OPERATING SYSTEM INDUSTRY STRUCTURE EVOLUTION AND ANTITRUST IMPLICATIONS

by

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Abstract

This paper presents a theoretical model that demonstrates the possible industry structures that may result from a four-stage game of operating system innovation and adoption. This model identifies incentives for firms to utilize anticompetitive practices, and demonstrates the mechanisms for these firms to engage in predatory pricing, exclusionary vertical contracting, and exclusionary tying. This model is consistent with several key assertions made in regulatory and legal actions levied against Microsoft relating to its Windows operating system. It is also consistent with existing theories of operating system markets, and appears to be consistent with observed developments in the evolution of several operating system markets.

Introduction

Modern consumer computing devices have two essential components: hardware and an operating system. The hardware of a device simply includes all of the physical components of the device, while "What constitutes an operating system?" is a more complex conceptual question. In the modern context, an operating system is a bundle of software including a kernel and user interface system, as well as system utilities such as: editors; compilers; file system managers; fonts; drivers; low-end word processing applications; basic computational applications; and internet browsers (Crandall and Jackson 2011). This amounts to a collection of software that gives a device basic functionality, though the definition of basic functionality, and therefore the definition of an operating system, has evolved considerably over time (Crandall and Jackson 2011). Operating systems, such as those found in a personal computer, smartphone, or tablet computer, exist primarily to run advanced software applications and to facilitate interpersonal communications, which each add considerable functionality to the rudimentary software included in the operating system.

There has been considerable interest in the competitiveness of operating system markets since regulatory actions and antitrust cases were levied against Microsoft in the United States in the mid to late 1990s. These proceedings primarily focused on whether Microsoft used anticompetitive practices to maintain the dominant market share of Windows in the operating system market (Gilbert and Katz 2001). Klein (2001) noted that central to the case *U.S. v. Microsoft* was the question of whether Microsoft used anticompetitive practices to disadvantage Netscape Navigator as a platform competitor to Windows. In this case, Microsoft was alleged to have acted anticompetitively in four ways: investing substantially in quality improvements for Internet Explorer; setting a zero price for Internet Explorer; negotiating preferential distribution contracts for Internet Explorer with major internet service providers; and tying Internet Explorer to Windows.

This paper proposes a theoretical model that details how operating system industry structures evolve, from committed market entry and innovation to the resulting market equilibrium via competitive interactions between hardware firms and operating system firms. This model identifies these competitive interactions and resolves the possible equilibrium industry structure outcomes in the operating system market. This model is then used to identify opportunities for anticompetitive practices by firms in the operating system market, including the mechanisms for, and implications of, predatory pricing, exclusionary vertical contracting, and exclusionary tying. These implications are also examined in the context of the allegations presented in the case *U.S. v. Microsoft*, in order to identify the merits of the case presented by the U.S. Department of Justice, and the merits of the conclusions of Judge Jackson.

Competition Considerations in Operating System Markets

There is a long history of investigations, complaints, and legal proceedings levied by U.S. government entities against Microsoft, which have raised important questions regarding the role of competition policy in technology markets (Gilbert and Katz 2001). Most of these contentions centered on Microsoft Windows possessing a dominant market share in the personal computer operating system market, and the implications of Microsoft's activities in related software markets on this operating system market. Microsoft's activities in software markets have consistently been designed to protect its dominant position in operating system market, but it is not always clear whether Microsoft has acted in a competitive or anticompetitive manner (Gilbert and Katz 2001). Klein (2001) notes that the important distinction between competitive and anticompetitive business practices is whether consumers are made better off or worse off, an analysis of which can be confounded by contrary welfare implications of some practices on short term and long term consumer welfare. He also indicates that competitors are always made worse off by effective competitive or anticompetitive practices, and thus harm to competitors is not an appropriate standard by which to judge the competitiveness of a particular practice.

Microsoft has consistently made the case that it is a vigorous competitor in the operating system market, and as such does not possess significant market power, despite pricing Windows well above its near zero marginal cost of production (Gilbert and Katz 2001). Microsoft makes this assertion because it charges a price for Windows that is well below the price that would be charged by a company with a similarly dominant market share in a conventional, non-network industry (Reddy et al. 1999). In network industries, competition often takes the form of competition for the market rather than competition in the market, where firms invest significant resources initially in order to become the industry standard, on which they expect to earn a monopoly return (Klein 2001). Reddy et al. (1999) indicate that Microsoft faces potential entry from countless competitors, both known and unknown to them, who will design products to attempt to displace Windows as the industry standard personal computer operating system. Linux, an open source operating system platform, with a kernel designed by Linus Torvalds while he was a student, is commonly presented as representative of this type of competitive threat. Reddy et al. (1999) indicate that, because of these competitive pressures, Microsoft must price Windows in competition with potential competitors as well as actual competitors. However, Gilbert and Katz (2001) conclude that due to network effects, and a significant barrier to entry resulting from the existence of a large quantity of Windows compatible software applications, Microsoft does have significant market power in the operating system market, even if it faces the types of competitive pressures espoused by Reddy et al. (1999). Furthermore, Gilbert and Katz (2001) conclude that the fact that Microsoft possesses significant market power in the operating system market provides it an incentive to act to protect the dominant market share of Windows, either competitively or anticompetitively.

Reddy et al. (1999) indicate that Microsoft must invest significant resources in research and development to improve the functionality of Windows, based on the same competitive pressures that drive its pricing decisions. As such, the included software, features, and functionality of Windows have improved considerably when new versions of the operating system have been released. This view is supported by Crandall and Jackson (2011), who indicate that the included features have improved similarly in new versions of Windows and Apple OS X operating systems, indicating robust investment from incumbent firms in the operating system market. Klein (2001) also supports this position, indicating that if another incumbent or a potential entrant invests in producing a new or improved technology, the dominant incumbent must also invest in improving the quality of its offerings to remain competitive. Reddy et al. (1999) also observe that the cost of purchasing a copy of Windows has risen less rapidly than its value, which they attribute to robust competition between Microsoft and potential entrants. Crandall and Jackson (2011) and Gisser and Allen (2001) identify that bundling new or improved software with an operating system can be viewed as an attempt to extend monopoly power in the operating system market into related software markets. However, Crandall and Jackson (2011) indicate that this can be difficult to distinguish from the natural competitive process of product improvement, because if the functionality of the operating system increases as a result, it will increase consumer welfare.

There is at least one notable exception to the assertion by Crandall and Jackson (2011) that bundling additional software with an operating system is likely procompetitive. This exception is when bundling software with an operating system is done to prevent a software application from evolving into a competitive threat in the operating system market. The incumbent firm bundling software with its operating system can deny the software application the necessary scale and network effects to develop into a platform to challenge the incumbent's operating system. In the case *U.S. v. Microsoft*, Microsoft was alleged to have used several anticompetitive practices, including predatory pricing and investment, but especially tying and exclusionary contracting, to disadvantage Netscape Navigator from developing into a platform that would compete with Windows.

U.S. v. Microsoft

The key question in the case of *U.S. v. Microsoft* was whether Microsoft used anticompetitive tactics in producing and distributing its browser, Internet Explorer, to the detriment of competitor Netscape and its Navigator browser. Whinston (2001) noted that if Netscape were a substitute for Windows, Microsoft would have an incentive to engage in anticompetitive behavior to exclude it from the market, while if Netscape was a complement to Windows, Microsoft should have no such incentive. Microsoft presented Internet Explorer in legal proceedings as an integral complement to, and to an extent as a component of, Windows, while internally discussing using tying and exclusionary contracts to reduce Netscape Navigator's competitiveness (Whinston 2001). These two stances taken by Microsoft appear contradictory, but suggest that Microsoft likely viewed Navigator as a contemporaneous complement to Windows, with the potential to develop into a platform competitor to Windows. This provided Microsoft ample incentive to aggressively develop, price, and market Internet Explorer, producing a complement to Windows, while minimizing the probability that Navigator could develop into a platform that could compete in the operating system market.

In the 1990s, Microsoft invested in significant quality and performance improvements for Internet Explorer, as well as offering it at a zero price to all consumers, a lower price than Netscape Navigator charged many of its customers (Gilbert and Katz 2001). In fact, Microsoft charged an effective negative price to internet service providers for Internet Explorer, which Klein (2001) described as appropriate, stating "the equilibrium competitive price in this circumstance was clearly negative". Klein (2001) further concluded that Microsoft's investments in improving Internet Explorer, as well as its zero pricing for all consumers, resulted in considerable consumer welfare benefits, even if the rationale behind these actions was to protect Microsoft's dominant position in the operating system market. However, the analysis Klein (2001) presents only superficially considers the possibility that protecting the dominant position of Windows in the operating system market could lead to suboptimal long term welfare effects in the operating system market. Predatory pricing, by its very nature, is pricing a product such that the price is profitable only because of the long-term benefits of eliminating or significantly weakening one or more competitors (Gilbert and Katz 2001). As well, Fudenberg and Tirole (2000) demonstrate that it is possible to price a network good in such a way that reduces the probability of socially efficient entry in an intertemporal model, and indicate that an incumbent firm will likely have a private incentive to do so.

There is reason to believe that Microsoft's intentions were to invest in, and price, Internet Explorer in such a way to harm Netscape, but the overall welfare effects of these actions are unclear, as even ill intended actions may not actually cause a reduction in consumer welfare (Gilbert and Katz 2001). Microsoft's investment in, and zero pricing of, Internet Explorer certainly increased consumer welfare in the short term, but may have reduced the probability of Navigator developing into a platform that could compete with Windows, which may have negative long term welfare effects (Gilbert and Katz 2001).

Microsoft also attempted to restrict the distribution of Navigator, by tying Internet Explorer to Windows, and by negotiating preferential distribution contracts for Internet Explorer with internet service providers (Gilbert and Katz 2001). As Windows was the dominant operating system in the personal computer market, and internet service providers routinely provided browsers to their customers, this gave Microsoft control of the two primary browser distribution channels. These actions likely resulted in a reduced distribution of Netscape Navigator, or at minimum, raised the cost of obtaining Navigator for consumers, as the most efficient browser distribution channels were partially foreclosed by Microsoft (Whinston 2001). However, neither of these actions completely foreclosed the browser market to Netscape, as customers of the internet service providers could still request Netscape Navigator as their browser, and Navigator could still be installed on all Windows computers (Klein 2001).

The results of Microsoft tying of Internet Explorer to Windows are likely similar to the results of Microsoft negotiating preferential distribution contracts for Internet Explorer with internet service providers: Microsoft put Navigator at a disadvantage as a potential platform competitor to Windows (Gilbert and Katz 2001). Since operating system markets involve significant network effects, it seems plausible to presume that any potential substitute for operating systems would as well. Thus, even a partial foreclosure of the browser market to Netscape Navigator by advantaging distribution of Internet Explorer would reduce its competitiveness as a potential platform competitor to Windows, without necessarily eliminating it as a competitor in the browser market (Gilbert and Katz 2001). While exclusive contracts can be welfare neutral or welfare increasing in some cases, their use as a tool to limit the size of the installed base of Netscape users had significant potential to harm long-term consumer welfare by reducing the probability of socially efficient entry in the operating system market (Klein 2001, Gilbert and Katz 2001). In addition, Whinston (2001) asserts that long term impacts on consumer welfare are likely more important than short term impacts, but that long term impacts on consumer welfare are often difficult to effectively identify and measure.

Microsoft was deemed guilty of violating the Sherman Act, as "Judge Jackson found that Microsoft illegally sustained the applications barrier to entry of operating system competitors" (Gilbert and Katz 2001). Klein (2001) indicated that the court did not deem Microsoft's investment in Internet Explorer or its zero price to be anticompetitive, but instead the court focused its findings on Microsoft's distribution contracts for Internet Explorer, and Microsoft's tying of Internet Explorer to Windows. Judge Jackson declared Microsoft tying of Internet Explorer to Windows illegal, but while condemning the preferential distribution contracts for Internet Explorer, did not find them to be illegal because they were not exclusive (Gilbert and Katz 2001). Both sides proposed conduct remedies to restrict Microsoft's practices, including barring the use of exclusionary distribution contracts for Internet Explorer and prohibiting some aspects of Microsoft's tying of Internet Explorer to Windows (Gilbert and Katz 2001). Judge Jackson accepted the remedies proposed by the government, including a breakup of Microsoft, but stayed their implementation pending appeals (Gilbert and Katz 2001). After a lengthy period of negotiation between Microsoft, the U.S. Justice Department, and litigating states, remedies were issued in a consent decree, which prohibited Microsoft from using several practices that could be used to artificially maintain its market power in the operating system market (Crandall and Jackson 2011). However, structural remedies, including the proposed breakup of Microsoft into separate companies producing Windows and software applications, were never implemented (Crandall and Jackson 2011).

Operating Systems and Network Effects

In the modern context of personal computers, tablet computers, and smartphones, the device serves a dual role, both facilitating person-to-person communications, and running advanced software applications. Consumer utility derived from each device results from these two functions, as well as a level of utility provided by the basic software components of the operating system. Consumer demand can thus be represented as a result of these three sources of utility, with the communications network and advanced software availability each being represented by a distinct network effect.

The first network effect results from the connectivity of devices to a communications network, which is assumed common to all devices and valued by all device owners. This effect represents connectivity of a device to communications networks such as the internet, telephone, and short message systems for personal computers, tablet computers, and smartphones. The utility that each subscriber derives from the network is assumed to increase monotonically as the number of users increases (Rohlfs 1974). This type of network effect has been commonly postulated to follow Metcalfe's Law, which would correspond to $n(n-1)/2$ possible connections in a network with n participants, which for a large n can be approximated by n^2 (Swann 2002, Odlyzko and Tilly 2005). Swann (2002) indicates that a quadratic functional form for the aggregate network effect implies that individual consumer utility is linearly dependent on network size, and implies that all consumers value each connection in a network equally. This also implies that individual consumer utility does not exhibit diminishing marginal utility to the number of network participants, which is not intuitively appealing to an economist. In addition, Odlyzko and Tilly (2005) indicate that utility not exhibiting diminishing marginal utility to network size is inconsistent with empirical observations of industry structures in mature network industries, and that Metcalfe's Law is an inappropriate way to characterize network effects in these industries.

Odlyzko and Tilly (2005) propose an alternative specification for this type of network effect of $n \cdot (ln(n))$, which describes an aggregate network effect which grows more slowly than n^2 but grows more rapidly than n for $n > 1$. This functional form implies that consumer utility depends on $ln(n)$, and therefore displays diminishing marginal utility to the number of network participants. This type of functional form does not necessarily need to hold for each individual consumer, because, when assuming that consumer utility is additive, in aggregate it only implies that all connections have equal average value (Rohlfs 1974). Assuming additive utility greatly simplifies this analysis, likely in reasonable ways, though it implies that incremental utilities do not depend on other goods or on other communications links available to the consumer (Rohlfs

1974). Technological convergence and integration of previously disparate communications networks likely makes this assumption more reasonable in the modern context than it would have been previously, and seems to mitigate the concerns expressed by Rohlfs (1974) about making this assumption.

The $n \cdot (ln(n))$ functional form proposed by Odlyzko and Tilly (2005) is representative of a class of functional form specifications for network effects that share the common properties of diminishing marginal utility to network size and equal average connection value. Rather than imposing a particular functional form for this network effect, this model includes a more general form that is consistent with these properties. This communication network effect is denoted in aggregate as $n \cdot (g(n))$, and on average as $g(n)$, where $g`(n) > 0$, and $g``(n) < 0$, which imply that this network effect is monotonically increasing, but at a decreasing rate. While the assumption of monotonicity is not necessary when considering a network effect in a communications context (Funk 2009), it makes the construction of the following model conceptually comprehensible, as it rules out multiple local maxima in the demand functions (Rohlfs 1974).

The second network effect results from the availability of software for each operating system, where each software application is assumed compatible with only one operating system. This type of network effect is related to Sarnoff's Law, which states that the total value of a broadcast network is equal to the number of individuals consuming the broadcasted content (Odlyzko and Tilly 2005). Software applications can be viewed analogously to a broadcast network, where the marginal cost of producing software is approximately 0, and where the communication network is assumed to be a distribution mechanism for software. This implies that the value of an aggregate network of this type is a multiple of n_x (n_x denotes the number of users of operating system x) and therefore the average individual utility from each software application is constant (Odlyzko and Tilly 2005). If there are n_x users of operating system x, and k_x software applications for operating system x, then the aggregate value of this network effect is $n_x k_x$. However, analogously to the problem of the lack of diminishing marginal utility observed in Metcalfe's Law, Sarnoff's Law does not indicate any mechanism by which the number of software applications for operating system x, k_x, is determined.

Imposing the assumption that the quantity of software produced for each operating system depends exclusively positively on the number of users of that operating system implies that k_x depends on n_x in a monotonically increasing manner. Additionally, assuming that n_x is always large enough that $k_x > 0$ for each operating system that is adopted ensures that the minimum scale of each operating system network is achieved to justify software development. It is also reasonable to assume that $n_x > k_x$, to justify the upfront costs of software development in a realistic manner, but this is not a necessary assumption. If device users have constraints on how much software they can use, then it is reasonable to assume that consumers, on average, experience diminishing marginal utility to an increasing number of software applications. A general specification for a relationship between k_x and n_x that satisfies these properties is $k_x = h(n_x)$, where $h`(n_x) > 0$, and $h``(n_x) < 0$, implying that this network effect is monotonically increasing in n_x but at a decreasing rate. This implies that, on average, consumers are always better off when more software is produced for their operating system of choice, but with diminishing marginal utility to the number of software applications, and thus diminishing marginal utility to the number of adopters of the operating system. The resulting specification for the aggregate network effect is $n_x(h(n_x))$, which, analogously to the network effect described previously, is representative of a class of potential specifications for this network effect which are logically and empirically consistent (Odlyzko and Tilly 2005).

The important distinction between these effects is that the communication network effect is based on the total number of users of devices, n, where the software network effect is based on the number of users of each operating system x, n_x (which is equal in the event of an operating system monopoly). The communications network is a common network in the sense that all devices connect to it, while the software networks are limited to users of each operating system. The general form of these effects presented here specifically avoids assuming that $g(\cdot) = h(\cdot)$, which while possible, is highly unlikely, even though they necessarily share common mathematical properties.

In this model, there is no explicit allowance made for the effects of negative components of operating systems, negative externalities of network size, or for users who actually subtract from the value of the network (Swann 2002, Odlyzko and Tilly 2005). For personal computers, tablet computers, and smartphones, these effects would represent crapware; communications network congestion; spam e-mail; unwanted telephone calls; viruses; and malware. These would constitute an additional network effect, with a negative effect on consumer utility as network size increases, which would mitigate some of the utility gains derived from the communications and software network effects. The sum of these negative network effects should be smaller than the smaller of the two positive network effects for each adopted operating system, or else they would likely preclude the operating system being adopted. As explicit functional forms have not been specified for either of the positive network effects, adding a negative network effect is not necessary, and while it would add a degree of realism to the model, it would not change this model's fundamental insights.

In this model, the hardware of each device is assumed to have no value besides facilitating interactions between the user and the software components of the device. This is not a necessary assumption, and is likely quite unrealistic, but simplifies the construction of the model considerably, and relaxing this assumption does not add substantial insight to an understanding of the operating system market. Therefore, demand for devices in this model will be based only on the value consumers derive from the basic software of the operating system, and from the two positive network effects.

Model Development

The consumer's willingness to pay to purchase a device in a model with network effects is best represented by an inverse demand function, as it most clearly illustrates a demand relationship between price and quantity demanded (Rohlfs 1974, Funk 2009). The assumptions underlying the construction of the inverse demand functions in this model are:

Assumptions:

1. Consumer utility is additive
2. All agents have perfect information
3. All agents are rational: firms maximize expected profits prior to innovation and maximize profits following innovation, while consumers maximize utility
4. $\infty > n > 1$, and $\infty > n_x > 1$ for each adopted operating system x
5. n_x is large enough that $k_x > 0$
6. $n_x > k_x$
7. $g`(n) > 0$, and $g``(n) < 0$
8. $h`(n_x) > 0$, and $h``(n_x) < 0$ for each adopted operating system x
9. Each consumer who purchases a device will only purchase only one device: $Q = n$, $Q_x = n_x$ for each adopted operating system x
10. Each device will only have one operating system installed on it: $\sum n_x = n$
11. There are no negative externalities from increased network size
12. The marginal cost of producing an operating system is 0
13. The marginal cost of producing hardware is 1
14. Consumers derive utility only from the basic software components of the operating system, and from the two positive network effects

The inverse demand function for each operating system, *x*, is derived from the demand for the underlying devices. As will be demonstrated in the four-stage game, there can be two different likely structures for operating system producing firms, which will have slightly different inverse demand functions. The first firm structure is a vertically integrated hardware and operating system firm (denoted *i*), while the second firm structure is an operating system only firm that exclusively licences its operating system to hardware only firms (denoted *l* for the licensing operating system firm, and denoted *j* for each licensee hardware firm). There is also one hybrid firm structure that is considered in this model, which has demand functions that are easily inferred from the vertically integrated and licensed firm structures illustrated here.

Vertically Integrated Firms

A Representative Vertically Integrated Firm's Inverse Demand Function:

$P_i = a_i + b\cdot(g(n)) + c_i\cdot(h(n_i)) - n_i - n_{-i}$

$P_i = a_i + b\cdot(g(n_i + n_{-i})) + c_i\cdot(h(n_i)) - n_i - n_{-i}$

- n_i: The quantity of devices produced using operating system *i*, which is identical to the quantity of copies of operating system *i* produced
- n_{-i}: The quantity of devices produced using operating systems other than operating system *i*
- a_i: A parameter indicating the value of the included features of operating system *i*, which is positive ($a_i > 0$), and is assumed to be equal for all operating systems
- *b*: A parameter indicating the magnitude of the communications network effect, which is common to all operating systems, is positive ($b > 0$), and is assumed to be equal for all operating systems
- c_i: A parameter indicating the magnitude of the software network effect for operating system *i*, which is positive ($c_i > 0$)

Demand for devices with operating system *i* depends on: parameters a_i, *b*, and c_i; the functional forms of the two network effects; the total quantity of devices sold with operating system *i*; and the total quantity of devices sold with other operating systems. Devices produced by vertically integrated firms are sold in Cournot competition, where these firms set quantity based on the total quantity of devices produced with other operating systems. The key element of being vertically integrated is that the hardware producing division of these firms receives the operating system at its marginal cost of production, 0. This results in each vertically integrated firm not facing a vertical pricing externality when it sets quantity, as it produces the optimal number of devices and copies of its operating system at equilibrium.

A Representative Vertically Integrated Firm's Profit Maximization:

$\pi_i = (P_i - 1)\cdot Q_i$

$\pi_i = (P_i - 1)\cdot n_i$

$\pi_i = (a_i + b\cdot(g(n_i + n_{-i})) + c_i\cdot(h(n_i)) - n_i - n_{-i} - 1)\cdot n_i$

$\partial\pi_i/\partial n_i = 0$ and $\partial^2\pi_i/\partial n_i^2 < 0$

Non-Vertically Integrated Firms

A Representative Operating System Licensee Firm's Inverse Demand Function:

$P_l = a_l + b\cdot(g(n)) + c_l\cdot(h(n_i)) - n_{lj} - n_{-lj} - n_{-l}$

$P_l = a_l + b\cdot(g(n_{lj} + n_{-lj} + n_{-l})) + c_l\cdot(h(n_l)) - n_{lj} - n_{-lj} - n_{-l}$

- n_{lj}: The quantity of devices produced with operating system *l* that are sold by hardware firm *j*
- n_{-lj}: The quantity of devices produced with operating system *l* that are sold by hardware firms other than firm *j*
- n_{-l}: The quantity of devices produced with operating systems other than operating system *l*
- a_l, b, and c_l: Defined analogously for a licensed operating system, *l*, to how they are for a vertically integrated operating system, *i*

Demand for devices with operating system *l* depends on: parameters a_l, b, and c_l; the functional forms of the two network effects; the total quantity of devices sold with operating system *l*; and the total quantity of devices sold with other operating systems. Devices produced by licensee hardware firms are sold in Cournot competition, where firms set quantity based on the total number of devices produced with each other operating system, and the total number of devices produced with operating system *l* by other hardware producers. The key element of exclusively licensing an operating system is that the hardware producing licensee firms produce devices in the quantity that maximizes their own profits, and pay a positive price for each copy of the licensed operating system. The hardware producing licensees do not take into account the effects their production decisions have on the profitability of the producer of operating system *l*.

This results in the firm that produces operating system *l* facing a vertical pricing externality, and therefore producing a suboptimal quantity of operating systems at equilibrium.

A Representative Operating System Licensee Firm's Profit Maximization:

$\pi_{lj} = (P_l - 1)\cdot Q_{lj}$

$\pi_{lj} = (P_l - 1)\cdot n_{lj}$

$\pi_{lj} = (a_l + b\cdot(g(n_{lj} + n_{-lj} + n_{-l})) + c_l\cdot(h(n_l)) - n_{lj} - n_{-lj} - n_{-l} - 1)\cdot n_{lj}$

$\partial\pi_{lj}/\partial n_{lj} = 0$ and $\partial^2\pi_{lj}/\partial n_{lj}^2 < 0$

The inverse demand functions presented in this section are representative forms of the inverse demand functions that can be used to construct the four-stage game of operating system innovation and adoption. The choice to represent *b* and *c* as having a multiplicative relationship with their respective network effects is sufficient but not necessary for this model. It is necessary that *b* and *c* each augment the value of their respective network effects, but this relationship could to take many disparate mathematical forms that would be sufficient to achieve such augmentation. Similarly, representing *a* as separate from the network effects is sufficient by not necessary for this model, as *a* could also be represented as an additive component of the software network effect. However, for the remainder of this paper, references made to the demand functions relate to the forms of the ones expressed explicitly in this section.

Each firm's optimization problem resulting from the first order conditions for profit maximization is not analytically solvable for n_i's and n_{lj}'s, even given a fixed number for each of *i*, *l* and *j*; with explicit functional forms for each of the network effects; and with explicit values for the parameters. As long as equilibrium is restricted to occurring only in downward sloping regions of the demand function, combined with the restrictions imposed previously, that $g'(n) > 0$, $g''(n) < 0$, $h'(n_i) > 0$, $h''(n_i) < 0$, $b > 0$, and $c_i > 0$, this optimization result is consistent with a unique equilibrium. This is a necessary restriction to rule out trivial equilibria, as well as suboptimal equilibria, which could occur in any non-downward sloping regions of each firm's demand function. The results of these assumptions are analogous to the results of the assumption of optimal consumer coordination used by Fudenberg and Tirole (2000): that equilibrium is unique and consumer welfare maximizing. Funk (2009) notes that it is possible to take into account different subgroups of the consumer population in an inverse demand function, which can result in an inverse demand function that is not monotonically decreasing and has several local maxima. This would result in the possibility of, but not the necessity for, multiple equilibria that are valid, which could be addressed by assuming optimal consumer coordination like Fudenberg and Tirole (2000).

Operating System Industry Structure Evolution

Operating system industry structure evolution is presented here as a four stage non-repeated game, with considerations given to the implications of a repeated version of this game. The stages are: Committed Entry Decisions; Operating System Innovation; Operating System Limit Price Competition; and Hardware Quantity Competition.

Stage I: Committed Entry Decisions

In the initial stage of this game, firms commit to entering hardware and operating system markets. Each market has a fixed entry cost that can only be paid once, y to enter the operating system market, z to enter the hardware market, and y + z to enter both markets.

The operating system market is an innovative market, where paying the entry cost, y, provides each firm a single random draw, c, from a non-negative probability distribution of possible innovation outcomes, f, where c is the multiplicative factor associated with the software network effect in the inverse demand function. This innovation represents a perpetual patent on the intellectual property required for the operating system, assumed to be distinct from each other firm's operating system innovations.

The hardware market is a non-innovative market, because all of the technology and resources required to participate in this market are available to each firm, and they are obtained by paying the fixed entry cost, z. The device hardware products produced are homogeneous, with each firm producing identical hardware, and with differentiation between devices determined entirely by the characteristics of its associated operating system.

Each firm that enters both markets simultaneously pays the entry cost $y + z$, and receives the ability to participate in the device hardware market, as well as a single realization of random draw, c, from f.

All firms have complete information about the entry costs, y and z, and distribution of possible innovations, f. Consequently, they are able to anticipate the number of firms that will enter each market, as they are able to infer each other firm's expected profits. As f is assumed continuous, the probability of two identical draws is 0. Since the demand for hardware and operating systems are interdependent, the expression for each firm's expected profit depends on the entry cost in both markets $E(\pi(y,z,f))$.

Firms entering each of these markets will have inherently different risk and return characteristics, and for each of these types of firms to exist, they would need to raise capital to pay the entry costs associated with each market. The assets of each of these firms can be priced through risk averse consumer optimization and a no arbitrage condition, which ensures that a finite number of firms will enter each market (Milne 2003).

Stage II: Operating System Innovation

In the second stage of this game, innovation in the operating system market takes place, with each firm that paid the entry cost, *y*, receiving a draw, *c*, from the distribution of possible outcomes, *f*. As this is the only source of uncertainty in this model, after receiving the realizations from *f*, the outcome of the game can be determined by backwards induction.

Stage III: Operating System Limit Price Competition

In the third stage of this game, firms that developed an operating system engage in limit price competition, and hardware firms choose the operating system that will maximize their profits. The profit maximizing operating system for hardware only firms to choose will always be the operating system that generates the greatest software network effect. The price offers that are made by each of the operating system firms are:

1. The operating system only firm with the highest realization, c_l, from the distribution *f*, will offer to licence its operating system at $P_{l(max)}$, where $P_{l(max)} > 0$
2. All other operating system only firms will offer to license their operating systems at P_l, where $P_l = 0$
3. The firm that can produce both hardware and an operating system with the highest realization, c_i, from the distribution *f*, will offer to licence its operating system at $P_{i(max)}$, where $P_{i(max)} > 0$
4. All other firms that can produce hardware and an operating system will offer to licence their operating system at P_i, where $P_{i(max)} > P_i > 0$

These price offers are made to all hardware firms equally, with no price discrimination, with the exception that all firms that developed hardware and an operating system offer their operating system to their own hardware division at $P_i = 0$. This limit price competition results in a competition for, at minimum, a segment of the market, and will result in a maximum of one operating system being licensed by all hardware producers that choose to licence an operating system.

Contrary to the result in a conventional Bertrand game, the hardware producers will, in every case, choose to licence an operating system provided at a positive price rather than one provided at the marginal cost, MC = 0 (except that vertically integrated firms may choose their own operating system at $MC = P_i = 0$). Firms that only produce hardware are a captive market for licensed operating systems, as each must licence an operating system to enter the consumer market in the fourth stage of the game. When choosing the operating system that maximizes its profits, each of these firms, firm *j*, may choose to:

1. License the operating system provided by an operating system only firm, *l*, at $P_{l(max)} > 0$ if:
    i. $c_{l(max)} > c_{i(max)}$
    ii. $c_{i(max)} > c_{l(max)}$ if $c_{i(max)}$ is not $>> c_{l(max)}$
2. License the operating system provided by a hardware and operating system firm at $P_{i(max)} > 0$ iff:
    i. $c_{i(max)} >> c_{i(max)}$

This indicates that one of only two possible operating systems will be licensed, the operating system offered at $P_{l(max)}$ or the operating system offered at $P_{i(max)}$. This is necessarily true because operating systems provided at a positive price generate the largest software network effect, and will in turn generate the largest communication network effect, which combine to maximize demand for devices. The successful licensed operating system firm sets a positive price for its operating system such that adopting its operating system makes the hardware producers no worse off, or incrementally better off, than they would be adopting the next best licensable operating system. This limit price setting mechanism allows the firm producing the licensed operating system to earn rents from the demand for devices, generated by the network effects of its operating system, in excess of the demand for devices generated by its next best competitor.

Firms that develop both an operating system and hardware have an additional option when choosing an operating system than the hardware only firms do. When choosing the operating system that maximizes its profits, each of these firms, firm *i*, may choose to:

1. Use its own operating system, *i,* provided to its hardware division at $P_i = 0$ if:
   i. $c_i = c_{i(max)} > c_{l(max)}$
   ii. $c_{l(max)} > c_i = c_{i(max)}$ if $c_{l(max)}$ is not >> $c_i = c_{i(max)}$
   iii. $c_{i(max)} > c_i > c_{l(max)}$ if $c_{i(max)}$ is not >> c_i
   iv. $c_{i(max)} > c_{l(max)} > c_i$ if $c_{i(max)}$ is not >> c_i
   v. $c_{l(max)} > c_{i(max)} > c_i$ if $c_{l(max)}$ is not >> c_i
2. License the operating system provided by an operating system only firm, *l*, at $P_{l(max)} > 0$ if:
   i. $c_{l(max)} >> c_i = c_{i(max)}$
   ii. $c_{l(max)} >> c_{i(max)} > c_i$
   iii. $c_{l(max)} > c_{i(max)} >> c_i$
   iv. $c_{i(max)} > c_{l(max)} > c_i$ if $c_{i(max)}$ is not >> $c_{l(max)}$ and $c_{l(max)} >> c_i$
3. License the operating system provided by a different hardware and operating system firm at $P_{i(max)} > 0$ if:
   i. $c_{i(max)} >> c_l > c_i$
   ii. $c_{i(max)} >> c_i > c_l$

There is no profit maximizing option for a firm to produce an operating system and hardware that does not utilize its own operating system at equilibrium, since, at minimum, this would subject the firm to two vertical pricing externalities with no associated benefits.

If firm *i* uses its own operating system, provided at $P_i = 0$, it becomes a vertically integrated producer. It is possible for a profit maximizing firm to choose to remain vertically integrated even if it is able to licence an operating system that generates a network effect of a greater magnitude. This is due to vertically integrated firms producing an optimal number of devices and operating systems at equilibrium, while from the perspective of firms that licence operating systems to hardware producers, the number of devices and operating systems produced at equilibrium will be suboptimal. This vertical pricing externality prevents licensed operating systems from achieving the maximum possible value of the network effects, while an independent vertically integrated firm, not suffering from a vertical pricing externality, will always maximize the value of the network effects generated by its operating system.

If firm *i* licenses the operating system from firm *l*, provided at $P_{l(max)} > 0$, it becomes analogous to the licensee hardware only firms, and does not produce its own operating system. If firm *i* licenses the operating system from a different hardware and operating system firm, provided at $P_{i(max)} > 0$, it again becomes analogous to the licensee hardware only firms.

There is an important distinction between a hardware firm licensing an operating system provided by an operating system only firm and a hardware firm licensing an operating system provided by a vertically integrated firm. When a hardware firm licences an operating system from an operating system only firm, all licensees are charged $P_{l(max)} > 0$ for the operating system, and the resulting Cournot competition between licensees in the device market is symmetric. In contrast, when a hardware firm licenses an operating system from a vertically integrated firm, it competes in asymmetric Cournot competition in the device market, where the hardware division of the vertically integrated firm is charged P = 0 for the operating system, while external licensees are charged $P_{i(max)} > 0$. A licensee hardware firm will always choose the operating system that maximizes its profit, but being a high cost producer in an asymmetric Cournot competition is a competitively disadvantageous position for a hardware firm. For this to be profit maximizing for the hardware firm, the operating system offered by the vertically integrated firm must generate network effects of a much greater magnitude than the next best alternative operating system.

Licensing its operating system to other hardware producers must also be profit maximizing for the vertically integrated firm, as it will suffer a vertical pricing externality in asymmetric Cournot competition, and will produce a suboptimal quantity of both operating systems and hardware at equilibrium. At equilibrium, the quantity of hardware produced by the vertically integrated firm will be even lower than the quantity of operating systems produced, as it licences its operating system to allow other firms to produce devices that are identical to its own. For this market structure to result, the rents extracted from the licensees must at least offset the decreased total quantity of operating systems and hardware that would be produced by the vertically integrated firm if it did not license its operating system. There is only one mechanism for it to be profit maximizing for a vertically integrated firm to impose a vertical pricing externality on itself (and to reduce its hardware production): by licensing its operating system, it prevents any of the operating system only firms from entering the market. This results in one fewer operating system in the market at equilibrium than there is if the vertically integrated firm does not offer to licence its operating system to other hardware producers. However, the larger the number of firms entering the operating system market initially, the less likely the asymmetric Cournot competition outcome is to be observed, unless the distribution of possible innovations is highly irregular and multimodal.

With horizontal mergers allowed, the final equilibrium will not include any licensed operating systems, and this equilibrium can only result in a monopoly or oligopoly of vertically integrated firms. A vertical pricing externality generates a merger incentive between the vertically integrated firm and its licensee hardware firms, which will result in all of the licensee firms merging with the vertically integrated firm. A similar result will occur if vertical mergers are allowed, as a licensed operating system firm will merge with each of its licensee hardware firms to form a single vertically integrated entity.

Stage IV: Hardware Quantity Competition

In the fourth stage of this game, firms enter the consumer market and devices are sold in Cournot competition. Since each device is differentiated solely based on operating system, devices sold with the same operating system made by different hardware producers are identical. Each operating system that is adopted by one or more hardware firms is assumed to be purchased by a non-zero number of consumers, who have heterogeneous preferences with respect to operating systems. Since all agents have perfect information, the firms enter the market selling the equilibrium quantity of devices using each operating system. Software firms are assumed to be competitive, and to provide the optimal number of software applications, k_x, for each operating system.

An equilibrium will be reached where one of several possible industry structures are observed (not allowing for extensive horizontal or vertical mergers). These structures include:

I. An operating system monopoly and a symmetric hardware producer oligopoly; where an operating system only firm licenses operating system *l* at $P_{l(max)}$, which is adopted by all hardware producers

II. An operating system monopoly and an asymmetric hardware producer oligopoly; where a vertically integrated firm licences operating system *i* at $P_{i(max)}$, which is adopted by all hardware producers

III. An operating system oligopoly and a hardware oligopoly with licensed and vertically integrated operating systems coexisting at equilibrium; where an operating system only firm licenses operating system *l* at $P_{l(max)}$, which is adopted by some but not all hardware producers (with no asymmetric Cournot competition)

IV. An operating system oligopoly and a hardware oligopoly with licensed and vertically integrated operating systems coexisting at equilibrium; where a vertically integrated firm licences operating system *i* at $P_{i(max)}$, which is adopted by some but not all hardware producers (asymmetric Cournot competition between licensee hardware firms and firm *i*)

Intertemporal Considerations in a Repeated Game

This framework can be easily adapted to create an intertemporal model that includes additional iterations of innovation and adoption, as well as: evolving operating system components; switching costs; imperfect information; and an evolving distribution of innovation outcomes. It is evident that even a competitive result in the first iteration of this game can have suboptimal welfare implications in subsequent iterations when an incumbent advantage due to the software applications barrier to entry is considered.

In the form presented, this model jumps directly to equilibrium upon consumer market entry, which is highly unrealistic. Fudenberg and Tirole (2000) remark that, in a dynamic model with a continuum of consumer types, the adjustments from market entry to a stable equilibrium, which may only be approached asymptotically, will be both protracted and complex. If software production were gradual in this model, it would explain a gradual adoption of technology, due to the positive, but diminishing, growth in network effects resulting from an increasing total number of devices adopted over time (Gilbert and Katz 2001). Gradual adoption of technology and the associated growth in network effects implies a progressively increasing barrier to entry, which would lead to greater innovation incentives and entry in iterations of this game shortly following market inception than in later iterations. This implies that shortly after inception, an operating system market is likely to see considerable innovation, entry, and market structure instability. In contrast, long after inception, an operating system market is likely to have a relatively stable industry structure. This also implies that an incumbent licensed operating system firm will gain the most significant advantage by stifling competition in the earliest iterations of this game, when its software barrier to entry is minimal and it faces the greatest number of potential entrants.

This model can also incorporate the observations of Crandall and Jackson (2011) that operating systems tend to evolve to include greater basic functionality over time. Operating system firms incorporating additional software into their operating systems is another mechanism for operating system evolution. This can be represented in this model as an incremental increase to a, or an additional type of innovation could be added to the model entirely, which would result in realizing a vector of innovations from some joint innovation distribution. This could result in increasing differentiation between operating systems and increasing levels of device demand, which could potentially result in operating system market entry that does not displace an existing operating system in the market in an intertemporal model. If additional operating systems enter the market, this will lead to a more competitive, more differentiated retail device market, which could increase or decrease the incumbent advantage of the firms in the operating system market.

Switching costs for consumers or hardware firms would present another form of incumbent advantage that deters entry in the operating system market (Fudenberg and Tirole 2000). Switching costs are a market friction that could deter what would otherwise be efficient entry in the absence of switching costs. This would reduce the frequency of entry in the operating system market, and would provide incumbents an additional incentive to make their products as differentiated as possible.

If this model includes firms or consumers with imperfect information, the results of market entry may function as an information discovery mechanism for the magnitudes of the network effects. This would be the case if firms did not have perfect information about the preferences of consumers, and thus the magnitudes of the network effects at equilibrium, and had to make entry, pricing, and operating system adoption decisions without knowing the resulting equilibrium in advance. This could result in operating systems that are initially adopted being commercially abandoned between market inception and market equilibrium in favor of operating systems that generate greater network effects.

A non-stationary distribution of innovations would allow this framework to incorporate, in subsequent iterations of the game, an incremental increase in the maximum possible value of c. This would prevent an unfortunate result of this model as presented, where the eventual realization of the maximum value of c results in no further innovation being possible. A non-stationary distribution of innovations rules out the possibility of an insurmountable incumbent advantage, which is intuitively unappealing and probably unrealistic.

Antitrust Implications

The market share of each operating system in a market will be based primarily on the magnitudes of the network effects, with licensed and vertically integrated operating systems each potentially having large, intermediate, or small market shares. Market share is therefore a highly inappropriate metric by which to judge the competitiveness of an operating system market. The competitiveness of an operating system market must be evaluated by examining whether or not a licensed operating system firm engages in anticompetitive practices, as licensed operating system firms in the market will almost certainly have an incentive to do so in a repeated, intertemporal game.

Predatory Pricing

The limit pricing result of this model is consistent with arguments made by Microsoft that Windows is priced significantly below the price an operating system monopoly would charge in an environment without potential competitors (Reddy et al. 1999). The network effects generated still result in the operating system licensing firm charging a price above marginal cost, identified as a clear indication of market power by Gilbert and Katz (2001), and resulting in the licensing operating system firm extracting rents from consumers. However, the existence of a competitive maximum limit price implies only that it can be charged, not that it will be charged, and this model allows the possibility of an operating system licensing firm engaging in predatory pricing.

Fudenberg and Tirole (2000) propose a model of limit pricing for consumer devices with network effects, overlapping generations of consumers, and consumers who value the devices at two distinct levels, high and low. Their model shows that, in order to reduce the probability of entry, the incumbent firm prices its devices such that all consumers will purchase the device, even though the short term profit maximizing price is one that results in only the high valuation consumers purchasing the device.

With a continuum of consumer valuations used in the model presented in this paper, all that is required to reduce the probability of entry in the licensed operating system segment of the market is to decrease the price of the operating system incrementally from the maximum rent extraction price. This can be represented as setting any price, $P_{predatory}$, on the interval $P_{l(max)} > P_{predatory} > 0$, with an optimal predatory price being the price which maximizes the net present value of the licensed operating system firm's expected rents. This price will increase the quantity of devices that the hardware manufacturers produce, which will further increase the magnitudes of the network effects, and thus will enhance the licensed operating system firm's incumbent advantage. Thus, an operating system licensing firm forgoing some rents in each iteration of the game by setting $P_{predatory}$ will increase the probability of that firm maintaining that stream of rents for a longer number of iterations of the game. It may also incentivize some would be vertically integrated firms to adopt the licensed operating system that would not do so at $P_{l(max)}$.

While the consumer welfare effects of lower operating system prices in the short term are unambiguously positive, in the long term, the welfare effects of potentially reducing efficient entry may be negative. The firm licensing its operating system setting $P_{predatory}$ does not necessarily prevent efficient entry, but any $P_{predatory}$ will reduce the probability of efficient entry in the operating system market. While in the short term a firm setting a $P_{predatory}$ may appear competitive and welfare increasing, in the long term it may be anticompetitive and have suboptimal consumer welfare implications. As a result, it is clear that welfare effects from predatory pricing are unambiguously positive in the short term, and either neutral or negative in the long term.

Exclusionary Contracting

This model is also consistent with the potential for anticompetitive vertical contracting between operating system licensing firms and its hardware producing licensees. Aghion and Bolton (1987) outline a mechanism for vertically related firms to design privately efficient contracts with liquidated damages that will deter some efficient entry and will extract rents from efficient entrants. These contracts are privately efficient, in that they make at least one contracting party better off and no contracting party worse off, but are socially inefficient in that they raise the cost of entry for entrants who must compensate a contracting party for its payment of liquidated damages.

This is similar to the vertical contracts Microsoft made with internet service providers to preferentially distribute Internet Explorer in order to reduce the ability of Netscape Navigator to develop into an operating system platform. While these contracts were of short duration and were not explicitly exclusive, short-term contracts can have competitive implications, and can be effectively exclusionary (Whinston 2001). Contracts of this sort need not be socially inefficient if they promote some type of investment between the contracting parties that would be impossible without such exclusive contracting, and if that investment leads to significant consumer welfare increases (Whinston 2001). However, Whinston (2001) concludes that there was little to nothing about the relationships between Microsoft and internet service providers that met the standard of a noncontractible investment that required an exclusionary contract.

The Innes and Sexton (1994) critique, that vertical contracting between hardware firms and potential entrants in the operating system market could lead to socially inefficient entry, does not apply in this limit pricing model with network effects. Contracting between incumbent hardware firms and potential entrants will only be profitable for hardware firms if the operating system firm would be an efficient entrant, as inefficient potential entrants will never be able to make a better offer to the licensee firms than the incumbent.

In this model, exclusionary vertical contracting between parties is likely to involve a transfer of rents from the licensing operating system producer to the licensee hardware producer. Any exclusive contract that has duration of at least a single iteration of the game is enough to reduce the probability of entry for at least that iteration. Delaying efficient entry to a subsequent period, or extracting liquidated damages from an efficient entrant, allows the incumbent operating system licensing firm to receive additional rents, even with a short duration exclusionary contract.

Rent sharing between licensee hardware firms and licensing operating system firms by vertical contracting is not necessarily distinct from the licensing operating system firm setting price at a $P_{predatory}$ less than $P_{l(max)}$. Both likely involve short-term reductions in rent extraction by the licensing operating system firm in order to maximize the expected net present value of its long-term rents. However, reducing price below the maximum rent extraction price necessarily has short-term welfare benefits, as it increases the quantity of devices produced by licensee hardware firms. In contrast, rent transfers via vertical contracting do not necessarily increase the quantity of hardware produced, unless the vertical contract also involves preferential pricing for the operating system or promotes some noncontractible investment between licensing and licensee firms. If exclusive contracts involve preferential pricing of the operating system, their welfare effects are closely analogous to the effects of predatory pricing. In the absence of noncontractible investment, it is clear that this type of contract reduces the probability of efficient entry and allows incumbent firms to obtain additional rents.

Crandall and Jackson (2011) present a counterargument to the implication that reduced consumer welfare results from firms pricing or contracting to protect their incumbent position in the operating system market. They propose that the ability to protect an incumbency is likely to stimulate additional entry in the initial iteration of the game, which would result in a more competitive operating system market initially, and would increase the probability of a higher starting level of consumer welfare. This would lead to a market that may have a lower probability of entry that may begin at a higher initial level of consumer welfare, which has ambiguous implications for long-term consumer welfare. In an existing market, preventing these anticompetitive practices will lead to a higher level of long-term consumer welfare in that market, but has the potential to reduce consumer welfare derived from future markets with similar dynamics by disincentivizing initial entry.

Exclusionary Tying

This model is consistent with, and has implications for, operating system firms tying software applications to their operating systems. Adding software to an operating system in this model can be represented as increasing a_i or a_l, and while distinct from the operating system innovations described previously in this model, this process could be an additional type of innovation in an intertemporal model. Tying software products to an operating system raises the value to consumers of the device, and increases device demand accordingly, which is welfare neutral or increasing if the software market is competitive (Crandall and Jackson 2011).

However, if tying software applications to the existing operating system has the potential to foreclose the market to competitors with that operating system, then the welfare implications of tying are uncertain. If the probability of efficient entry in the operating system is reduced by tying software applications to the operating system, then tying may decrease long-term consumer welfare. This is analogous to Microsoft tying Internet Explorer to Windows to reduce the usage of Netscape Navigator, and thus to reduce the probability of Navigator evolving into a platform that could compete with Windows (Gilbert and Katz 2001). Therefore, operating system firms tying competitive software products to the operating system is welfare neutral or increasing, unless tying these software products reduces market access or raises distribution costs for products that may develop into operating system market competitors. Tying is also not necessarily welfare increasing if the software market in question is not competitive (Gisser and Allen (2001).

Contemporary Empirical Evidence and Observations

While this paper has primarily discussed historical developments in the market for personal computer operating systems, developments in recent years in the smartphone and tablet computer operating system market are also consistent with the framework presented. However, at present, contrary to the relatively stable industry structure and market shares in the personal computer market, the market for operating systems in smartphones and tablet computers shows signs of being in flux. Large changes in market share, the commercial abandonment of operating systems by their firms, and large increases in aggregate market size, have been characteristic of each operating system market in the early stages of their development. This is a result of the complex, dynamic evolution of operating system markets, which is consistent with the intertemporal version of this model, and with the suppositions of Fudenberg and Tirole (2000).

Figure 1: Usage Share of Personal Computer Operating Systems Q1 2010

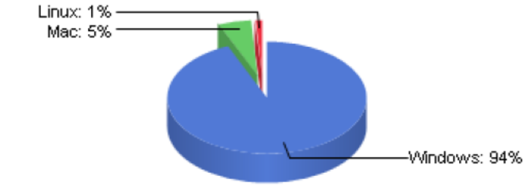


Figure 2: Usage Share of Personal Computer Operating Systems Q1 2011

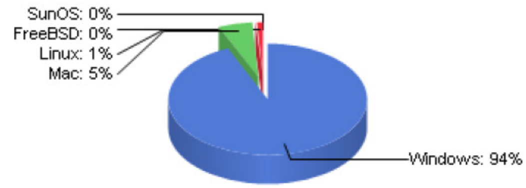
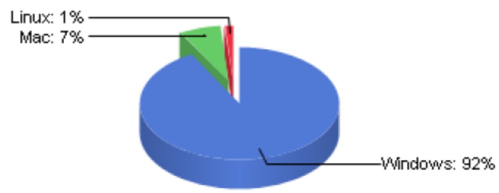


Figure 3: Usage Share of Personal Computer Operating Systems Q1 2012



Figures 1, 2, and 3 (NetMarketShare 2012) illustrate the quarterly usage shares of operating systems in the global personal computer market, which change slightly but are relatively stable during this period. The quarterly usage share is measured by identifying the operating system of unique visitors to over 40,000 websites around the globe, and then weighted by national internet usage, which provides an approximation of the market share of each operating system (NetMarketShare 2012). This market stability was not always the case in the personal computer operating system market, particularly prior to the development of graphic user interface operating systems, but this relative stability is what is predicted near equilibrium by the model presented. Editions of Microsoft Windows (XP, Vista, 7, etc), a licensed operating system, have a large combined market share, while versions of Apple OS X (Snow Leopard, Lion, Mountain Lion, etc), a vertically integrated firm, have a small but stable combined market share. The existence of a small, persistent market for a second licensed operating system, Linux, is not predicted by the model as presented. However, most of the current forms of Linux operating systems available in the personal computer market (Ubuntu, Red Hat, Fedora, Debian, etc) are highly differentiated from Apple and Microsoft operating systems, as they are extremely customizable but difficult to use for non-expert computer users. This provides Linux operating systems a small niche market of users for whom it is a superior product to the offerings of

Microsoft and Apple, though it is likely considered a poor substitute for Windows or OS X by a majority of consumers.

It may have seemed like a fanciful idea to many commentators in the 1990s that an internet browser could evolve into a personal computer operating system, but a contemporary example exists: Google Chrome OS (Epipheo Studios 2009). Chrome OS is a Linux based operating system that stores all of the user's files and applications on the internet, which are accessed using online software applications via the Google Chrome internet browser (Epipheo Studios 2009). While it has not achieved significant commercial success or market share to date, it is designed for use by non-expert computer users, unlike most of its Linux based contemporaries. Regardless, Google Chrome OS is a clear demonstration that the concerns of Bill Gates were warranted when he wrote in 1995 that internet browsers could "commoditize the underlying operating system" (Gilbert and Katz 2001).

Figure 4: Usage Share of Mobile Operating Systems Q1 2010

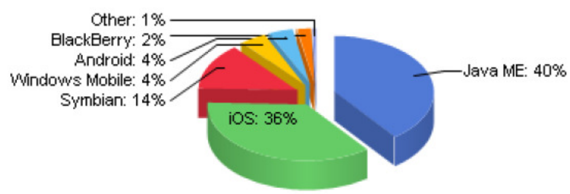


Figure 5: Usage Share of Mobile Operating Systems Q1 2011

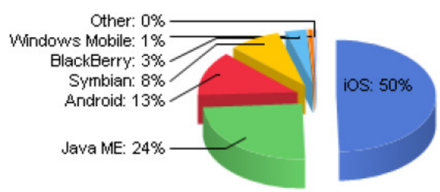
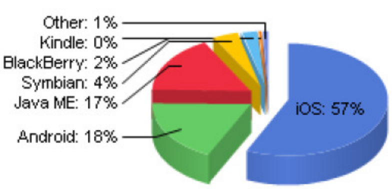


Figure 6: Usage Share of Mobile Operating Systems Q1 2012



Figures 4, 5, and 6 (NetMarketShare 2012) illustrate the quarterly usage shares of operating systems in the global mobile device market, which change rapidly, and are unstable during this period. The usage shares shown combine those from tablet computers and smartphones, as there is a great deal of integration between tablet and smartphone operating systems, and in many cases, these two distinct types of devices share operating systems and software applications. This market instability is what this model predicts in an operating system market that is far from equilibrium, where innovation and entry are occurring regularly. Instability is indicative that firms have not yet developed substantial enough user bases or enough software development to generate a substantial incumbent advantage, which is predicted to deter regular entry and result in a stable market structure.

Presently, in contrast to the personal computer operating system market, a vertically integrated platform, Apple iOS, has the largest market share in the mobile device operating system market. Google Android, an operating system licensed to numerous hardware producers, has the second largest market share. There are also numerous vertically integrated firms with lesser market shares, including Nokia (Symbian), Research in Motion (Blackberry), Amazon (Kindle), as well as additional licensed operating systems produced by Oracle (Java ME) and Microsoft (Windows Mobile). The presence of multiple licensed operating systems and rapidly changing market shares for operating system firms are characteristic of an industry structure that is not near equilibrium as predicted by this model. This model indicates that these markets are likely to continue evolving until they approach an equilibrium, which may include more intervening innovation and entry before a more stable market structure results.

Limitations and Extensions

Failures in this model may occur if the entry costs are sufficiently high to prevent a minimum number of firms from entering each market. High entry costs in either market will negatively affect the number of firms that will enter each market, while low entry costs in either market will positively affect the number of firms that will enter each market. A minimum of two firms entering the operating system only market, two firms entering the hardware only market, and one firm entering both markets are required for the results of this model to be valid. The entry costs and distribution of possible innovations are assumed to be such that these minimum requirements for entry will be satisfied. If they are not satisfied, the two competitive stages of this game will not necessarily be competitive, and the possible outcomes of this model may change considerably.

This model treats hardware as an empty vessel for an operating system, and ignores the fact that in observed consumer electronics markets, the consumer experience also depends on the characteristics of the hardware of the device. A more comprehensive analysis could also be undertaken including innovation in the hardware market, which would add an additional dimension of differentiation between devices. However, while relaxing this assumption would produce a more robust model of the market shares in the device market, it would not change the resulting operating system industry structures resulting from this model, which is the focus of this analysis.

This model also does not address the software market in anything more than the most superficial of ways, and elements of the software market may present incentives for additional anticompetitive activities in the operating system market. Gisser and Allen (2001) examine Microsoft extending its market power into the word processing and spreadsheet software markets, by exploiting the first mover advantage provided by having access to Windows prior to its commercial release. This is one example of an operating system firm having an incentive, and mechanism, to leverage its position in the operating system market in a non-competitive related software market. Extensions to this model involving more complex software markets may increase the robustness of the results, and may allow conclusions to be drawn regarding whether the activities of operating system firms in non competitive software markets are procompetitive or anticompetitive.

Innovation is treated as exogenous in this model, as a random draw from a distribution of possible outcomes, rather than as the outcome of hardworking and creative individuals making a conscious effort to design the best possible products. Particularly in intertemporal versions of the model, this may be a limitation, as this model does not make any allowances for human capital employed by firms. Disparate levels of human capital could provide some firms with a considerable advantage in innovation, which could strengthen incumbent firms, or could increase the level of competition in the operating system market by strengthening potential entrants.

This model can also incorporate price discrimination on the part of the licensed operating system firm, charging disparate prices to each hardware firm based on that hardware firm`s next best operating system option. If the licensed operating system firm can price selectively, it may entice some firms that would otherwise adopt their own operating system to choose the licensed operating system, resulting in the licensed operating system firm having an expanded market share and increased total rents. Again, more flexible operating system pricing may add a degree of realism to the model, but ultimately does not change the possible operating system industry structure outcomes. It will only affect likelihood of each possible outcome occurring.

Conclusions

Successful operating system firms naturally develop considerable market power based on network effects and the software applications barrier to entry (Gilbert and Katz 2001). Therefore, how these operating system firms choose to exercise this market power should be a matter of considerable interest to regulatory authorities. The model presented in this paper provides a detailed conceptual framework for how operating system markets can evolve, and provides insight into possible outcomes of the evolution of operating system markets.

These types of markets are likely to proliferate as new types of consumer electronic devices are developed, or as existing devices evolve, and future operating system markets may require scrutiny of competition authorities. This model identifies several areas where firms have incentives for anticompetitive practices and outlines the mechanisms by which firms can engage in predatory pricing, exclusionary vertical contracting, and exclusionary tying. The areas of operating system markets that can be exploited in this model provide some, but likely not all, of the areas that provide incentives for anticompetitive actions in operating system markets.

U.S. v. Microsoft Epilogue

In relation to the case *U.S. v. Microsoft*, this model leaves many questions about the welfare implications of some of Microsoft`s actions unresolved, though it does shed significant insight on Microsoft's use of preferential distribution contracts for Internet Explorer.

This model indicates that Microsoft's investment in Internet Explorer may have been procompetitive, as it includes no mechanism for an incumbent firm to invest in product development without associated consumer welfare benefits. This model only considers the software market in superficial ways, but while Microsoft may have invested in Internet Explorer with the intention to disadvantage Netscape Navigator, this investment also likely led to increased consumer welfare (Crandall and Jackson 2011).

This model indicates ambiguous welfare implications of Microsoft's zero pricing of Internet Explorer, as this model suggests it was possible for Microsoft to price Internet Explorer either procompetitively or anticompetitively. However, this zero price most likely led to net consumer welfare increases, and in the present day, there are numerous high quality browsers available at no cost to the consumer provided by both non-profit and for profit enterprises (Crandall and Jackson 2011). This indicates that, at least at present, the competitive price of an internet browser is at most zero, and though this does not necessarily imply that it was true in the mid 1990s, Klein (2001) stated it to be true.

This model also indicates ambiguous welfare implications of Microsoft tying Internet Explorer to Windows, as it suggests there are ways this could have been procompetitive or anticompetitive. There is no clarity as to the welfare implications of these activities, since the tying was nonexclusive, and the eventual zero price for Netscape Navigator implies that it was easily possible for all consumers to obtain the competing product (Klein 2001). While it was clear that Microsoft believed this would disadvantage Navigator, it is unclear whether tying Internet Explorer to Windows had a significant negative consumer welfare impact (Whinston 2001).

However, this model indicates that Microsoft`s vertical contracting with internet service providers for preferential distribution of Internet Explorer was almost certainly anticompetitive. This model identifies that Microsoft had an incentive to use exclusionary contracts to disadvantage the distribution of Netscape Navigator, in order to prevent it from developing the necessary scale required to evolve into a competitor in the operating system market. Microsoft presented no efficiency justification for these contracts, and there is little reason to believe that such a justification existed (Gilbert and Katz 2001). Therefore, it is reasonable to conclude that the only justification for Microsoft to enter into these exclusionary contracts was to effectively foreclose an efficient distribution channel for internet browsers (Whinston 2001). Microsoft's use of nonexclusive, but exclusionary, vertical contracts to advantage Internet Explorer likely had neutral to negative consumer welfare impacts without any identifiable positive welfare impacts.

These results indicate that many aspects of the U.S. Department of Justice's case had merit, but some of the allegations that had merit were likely to be difficult to prove due to the lack of clarity about the welfare implications of Microsoft's actions. This model indicates that Judge Jackson reached a reasonable conclusion at the conclusion of the trial, that Microsoft had likely acted anticompetitively in at least one of the ways alleged. However, his strongest condemnation was of Microsoft tying Internet Explorer to Windows, rather than its exclusionary contracts with internet service providers, which he described as a form of monopolization, but not illegal when not completely exclusive (Whinston 2001, Gilbert and Katz 2001). This indicates that Judge Jackson was likely right that Microsoft had acted to harm consumers in order to protect the dominant position of Windows in the operating system market.

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