good sufficiently that it sacrifices some sales of the complementary good because some potential consumers find it too expensive to buy along with the base good. The results for $d\tilde{\Pi}_B / dq_C$ differ from that for independent firms. When $\tilde{\alpha} = 0$ base good profits are unaffected by changes in q_C because the joint monopolist has two price instruments and can adjust p_C without pricing any base-good only customers out of the market. When $\tilde{\alpha} > 0$, otherwise, $d\tilde{\Pi}_C / dq_B < 0$ because the joint monopolist does not have two prices it can set independently. The two prices are linked through the network effects. Each base good customer cares about how many other consumers buy the base good (the network effects) and buyers of the complementary good must also buy the base good affecting its installed base. As a result, adjusting $\tilde{p}_C$ affects x_B through $\tilde{\alpha}$.

Comparing columns 1 with 5 and 7 of Table 7.5, increases in the quality of the base good have a smaller positive effect on the total (base and complementary good) normalized profits of the joint monopolist than on the normalized profits of the base good monopolist when there are independent monopolists. Thus, an independent base good monopolist has a greater marginal incentive to improve the base good than a joint monopolist. This is because the independent monopolist does not internalize the negative effect that a higher base good price has on the profits of the complementary good (as reflected in the negative values of $d\tilde{\Pi}_C / dq_B$ in column 3), while the joint monopolist does (as reflected in the negative values of $d\tilde{\Pi}_C / dq_B$ in column 7).

Comparing columns 4 with 6 and 8 of Table 7.5, increases in the quality of the complementary good have a greater positive effect on the total (base and complementary good) normalized profits of the joint monopolist than on the normalized profits of the complementary good monopolist when there are independent monopolists. Thus, the joint monopolist has a greater marginal incentive to improve the complementary good than an independent monopolist selling the complementary good in the presence of an independent base good monopolist. This is because the joint monopolist can adjust the complementary good price fully (partially) to reflect the complementary good quality increase without affecting sales of the base good (as much) when $\tilde{\alpha} = 0$ ($\tilde{\alpha} > 0$). The independent complementary good monopolist, on the other hand, has to share some of the benefits of the complementary good improvement with the independent base good monopolist as reflected in the positive values of $d\tilde{\Pi}_B / dq_C$ in column 2.

Also, note that $d\tilde{\Pi}_B / dq_B + d\tilde{\Pi}_C / dq_B$ is greater for the joint monopolist than for the independent firms, which means that the effect on the joint monopolist's normalized profits from an increase in the base good quality is greater than the effect on the combined normalized profits of the independent firms. This is because the joint monopolist is better able to capture the benefits of increasing the base good quality by adjusting the complementary good price optimally.

The model can be used to assess the marginal incentive to increase compatibility between the base good and complementary goods. Firms in markets with network effects, like software, often face decisions about the degree to which their product should be made compatible with other products or conform to industry standards. In our model, this is equivalent to determining the effect on profits of an increase in normalized network effects ($\tilde{\alpha}$). Comparing this incentive at different normalized quality levels and for different market structures (independent firms versus a joint monopolist) shows the effect of increasing network effects on the normalized profits of independent base good and complementary good monopolists. Values of $d\tilde{\Pi}_B / d\alpha$ are in column 1 of Table 7.6 and values of $d\tilde{\Pi}_C / d\alpha$ in column2.[23] Second, the effect of increasing normalized network effects on the normalized profits of the joint monopolist is assessed. Values of $d\tilde{\Pi}_B / d\alpha$ are in column 3 and values of $d\tilde{\Pi}_C / d\alpha$ are in column 4 of Table 7.6 and the effect on the total normalized profits of the joint monopolist is the sum of the two columns. Each row of Table 7.6 provides the effect at a given

Table 7.5 Effect of quality increases on profits

		1	2	3	4	5	6	7	8
Normalized α	Normalized Complementary Good Quality	IF	IF	IF	IF	JM	JM	JM	JM
$\left(\tilde{\alpha}=\frac{\alpha}{q_B}\right)$	$\left(\tilde{q}_C=\frac{q_C}{q_B}\right)$	$\frac{d\tilde{\Pi}_B}{dq_B}$	$\frac{d\tilde{\Pi}_B}{dq_C}$	$\frac{d\tilde{\Pi}_C}{dq_B}$	$\frac{d\tilde{\Pi}_C}{dq_C}$	$\frac{d\tilde{\Pi}_B}{dq_B}$	$\frac{d\tilde{\Pi}_B}{dq_C}$	$\frac{d\tilde{\Pi}_C}{dq_B}$	$\frac{d\tilde{\Pi}_C}{dq_C}$
0	1	n.a.	n.a.	n.a.	n.a.	0.4444	0.0000	-0.1852	0.2870
0	2	0.3270	0.0366	-0.0571	0.2194	0.4444	0.0000	-0.1482	0.2593
0	3	0.3675	0.0199	-0.0816	0.2298	0.4444	0.0000	-0.1358	0.2541
0	4	0.3934	0.0124	-0.1030	0.2357	0.4444	0.0000	-0.1296	0.2523
0	5	0.4110	0.0084	-0.1193	0.2394	0.4444	0.0000	-0.1259	0.2515
0.4	1	0.2302	0.0587	-0.0441	0.2203	0.4603	-0.0335	-0.2282	0.3061
0.4	2	0.3065	0.0259	-0.0796	0.2306	0.4343	-0.0083	-0.1676	0.2641
0.4	3	0.3472	0.0142	-0.1061	0.2368	0.4259	-0.0037	-0.1475	0.2563
0.4	4	0.3724	0.0089	-0.1262	0.2405	0.4218	-0.0021	-0.1376	0.2535
0.4	5	0.3894	0.0060	-0.1418	0.2429	0.4193	-0.0013	-0.1316	0.2523

Notes: (a) n.a. means at the corner solution derivatives not defined. (b) IF = Independent Firms, JM = Joint Monopolist.

combination of normalized network effects and quality levels. For example, row two of the table indicates that at normalized complementary good quality of $\tilde{q}_C = 3$ and normalized network effects of $\tilde{\alpha} = 0.2$, a marginal increase in compatibility (normalized network effects) increases the normalized profits of the independent base good monopolist by 0.3644, the independent complementary good monopolist by 0.1853, the normalized base good profits of the joint monopolist by 0.3939 and the normalized complementary good profits of the joint monopolist by 0.1284.

Comparing the sum of columns 3 and 4 to columns 1 and 2 of Table 7.6, observe that normalized profits are more sensitive to normalized network effects for a joint monopolist than for either independent monopolist. When network effects are greater, the value goes up both to consumers of the base good and to consumers of the complementary good. The value of the base good goes up directly because of the network effects. The value to complementary goods consumers goes up because they must buy the base good to use the complementary good and therefore also benefit indirectly from the increased network effects. This is why $d\tilde{\Pi}_B / d\alpha$ and $d\tilde{\Pi}_C / d\alpha$ are both positive for the independent monopolists (columns 1 and 2 of Table 7.6). In fact, the complementary good monopolist receives substantial benefits from the increase of network effects. However, because each of the independent firms does not take fully into consideration the effect they have on each other, their individual incentives to make their products more compatible are lower than the incentive of the joint monopolist to make its two products more compatible with other firms' goods. Since consumers of both the base and complementary goods benefit, the joint monopolist captures both benefits, while in the case of the independent monopolists this benefit is shared between the two firms.

Table 7.6 Effects of the intensity of network effects on profits

		1	2	3	4
Normalized α $\left(\tilde{\alpha} = \frac{\alpha}{q_B}\right)$	Normalized Complementary Good Quality $\left(\tilde{q}_C = \frac{q_C}{q_B}\right)$	IF $\frac{d\tilde{\Pi}_B}{d\alpha}$	IF $\frac{d\tilde{\Pi}_C}{d\alpha}$	JM $\frac{d\tilde{\Pi}_B}{d\alpha}$	JM $\frac{d\tilde{\Pi}_C}{d\alpha}$
0.1	3	0.3260	0.1776	0.3606	0.1214
0.2	3	0.3644	0.1853	0.3939	0.1284
0.3	3	0.4089	0.1900	0.4301	0.1352
0.4	3	0.4620	0.1892	0.4698	0.1415
0.5	3	0.5255	0.1807	0.5145	0.1461
0.6	3	0.6024	0.1615	0.5666	0.1470
0.7	3	0.6941	0.1300	0.6304	0.1412
0.8	3	0.7979	0.0879	0.7131	0.1231
0.9	3	0.9045	0.0416	0.8266	0.0831
0.1	5	0.3116	0.1999	0.3475	0.1319
0.2	5	0.3461	0.2098	0.3820	0.1354
0.3	5	0.3866	0.2170	0.4207	0.1380
0.4	5	0.4347	0.2199	0.4641	0.1393
0.5	5	0.4931	0.2158	0.5137	0.1386
0.6	5	0.5651	0.2009	0.5716	0.1343
0.7	5	0.6541	0.1714	0.6413	0.1242
0.8	5	0.7613	0.1249	0.7282	0.1042
0.9	5	0.8815	0.0644	0.8419	0.0673

Notes: IF = Independent Firms, JM = Joint Monopolist.

PRICING OF WINDOWS AND OFFICE

A puzzle of the Microsoft antitrust case is that Microsoft was charging a price for its Windows operating system significantly lower than most economic models predict (e.g., Direct Testimony of Schmalensee in *United States v. Microsoft* (1999) at paragraph 163). At the same time, Microsoft was selling the Microsoft Office suite of applications[24] at a significantly higher price than Windows, even though Microsoft's market share was comparable in the Windows and Office markets.[25] At the time of the antitrust trial, Microsoft sold the majority of Windows and Office units through original equipment manufacturers (OEMs). While precise OEM price data is proprietary and difficult to obtain, estimates of the Office to Windows price ratio are in the range of 1.4 to 3.75.[26] Explanations of the price difference no not explain the low relative Windows price except for the possibility of very strong potential competition in the operating systems market (see Economides 2001).

Four main failing explanations have been offered. The first explanation is that Microsoft was keeping the price of Windows low to increase network effects, allowing it to possibly increase its price in the future. This explanation is unsatisfying given that Microsoft continued pricing Windows low even after it had gained a very high market share. A second possible explanation is that the existing installed base of Windows constrained Microsoft's pricing because consumers who bought a new computer would uninstall Windows from their old computer and install it on the new one. However, Microsoft's licensing requirements and the sheer complexity of uninstalling the operating system make it almost impossible for a user to uninstall a Windows operating system that was pre-installed by a computer hardware manufacturer and move it to a different (presumably new) computer. Moreover, typically, U.S. users who buy Windows pre-installed on their new computer are not given software that would allow them to install Windows to a differen*t* computer.[27] So it is unlikely that the Windows installed base constrained the Windows price. A third possible explanation is that since computer systems (hardware and software) are durable, pricing of new versions of Windows is constrained by the availability of old computer system versions (including Windows). However, very rapid technological change in hardware has prompted consumers to buy new computers much faster than traditional obsolescence rates would imply and Windows was only a small part of the price of a new personal computer. Thus, it is unlikely that durability was a significant factor constraining the price of Windows. A fourth possible explanation is that the price of Windows is constrained by the possibility of consumers pirating the software. Although pirating of both Microsoft Office and Windows would have the same effect, it is more difficult to pirate Windows. Therefore, piracy issues do not explain the price difference between Windows and Microsoft Office.

Another explanation that has been proposed and dismissed in the context of pure monopoly models for Windows and Microsoft Office (see Economides 2001) is that Microsoft kept the price of Windows low because this allowed Microsoft to charge more for complementary goods, such as Microsoft Office, that it produces. In the context of pure monopoly models for Windows and Microsoft Office, this explanation was insufficient to explain the very different prices charged for Windows and Office. In contrast, the model, in which a joint monopolist sets prices of the base and complementary goods in the presence or absence of network effects from direct consumption externalities or other complementary goods, is able to explain the relative prices of Windows and Office.

Model 4 is applied, with Windows as the base good and Microsoft Office as the complementary good.[28] Using equations (7.20) and (7.21), the ratio of prices in Model 4 can be expressed analytically as

$$\tilde{R}_{CB} = \frac{p_C}{p_B} = \frac{3q_C}{4q_B} - \frac{1}{2}. \tag{7.25}$$

Ratios of the price of Office to the price of Windows reported during the Microsoft antitrust trial can be explained as equilibrium of the model. Ratios of 1.4 to 3.75 for the price of Office relative to Windows reported in the Microsoft antitrust trial require $\frac{76}{30} \le \frac{q_C}{q_B} \le \frac{17}{3}$.[29] The equilibrium of Model 4 also implies

$$\frac{x_C}{x_B} = \frac{3}{4} + \frac{q_B}{6q_C}, \tag{7.26}$$

from (7.20) and (7.21). The actual relative sales ratio of Microsoft Office and Windows can be used to infer the underlying relative qualities of the two goods and the equilibrium price ratio they imply. To determine the relative sales of Word and Office we obtained survey data from the Current Population Survey (CPS) Supplement on Computer and Internet Use from September 2001.[30] The survey asked the following questions about spreadsheet and word processors for both home and office use: (a) Do you use the computer at home (at the office) for word processing or desktop publishing?; or (b) Do you use the computer at home (at the office) for spreadsheets or databases?

Assuming that respondents answer 'yes' to using a word processor either at work or at home used a word processor and similarly for spreadsheets. Accordingly, respondents are assumed to use either a word processor or a spreadsheet (there are no questions relating to use of presentation or database software) owned an office suite.[31] Since only respondents who owned a computer answered either of these two questions, dividing the number of respondents we defined as owning an office suite by the number of respondents would yield office suite owners as a fraction of operating system (OS) owners (since computers and operating systems are purchased in fixed proportions) or:

$$\frac{\text{Office owners}}{\text{OS owners}} = \frac{\text{Microsoft Office} + \text{non-Microsoft Office Owners}}{\text{Windows OS} + \text{non-Windows OS Owners}}. \tag{7.27}$$

From the survey, we obtained a fraction of 0.82 for this ratio. Since,

$$\frac{x_C}{x_B} = \frac{\text{Microsoft Office owners}}{\text{Windows OS owners}} \tag{7.28}$$

the numerator of (7.27) must be adjusted by Microsoft's share in the Office suite market and the denominator of (7.27) by Microsoft's share in the operating system market so that to obtain:

$$\frac{x_C}{x_B} = 0.82 * \frac{\text{Microsoft Office share}}{\text{Windows OS share}}. \tag{7.29}$$

At the time of the antitrust trial, the market share of Windows among personal computers was estimated to be between 95 per cent and 97 per cent, while Microsoft Office's share among office suites was estimated to be 95 per cent. This implies the ratio of Microsoft Office to Microsoft Windows sales in (7.29) is between 0.80 and 0.82. Using (7.26) this yields a normalized quality ratio of between 2.38 and 3.14 and, using (7.25) a price ratio of between 1.29 and 1.85, which is at the lower end of the range estimated during the trial.

It is interesting to compare the ratios of these prices under the two different market structures. Table 7.7 displays the normalized relative complementary good price obtained at given normalized quality levels for the joint monopolist (Model 4) versus independent firms (Model 2). Since Model 2 cannot be solved analytically, we have displayed these results numerically. Except at low normalized quality levels of Office, a joint monopolist (such as Microsoft) has a higher normalized relative complementary good price than if an independent firm controlled Office. Microsoft, as a joint monopolist, internalizes the complementary good profits and therefore prefers to keep the price of the base good low so as to not choke off the positive feedback with those complementary goods that Microsoft does not produce, while pricing the complementary good relatively high to benefit from sales to those with high demand for Office. If, on the other hand, an independent firm were to sell Office, Microsoft can only benefit from sales of those with high demand for Office by increasing the price of Windows. If the normalized quality of Office is sufficiently low, then it is more important for the joint monopolist to capture profits from the base good and it is priced relatively high, but for reasonably high-normalized quality levels of the complementary good, the base good monopolist has an incentive to keep the base good price relatively low.

Davis et al. (1999) show that a monopolist selling a base and complementary good can have an incentive to price the complementary good

Table 7.7 Complementary to base good price ratio, joint monopolist versus independent firms

Normalized Complementary Good Quality $\left(\tilde{q}_C = \frac{q_C}{q_B}\right)$	Normalized Relative Price of Complementary Good $\left(\tilde{R}_{CB} = \frac{p_C}{p_B}\right)$	
	JM	IF
1	0.2500	0.7071
2	1.0000	1.2292
3	1.7500	1.7375
4	2.5000	2.2417
5	3.2500	2.7439
6	4.0000	3.2455
7	4.7500	3.7465
8	5.5000	4.2472
9	6.2500	4.7477
10	7.0000	5.2482

lower than the base good. They assume a linear demand function for each good and that each product's demand depends negatively on the other good price. The goods have symmetric demand except for the intercept and the base good has the bigger demand. Given this setup, the monopolist prices the base good higher than the complementary good, the opposite of the current finding. The intuition for the Davis et al. result is that the monopolist wants to price the base good relatively high to garner greater demand while pricing the complementary good relatively low so as to not choke off demand for the good. In current modelling, the monopolist does not is not concerned about choking off demand for the base good if it sets a relatively high price for the complementary good as consumers who place a low value on the complementary good simply purchase only the base good. The monopolist can set the price instruments independently. Davis et al., on the other hand, can be viewed as a representative agent model. Since the representative consumer purchases units of both goods, demand for the base good is always negatively affected by the price of the complementary good.

RELATION TO THE EMPIRICAL LITERATURE

This section demonstrates that the model can be used to simulate and calibrate results from the empirical literature estimating pricing effects of complementary goods and network effects. The model could thus be used to estimate counterfactuals in these situations, sometimes with extensions to our model. To allow calibration to the empirical data, we introduce an intercept term into the utility consumers obtain from the base and complementary goods. Specifically:

$$U = k_B + \theta q_B - p_B + \alpha x_B + \delta V$$

and

$$V = k_C + \varphi q_C - p_C \, ,$$

where k_B and k_C are constants and represent the baseline utility that the lowest type consumer obtains from purchasing the goods. Thus, our earlier theoretical results assume that the baseline utility obtained from each good is zero for both goods.

Gandal et al. (2000) estimate a structural model of adoption of CD players and complementary CD titles to determine the magnitude of network effects. Using data on the number of titles and CD players sold between 1985 and 1992, the authors find that the elasticity of the number of CD titles with respect to CD player sales is 0.56 while the elasticity of CD player sales with respect to the number of CD titles available is 0.033. This does not exactly correspond to the current setup since there are multiple complementary goods; however, total sales of CDs can be treated as a composite good to apply this framework.

Model 2 is calibrated to these results, as Model 2 is appropriate since firms selling CD players generally differ from those selling CD titles. Assuming that the base good corresponds to CD players and the complementary good to CD titles, the equilibrium quantities of the base (x_B) and complementary (x_C) goods are found at given normalized quality level $(\tilde{q}_C)$ and normalized utility intercepts[32] (defined as $\tilde{k}_C = k_C / q_B$ and $\tilde{k}_B = k_B / q_B$). Increasing the complementary good normalized utility intercept to $\tilde{k}'_C$ results in the equilibrium quantity of the complementary (x'_C) and base goods (x'_B). Also, increasing the complementary good normalized utility intercept simulates an increase in sales of the complementary good. Computing the elasticity of base good sales with respect to complementary good sales: $\varepsilon_{BC} = (x'_B - x_B)x_C / ((x'_C - x_C)x_B)$, provides the elasticity of complementary good sales with respect to base good sales in a similar manner by increasing the base good normalized utility intercept to $\tilde{k}'_B$ (while holding $\tilde{k}_C$ constant) and calculating $\varepsilon_{CB} = (x'_C - x_C)x_B / ((x'_B - x_B)x_C)$.

At $\tilde{k}_B = 0.3$, $\tilde{k}_C = 0.1$, and $\tilde{q}_C = 2$, $\varepsilon_{BC} = 0.018$ and $\varepsilon_{CB} = 0.319$ are obtained (which are close to the empirical results). At these values, $\tilde{R}_{CB} = 1.071$, normalized profits of the base good monopolist are 0.587 and normalized profits of the complementary good monopolist are 0.462. Once calibrated, various counterfactuals can be performed. For example, the sales, prices and profits of CD players and CD titles resulting from a merger of CD player and CD title manufacturers could be simulated by evaluating Model 4 at these parameter values. The effect of increased title variety could be examined by increasing $\tilde{\alpha}$ and solving for the new equilibrium, while increases in CD player quality (relative to CD quality) could be simulated by decreasing $\tilde{q}_C$ and solving for the new equilibrium.

Gandal (1995) estimates a hedonic model of personal computer database management systems (DBMS) software pricing. Using data on all major products offered from 1989 to 1991, Gandal estimates the value of a DBMS being compatible with the Lotus spreadsheet, the dominant spreadsheet at the time. Compatibility with the Lotus standard meant that the DBMS could export files in a Lotus-compatible format. Gandal finds that DBMS products compatible with the Lotus standard had a 31 per cent higher price relative to incompatible DBMS's, controlling for other quality variables.

To simulate this using again Model 2 (since the DBMS's and Lotus spreadsheet were produced by separate firms) and assume that the base good is a DBMS and the complementary good is the Lotus spreadsheet. First, the equilibrium normalized relative complementary price $(\tilde{R}_{CB})$ is found at a given normalized quality level $(\tilde{q}_C)$. Then increasing the normalized quality to $\tilde{q}'_C$ the new equilibrium normalized relative complementary good price $(\tilde{R}'_{CB})$ allowing the quantity to adjust optimally is obtained. Finally, the elasticity of the complementary good price with respect to the complementary good quality is: $\varepsilon_{Pq} = (\tilde{R}'_{CB} - \tilde{R}_{CB})\tilde{q}_C / ((\tilde{q}'_C - \tilde{q}_C)\tilde{R}_{CB})$. The mode is not calibrated to the empirical results in this case since the quality improvement equivalent to compatibility with the Lotus standard cannot be measured. However, at $\tilde{k}_B = \tilde{k}_C = 0$ and $\tilde{q}_C = 2$, $\varepsilon_{Pq} = 1.075$.

There are several papers which estimate the pricing effects of complementary goods and network effects but would require incorporating dynamic effects in the model. Brynjolfsson and Kemerer (1996) estimate a hedonic model of personal computer spreadsheet pricing on products sold between 1987 and 1992. The authors estimate the elasticity of the spreadsheet price with respect to the size of the spreadsheet's installed base. Ohashi (2003) uses a random-coefficients discrete choice model to estimate the importance of indirect network effects in the standards battle between the Beta and VHS formats in the U.S. videocassette recorder market between

1978 and 1996. Ohashi estimates elasticities of market share with respect to the installed base of recorders. Park (2003) estimates indirect network effects in the VCR market. The author estimates the response of one format's network 'advantage' (relative strength of its network) to relative sales in each period.

Application to two other papers would involve extending the model to consider multiple competing base goods. Dranove and Gandal (2003) test for indirect network effects in the DVD market and the extent to which pre-announcement of the competing DIVX technology slowed adoption. Since the DVD format was an open standard, multiple studios were deciding whether to issue films in the DVD format. Nair et al. (2004) estimate indirect network effects in the market for personal digital assistants (PDAs). In this case, the market includes two competing base good (PDA) firms and many software (complementary) good providers. Finally, Rysman (2004) uses a structural model to estimate the indirect network effects between consumer usage (measured by number of references per household per month from surveys) and quantity of advertisements in the yellow pages directory market. Approximately 41 per cent of these markets have a single publisher so that the model can be calibrated in these monopoly markets. However, to do so would require a model of advertising demand to appropriately model the price of consumer advertising usage.

CONCLUDING REMARKS

A model is solved with two goods, a base good and a complementary good whose use requires the base good, for two alternative industry structures, joint monopoly and two independent monopolists. This is related to a model with network effects summarized in the consumers' utility functions and find the appropriate parameter values for network effects that produce the same equilibrium results. The effect of changes in the inherent quality of the base and complementary goods are assessed and equate them to increases in the intensity of network effects required to maintain the same base good profits. Also, the incentive to invest, in either the base or complementary good quality and product compatibility is evaluated. Finally, an economically rational explanation of Microsoft's relative pricing of Windows and Office is provided with a demonstration of how the model can be calibrated to empirical network effects studies to perform counterfactuals.

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NOTES

1. The model is an example of a micro model as defined by Economides (1996a) or the components approach as defined by Shy (2001).
2. The approach does not consider the more distantly related effect of changes in software variety considered in Church and Gandal (1992) or Chou and Shy (1990). The former evaluate how the compatibility decisions of software firms affect the degree of standardization in the hardware market, while the latter demonstrate that increasing returns in the production of complementary goods can substitute for the assumption of network effects. This paper attempts to take network effects and a complementary good as given and evaluate their equivalence.
3. This is an example of a 'macro' model as defined by Economides (1996a) or the 'network externalities approach' as defined by Shy (2001).
4. Since the complementary good requires the presence of the base good but not conversely, it is expected that the equilibria in terms of prices and quantities will be asymmetric across firms.
5. Assume that that the influence of positive consumption (network) effects on the willingness to pay for the base good can be summarized by an additive term which is proportional to sales of the base good. This assumes that higher sales of the base good are reflected in higher sales of other complementary goods and vice versa.
6. This specification requires $\alpha < q_B$ for demand to be download sloping.
7. While the model assumes zero costs, positive costs could easily be added. That is, $d\Pi_B / dp_B = (q_B - 2p_B)/(q_B - \alpha) = 0$ and $d^2\Pi_B / dp_B^2 = -2/(q_B - \alpha) < 0$ since $q_B > \alpha$.
8. Also the model requires that everyone does not buy the good which implies $x_B^* < 1$ or $2(q_B - \alpha) > q_B$, i.e., $\alpha < q_B / 2$.
9. The second-order conditions are $-(3p_B + 2p_C)/q_B q_C < 0$ and $-2/q_C < 0$ respectively, both of which are met for all parameter values.
10. Note that the first-order conditions place no restrictions on the relative qualities. The positive root of the first first-order condition is $1/3(-2p_C + \sqrt{4p_C^2 + 6q_B q_C})$ which is always positive. Solving the second first-order condition for p_C gives $q_C / 2 + p_B^2 / 4q_B$ which is always positive.
11. Also verified numerically is that the nonlinear second-order conditions hold and that $\Pi_B^n(p_B; p_C^*)$ is quasi-concave in p_B and $\Pi_C^n(p_C; p_B^*)$ is quasi-concave in p_C.
12. The second-order condition is met as the Hessian is negative definite for all parameter values.
13. Also notice that, for independent firms, the first-order conditions cannot be decomposed as in joint monopoly, and therefore the equilibrium prices of both the base and complementary good do depend on the quality levels of both goods. For independent firms, the first-order conditions are:

    (A) $D_B + p_B D_B' + D_C + p_B D_C' = 0$,

(B) $D_B + p_B D'_B + D_C + p_B D'_C = 0$.

Substitution from (B) into (A) cannot accomplish decomposition as in joint monopoly. Of course, comparison of (B) with (22) confirms Cournot's result that the total price $p_B + p_C$ is lower under joint monopoly.

14. Although in principle the joint monopolist could choose to sell the complementary good below cost, such action could raise serious antitrust concerns.
15. Also verified is that the second-order conditions are met. The conditions are solved over a grid of possible prices to ensure that the global maximum is obtained.
16. The possibility of anti-competitive leveraging of monopoly power from the base to the complementary good is not discussed.
17. As shown in general in Note 13, the sum of the prices $p_B + p_C$ is lower for the joint monopolist than for the independent monopolists.
18. Also observed is that the $\tilde{\alpha}$'s are neither consistently higher or lower for the joint monopolist relative to the independent firms. At high levels of complementary good quality the independent firms' $\tilde{\alpha}$-equivalent is greater, while at low quality levels the opposite is true.
19. All modern computer operating systems contain a functions useful to applications developers but typically not directly useful to end-users. For example, Windows has timing functions that are useful to applications developers and have no direct functional value to end-users and built-in abilities to print to a variety of printers, a necessary capability for applications.
20. The demand equation for the complementary good firm simplifies to $x_C = 1 - p_C / q_C - \theta_B p_B / 2q_C$.
21. The base good monopolist's incentives based could be evaluated on total rather than marginal profits but this would require specifying the cost structure for quality improvements. The results would thus depend arbitrarily on the functional form of the cost function. Also the base good monopolist's incentives could be evaluated based on base and complementary goods profits rather than just base good profits. However, the objective is instead to assess the base good monopolist's incentive beyond that provided by complementary good profits alone since these incentives would be the same for both a joint monopolist and an independent firm facing the same cost structure and in the absence of complementarities.
22. Derivatives are calculated using Richardson extrapolation (see, Acton 1990, p. 106) with a step-size of one per cent of q_B or q_C .
23. Derivatives are calculated using Richardson extrapolation with step-size of one per cent of $\tilde{\alpha}$.
24. Microsoft Office typically includes Word (word processor); Excel spreadsheet; PowerPoint presentations tool; Outlook personal information management tool; and Access database.
25. The marginal cost of Windows and Office are near zero and almost the same since neither ships with paper manuals, and are generally preloaded by OEMs on computers at this time.
26. See e.g., 'Some Experts Blame Rising Software Prices on Microsoft,' *PCWorld.com.*
27. U.S. users are typically given a recovery CD that allows them to restore the particular computer model they own, including Windows, to the original condition when it was shipped from the factory. Such a CD is unable to install Windows on any other computer model.
28. The case of zero network effects $\alpha = 0$ is presented for brevity. The same result holds for positive network effects $(\alpha > 0)$ using Models 3 and 5.
29. See Direct Testimony Schmalensee in *United States v. Microsoft* (1999) at paragraph 163 and footnote 164.
30. See http://www.bls.census.gov/cps/ for details.

31. Although consumers could have purchased stand-alone word processor or spreadsheet software this was rare by 2001.
32. Model 2 is 'scalable' in k_B, k_C, q_B and q_C in the sense that multiplying all four by a factor λ leaves sales of both goods unaffected and the normalized price unchanged.

REFERENCES

Brynjolfsson, E. and Kemerer, C. (1996), 'Network Externalities in Microcomputer Software: An Econometric Analysis of the Spreadsheet Market', *Management Science*, **42**, 1627–47.

Chou, C. and Shy, O. (1990), 'Network Effects without Network Externalities', *International Journal of Industrial Organization*, **8**, 259–70.

Church, J. and Gandal, N. (1992), 'Network Effects, Software Provision and Standardization', *The Journal of Industrial Economics*, **40**, 85–103.

Clements, M. (2004), 'Direct and Indirect Network Effects: Are they Equivalent?', *International Journal of Industrial Organization*, **22**, 633–45.

Davis, S., MacCrisken, J. and Murphy, K. (1999), 'The Evolution of the PC Operating System: An Economic Analysis of Software Design', Working paper, University of Chicago.

Dranove, D. and Gandal, N. (2003), 'The DVD vs. DIVX Standard War: Empirical Evidence of Network Effects and Preannouncement Effects', *Journal of Economics and Management Strategy*, **12**, 363–86.

Economides, N. (1989), 'Desirability of Compatibility in the Absence of Network Externalities', *American Economic Review*, **79**, 1165–81.

Economides, N. (1996a), 'The Economics of Networks', *International Journal of Industrial Organization*, **14**, 673–99.

Economides, N. (1996b), 'Network Externalities, Complementarities, and Invitations to Enter', *European Journal of Political Economy*, **12**, 211–32.

Economides, N. (2001), 'The Microsoft Antitrust Case', *Journal of Industry, Competition and Trade: From Theory to Policy*, **1**, 7–39.

Farrell, J. and Saloner, G. (1986), 'Installed Base and Compatibility: Innovation, Product Preannouncements, and Predation', *American Economic Review*, **76**, 940–55.

Gandal, N. (1995), 'Competing Compatibility Standards and Network Externalities in the PC Software Market', *The Review of Economics and Statistics*, **77**, 599–608.

Gandal, N., Kende, M. and Rob, R. (2000), 'The Dynamics of Technological Adoption in Hardware/Software Systems: The Case of Compact Disc Players', *RAND Journal of Economics*, **31**, 43–61.

Katz, M. and Shapiro, C. (1985), 'Network Externalities, Competition and Compatibility', *American Economic Review*, **75**, 424–40.

Matutes, C. and Regibeau, P. (1988), 'Mix and Match: Product Compatibility without Network Externalities', *Rand Journal of Economics*, **19**, 221–34.

Nair, H., Chintagunta, P. and Dubé, J. (2004), 'Empirical Analysis of Indirect Network Effects in the Market for Personal Digital Assistants', *Quantitative Marketing and Economics*, **2**, 23–58.

Ohashi, H. (2003), ‘The Role of Network Effects in the US VCR Market’, *Journal of Economics and Management Strategy*, **12**, 447–94.

Park, S. (2003), ‘Quantitative Analysis of Network Externalities in Competing Technologies: The VCR Case’, *Review of Economics and* Statistics, **86**, 937–45.

Rysman, M. (2004), ‘Competition between Networks: A Study of the Market for Yellow Pages’, *Review of Economic Studies*, **71**, 483–512.

Schmalensee, R. (1999), Direct Testimony of Richard L. Schmalensee in United States v. Microsoft.

Shy, O. (2001), *The Economics of Network Industries*, New York: Cambridge University Press.