Inefficient Standard Adoption: Inertia and Momentum Revisited[*]

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Abstract

This paper examines the possibility that consumers will adopt an inefficient standard. When there are successive generations of consumers, the current generation will not consider the costs and benefits to past and future generations of adopting a new standard. If a standard is proprietary, the incentives of a firm to induce adoption of the standard generally do not match the social incentives. The divergence is caused by the firm's imperfect ability to appropriate the future surplus generated by the standard.

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1 Introduction

Since the establishment of the theory of network effects, economists have been concerned with the question of whether a market with network effects will tend to settle on the socially optimal standard. It has been postulated that markets may exhibit excess inertia: Once a technological standard is in place, a new, superior standard may not displace it because of installed base effects. Alternatively, markets may exhibit excess momentum: consumers may adopt a new standard too quickly, ignoring the stranding effect they are having on previous users. Similar issues arise in the adoption of language and social norms.

The literature has investigated various conditions under which one of these inefficiencies arises. Such inefficiencies are of particular concern for open technologies, such as the QWERTY and Dvorak keyboards.[1] The situation is somewhat different when individual firms own standards. In that case, a simple argument seems to indicate that there is no possibility that an inefficient standard will persist. If a new standard is superior in any objective sense, there are gains to be made from switching to the new standard. Once the standard has been adopted, the firm can appropriate these gains. Therefore, the firm has incentive to lower the initial price enough to induce adoption of the standard.

The preceding argument is made in Liebowitz and Margolis (1999) and repeated in Spulber (2002). Spulber expresses a general skepticism about the likelihood of inefficiencies when property rights are defined and markets exist. Critics might claim that previous models that imply inefficient standard adoption are unrealistic in some way, and that if such models were modified slightly, the inefficiency would disappear. I reconsider the issue of inefficient standard adoption using a parsimonious yet compelling model. Assuming only that there are successive generations of finitely-lived consumers, that preferences are heterogeneous, and that there are network effects

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[1] The literature has taken opposing views on whether the QWERTY keyboard is in fact evidence of persistence of an inefficient standard. See, in particular, David (1985) and Liebowitz and Margolis (1990). I discuss this example further in Section 5.

among users, adoption decisions can be inefficient. This is true even if consumers can coordinate efficiently within a generation and a firm can act as a coordinating device across generations. The model presented here generates some of the same results found in other papers collectively, but in a more general setting and with more robust results.

If there is an established standard and a superior alternative emerges, no single generation of consumers will be willing to switch to the new standard if the switching cost (the loss of network benefit from breaking with past users) is too high. It may be that the benefits to future generations of consumers are large enough that, from a social standpoint, it would be efficient for one generation to adopt the new standard, even if it is privately optimal for that generation to retain the old standard. On the other hand, the current generation considers only its own switching cost and not the cost it imposes upon the previous generation, leading to potential overadoption of new technology. Even for proprietary standards, it is not clear that the incentive of the firm to induce adoption matches the social incentive. In particular, if consumer preferences are heterogeneous, the firm will not be able to price in such a way to extract all the additional surplus gained from the new standard. On the other hand, the firm will be able to appropriate some of the surplus generated by the network effect itself, which is present for any standard and thus does not affect the social incentive to change standards. It is not possible to address this issue with a two-period model, as in some of the previous literature.[2] If a new technology is introduced in the second period, but then the game ends, the welfare of future generations of consumers is neglected.[3]

This paper also differs from previous infinite-horizon models of technology adop-

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[2]See, for example, Katz and Shapiro (1986), Choi (1994), and Choi and Thum (1998).

[3]We might use a three-period model to address this question, where there is one generation of consumers born after the introduction of the new technology. However, it would seem a bit contrived if the utility of the third generation outweighed the first two generations put together. This could be the case if the third generation was meant to represent all future generations, and the rate of discount was low enough.

tion. Shy (1996) considers how frequently new technologies are introduced in terms of the substitutability between quality and network size, but welfare effects are not considered. In Farrell and Saloner (1986), there are successive generations of consumers, and the same externalities exist as in the present paper. However, heterogeneity of consumer preferences is considered in only a very limited sense, and there is very little analysis of strategic pricing by technology sponsors. The focus is instead on the effect of product preannouncements. A firm has no incentive to price strategically if it can publicize the existence of its technology in advance; the preannouncement itself is sufficient to overcome the entry barrier created by an installed base for a competing technology. Kennedy and King (2000) develop a model similar to that found here to consider workers' decisions of whether to adopt new skills. Their focus is on the welfare implications of different levels of coordination within and across generations.[4]

In contrast to other past work, I specifically consider whether a new, disruptive technology is *ever* adopted. In Katz and Shapiro (1992) and Regibeau and Rockett (1996), a new technology is continually improving, and the sponsor of the technology decides when to introduce it. The firm may introduce the technology earlier than is socially optimal, but whenever it does, the technology is adopted. More importantly, both of these papers assume that consumers are infinitely-lived and homogeneous. If consumers never leave the market and have identical preferences, there is a greater tendency toward inertia than under the more realistic assumptions that new consumers enter as old consumers exit and that consumers have heterogeneous preferences. Furthermore, the assumption that consumers within a generation coordinate efficiently contrasts with the aforementioned papers.[5] This assumption accounts for coordinating mechanisms that exist in many markets but are not modeled explicitly,

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[4]The major differences from the present model are that all workers within a generation have identical preferences, and the cost of acquiring new skills is exogenous. This corresponds to the homogeneous consumer, open technology case here.

[5]Regibeau and Rockett assume that consumers are myopic. Katz and Shapiro assume that consumer expectations are fulfilled in equilibrium, but there are multiple equilibria because of the inability of consumers to coordinate.

and allows for the result that inefficiency can result *even if the market is functioning as well as we can possibly expect.*

This paper is also related to the literature on switching costs.[6] In Farrell and Shapiro (1988) and Klemperer (1995), sales to successive generations of new users alternate between firms. This result is driven by the non-durability of the good; consumers must make repeat purchases. I will refer to the temporary loss of network benefit (to all affected consumers) as a switching cost. The implications will differ from the switching cost literature, but only because consumers do not make repeat purchases, not because of the nature of the cost itself.

In the following section, I introduce the model. In Section 3, I consider potential differences in the private and social incentives for adoption of open standards. I examine the potential divergence in incentives for proprietary standards in Section 4. A firm can mitigate one inefficiency (by appropriating some of the future stand-alone surplus generated by adoption of a new standard), but it introduces a new distortion (by appropriating some of the future network benefit). I characterize the conditions under which there is inefficient under- or overadoption. In Section 5, I note some considerations outside of the model that lead to persistence of inferior standards. Section 6 concludes.

2 The model

Consumers live for two periods. In any time period t there are N new consumers ("youngsters") as well as N old consumers ("oldsters"). The effects of population growth are noted below. I assume that, within a generation, consumers can coordinate on the outcome that is Pareto efficient within that generation.[7] Relaxing this

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[6]Examples of such costs are learning how to use a new technology and replacement of complementary goods.

[7]Farrell and Klemperer (forthcoming) discuss potential coordination mechanisms, including cheap talk and sequential consumer choice. Bresnahan (2002) also discusses how market forces can achieve coordination. It may be that the underlying source of the network effect is the provision of a

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assumption would only increase the tendency toward inefficiency.

There are two incompatible technologies, A and B, with marginal production costs c_A and c_B. At time t, I assume that A has been in existence for some time and has been adopted by old consumers, and that B is introduced and possibly adopted by some or all of the new consumers. Each technology has a stand-alone value and a network benefit, and consumer utility is additively separable in these components. There are two consumer types, H and L. Their respective proportions are α and β, where $\alpha + \beta = 1$.[8] The two types' stand-alone valuations of A are a_H and a_L, where $a_H > a_L$. Similarly, stand-alone valuations of B are b_H and b_L, where $b_H > a_H$ and $b_L > a_L$. I further assume that the margin of stand-alone value above marginal cost is greater for technology B: $b_j - c_B > a_j - c_A$ for $j = H, L$. This is the sense in which technology B is superior.[9]

I assume that the qualities of A and B are fixed. Alternatively, it could be that both technologies are improving over time, but at approximately the same rate.[10] Either way, technology B is fundamentally different from, and inherently superior to, technology A. The potential adoption of the Dvorak keyboard when QWERTY is an established standard is one example that this paper illustrates. Every quality characteristic of a keyboard, other than the layout of the keys, would be the same for both kinds of keyboard at any point in time. Apart from technologies, the model also applies to language and many social norms, wherein individuals would like to use the same standard as everyone else, but some standards are inherently superior.[11]

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complementary good; a dominant provider of this good could facilitate coordination.

[8] This is specified for the sake of completeness; the qualitative nature of the results will not depend on α or β.

[9] Essentially the same implications would hold if the network benefit associated with technology B were greater than that of A.

[10] This is in contrast to Katz and Shapiro (1992) and Regibeau and Rockett (1996), wherein the quality of one technology is fixed and the other is continually improving. The latter technology eventually becomes sufficiently superior that it is adopted. The welfare issue is whether this adoption comes too soon or too late.

[11] For example, one language might dominate another in terms of the degree to which the language facilitates communication or the ease with which one may learn the language.

The network benefit function is $f(n)$, where n is the number of users. If all current consumers use technology A, the value to each high-valuation user during one period is $a_H + f(2N)$. The network benefit function is increasing $(f' > 0)$ and exhibits weakly decreasing returns to scale $(f'' \leq 0)$.[12] I define the strength of the network effect by the first derivative: $f_1(n)$ represents a stronger network effect than $f_2(n)$ if $f_1'(n) > f_2'(n)$ for every n.

Consumers incur the cost of adopting a technology once, but they derive value from it for two periods. The value of each technology relative to its cost is large enough that all consumers will buy one technology once, but the marginal value from a second technology is so low that it is never worth incurring the additional cost.[13] This assumption makes the analysis more straightforward, and no additional welfare issues would arise if this assumption were relaxed.[14]

The discount factor is δ. This reflects the usual discounting of future benefits as well as the probability that some vastly superior technology will displace the current technology. In deciding whether to adopt technology B, a consumer knows the current benefit for certain, and discounts the next period's benefit at δ. If there is a high probability that some technology C will be introduced and adopted by future consumers, this is reflected in a low value of δ; this would indeed be the case for many network industries, since there is often rapid technological progress in such industries. Over time, there may be many points at which consumers must choose between an incumbent technological standard and a new standard. This model illustrates welfare issues at one such point. The discount factor is taken to be a constant for tractability, but it could depend on various parameters.[15] If population growth is incorporated

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[12]Decreasing returns to scale is a common characteristic of actual network effects. All of the results hold if the network benefit function exhibits strictly decreasing or constant returns to scale, but not increasing returns to scale $(f'' > 0)$.

[13]A sufficient condition for this is that stand-alone valuations are not too far above marginal costs. E.g., $a_L - c_A < D$ for a suitably chosen constant D.

[14]The most substantive contrast with the switching cost literature is the durability of the good. In Farrell and Shapiro (1988), consumers *must* make repeat purchases in order to continue to derive utility from the good. Here, consumers *can* make repeat purchases, but they need not do so.

[15]For example, the likelihood of a technology C being developed in a future period could increase if

into the model, it generally has the same effect as a higher discount factor.[16]

I focus on Markov perfect Nash equilibria, i.e. I assume that firms' strategies at any given time depend only on the payoff-relevant variables at that time. In the case of open technologies, A and B are each sold at marginal cost. In the proprietary case, each technology is sold by a monopolist. In Section 5, I discuss the implications of limitations on monopoly power over a standard.

3   Open standards

In this section, technologies A and B are non-proprietary, and the hardware market is competitive. Thus, the prices of A and B are equal to their respective marginal costs. I assume that, in period t, all oldsters have adopted A.[17] Technology B is introduced, and youngsters in period t have the choice between adopting A and being part of a network including all consumers, or adopting B and having a superior technology but a smaller network benefit. Since consumer preferences are heterogeneous, it is possible that one group of youngsters adopts A and the other adopts B. There are then different possible degrees of under- and overadoption.[18] If all youngsters adopt B, the extent of overadoption is greater (although the welfare cost may be lower, since dividing youngsters between two standards reduces the total network benefit in every successive period). In the proof of Propositions 1 and 2, I present comparisons

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technology B is adopted in the current period: this translates into a lower value of δ if B is adopted. This clearly makes adoption of B less attractive to the current generation of consumers. However, given the complexity of the model, it is difficult to formalize this insight by explicitly allowing δ to vary.

[16]I.e., if the rate of population growth is γ, then for most purposes, the effective discount factor is $\delta\gamma$. Some complications arise if γ is very high; most obviously, if $\delta\gamma > 1$ then it is always socially optimal to adopt any marginally superior technology. The population growth rate introduces other potential problems, but only at certain extremes. The general intuition of the results presented here would not change.

[17]I am only considering the issues around potential switching to a new technology, not initial adoption of a technology. Some of the same issues would arise in the initial adoption case.

[18]For example, if the social optimum is for all youngsters to adopt A, but H-types adopt B, this is overadoption.

of the private and social incentives for uniform adoption of either technology and for the case in which H-types adopt B and L-types adopt A. For any configuration of consumer adoption, the qualitative nature of the welfare results is the same. I assume that the crucial adoption decision is made in period t, i.e. that whatever decision today's H-type youngsters make, tomorrow's H-type youngsters will follow suit, and similarly for L-type youngsters.[19]

To facilitate the exposition, I will first consider the special case in which consumers have homogeneous preferences. I will then state the formal results for the general case. When consumers are homogeneous, $a_H = a_L = a$ and $b_H = b_L = b$. Given that consumers can coordinate on the outcome that is Pareto efficient within their own generation, all consumers of one generation will always adopt the same technology. First I characterize the social costs and benefits that arise if youngsters adopt B, relative to youngsters adopting A. The benefit of adopting B is the increased stand-alone value from period t onward ($b - c_B$ instead of $a - c_A$). The cost is the loss of network benefit during period t: oldsters and youngsters will both obtain less network benefit than they would if they all used the same technology. Let

$$F_s = 2\left[f\left(2N\right) - f\left(N\right)\right]. \tag{1}$$

This is the social loss of network benefit per current youngster; the total social loss of network benefit is NF_s. Note that F_s increases with the strength of the network effect. The additional stand-alone benefit to each future consumer is $(1 + \delta)(b - a) - (c_B - c_A)$, because benefits are gained for two periods but cost is incurred only once.

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[19]It is theoretically possible that consumers adopt B in stages. For example, say H-type oldsters have adopted A, and L-type oldsters have not adopted A. In period t, H-type youngsters adopt B, but L-type youngsters do not. It may be that L-type youngsters in period $t+1$ do adopt B, because they would be joining a network including all H-type consumers, not just H-type youngsters. This kind of staggered adoption is only possible if the network benefit function exhibits sharply decreasing returns to scale and the discount rate is very high. Here again, the welfare issues would be qualitatively the same.

The total benefit is the sum over all future consumers:

$$\sum_{i=0}^{\infty} \delta^i N \left[(1+\delta)(b-a) - (c_B - c_A) \right] = \frac{N}{1-\delta} \left[(1+\delta)(b-a) - (c_B - c_A) \right]. \quad (2)$$

It is then socially optimal for youngsters to adopt B if

$$(1+\delta)(b-a) - (c_B - c_A) > (1-\delta) F_s. \quad (3)$$

This condition says that the additional stand-alone benefit to all generations (net of the additional cost) outweighs the loss of network benefit to consumers during period t.

Next I characterize the private incentives of youngsters to adopt B. They incur only part of the social cost F_s. Let

$$F_p = f(2N) - f(N). \quad (4)$$

This is the private loss of network benefit per youngster. Note that $F_s > F_p$ always. It is privately optimal for youngsters to adopt B if

$$(1+\delta)(b-a) - (c_B - c_A) > F_p. \quad (5)$$

Using Choi's (1994) terminology, there is a forward externality (youngsters do not take into account the benefit to future generations of their adoption of B) and a backward externality (youngsters do not take into account the cost to the previous generation).[20]

Conditions (3) and (5) are both satisfied if $b-a$ is very large, and neither is satisfied if $b-a$ is very small. There is a potential inefficiency only if $b-a$ is intermediate relative to the strength of the network effect. We can also state the result in terms

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[20] In Choi (1994), the forward externality dominates. This would not necessarily be the case if the model were extended beyond two periods.

of the discount factor. If δ is large, the stand-alone benefit to future generations has a large impact on social welfare. Since the current generation of consumers does not take this benefit into account, they may not adopt B when it is socially optimal to do so. If δ is small, this future benefit is not as great, and the current generation's disregard for the loss of oldsters' network benefit may lead youngsters to adopt B when it is not socially optimal.

Note that a stronger network effect implies that $f(m+n)-f(n)$ is larger for any values of m and n. If we fix $b-a$ and decrease the strength of the network effect, F_p and F_s both decrease. For a sufficiently weak network effect, $\frac{1}{1+\delta}[c_B - c_A + F_p]$ and $\frac{1}{1+\delta}[c_B - c_A + F_s(1-\delta)]$ are both smaller than $b-a$. For a sufficiently strong network effect, the opposite is true. In either case, the equilibrium is socially optimal.[21]

I now illustrate the potential inefficiencies under the further assumption that the network benefit function exhibits constant returns to scale (CRS). This dramatically simplifies the algebra but does not change the qualitative nature of the results. Under CRS, $F_s = 2f(N)$ and $F_p = f(N)$, and so $F_s = 2F_p$. If $\delta = \frac{1}{2}$, then $(1-\delta)F_s = F_p$, and the conditions for adoption of B to be privately and socially optimal match. If $\delta > \frac{1}{2}$, then $(1-\delta)F_s < F_p$, and there is potential underadoption. If $\delta < \frac{1}{2}$, then $(1-\delta)F_s > F_p$, and there is potential overadoption. Say $\delta = \frac{1}{4}$. This could most reasonably be interpreted to mean that the effective discount rate is very high because there is a high probability that a disruptive technology will be introduced in any given time period. Then there is overadoption if $b-a > \frac{1}{1+\delta}[c_B - c_A + f(N)]$. If, on the other hand, $\delta = \frac{3}{4}$, then there is underadoption if $b-a < \frac{1}{1+\delta}[c_B - c_A + f(N)]$. Let $g(N) = \frac{1}{1+\delta}[c_B - c_A + f(N)]$. The heavy line in Figure 1 is where $b-a = g(N)$. Above this line, it is privately optimal for youngsters to adopt A; below, to adopt B. However, if $\delta = \frac{3}{4}$, it is socially optimal for youngsters to adopt A in region I but not region II; youngsters adopt A in equilibrium in both regions. If $\delta = \frac{1}{4}$, it is socially optimal for youngsters to adopt B in region IV but not region III; youngsters adopt

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[21] Farrell and Saloner (1986) have a similar result, but with multiple equilibria arising from the lack of ability of consumers to coordinate.
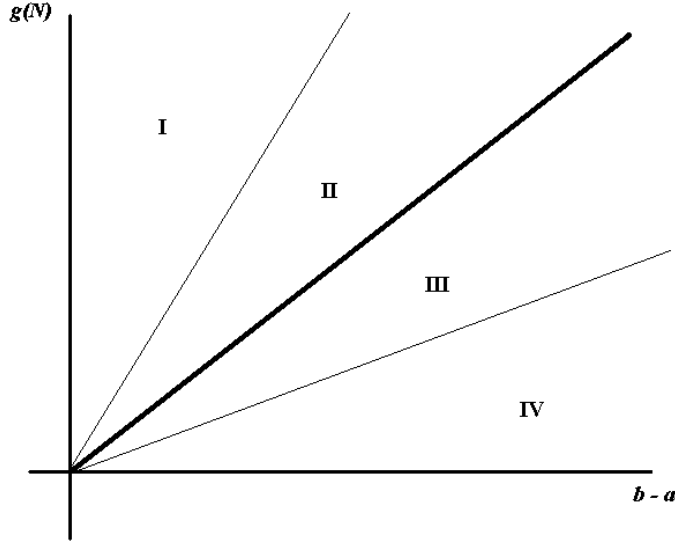
Figure 1:

B in equilibrium in both regions. Inefficiency arises only in regions II and III, where $b - a$ is close to $g(N)$.

Taking consumer heterogeneity into account does not change the intuition discussed above. In the absence of strategic behavior on the part of a technology provider, heterogeneity has no systematic effect on the efficiency of youngsters' adoption choice. In the homogeneous consumer case, the conditions for adoption of B to be privately and socially optimal depend on the differences in consumers' stand-alone valuations of A and B. Generally, these expressions depend on the weighted average of the differences in valuations for the two consumer types. The nature of the forward and backward externalities is the same. Formal proofs of the following propositions can be found in the Appendix.

Proposition 1 *When technologies are open, if δ is sufficiently high (low), there is potential underadoption (overadoption) of new technology.*

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Proposition 2 *When technologies are open, over- or underadoption of new technology arises if and only if the strength of the network effect and the degree of superiority of the new technology are relatively close together.*

Consumer heterogeneity does have an important effect when technologies are proprietary, as we shall see below.

4   Proprietary standards

Now I assume that there are two firms (firm A and firm B), each of which controls one technology. In Section 5, I discuss the possibility that these monopolies cannot be maintained indefinitely, perhaps because of limited intellectual property rights.

When technologies are proprietary, strategic pricing plays a key role in standard adoption. Firm B can try to induce adoption of its technology by offering a low introductory price to consumers in period t. The firm would then hope to profit in future periods, after the standard has been adopted. As above, the social cost of youngsters' adoption of B is the loss of network benefit to current youngsters and oldsters, and the benefit is the additional stand-alone surplus in current and future periods. If, after inducing adoption of technology B, firm B could appropriate exactly the additional stand-alone surplus less the switching cost, the firm would induce adoption of B precisely when it is socially optimal. In this section I examine the factors that influence firm B's ability to appropriate surplus, and the implications for welfare. In all cases, the costs and benefits are in comparison to all youngsters adopting technology A in period t.

As in the preceding section, I first consider the special case in which consumers are homogeneous. Again I assume that oldsters have all adopted A before the introduction of B. In any time period, each firm will price as aggressively as it has to in order to win over youngsters, unless it is unprofitable to do so. Specifically, the pricing strategy of firm i in period t is $p_t^i = \max\left\{p_1^i, p_2^i\right\}$, where p_1^i is the highest price at which the

current period's youngsters will adopt firm i's technology and p_2^i is the price for which the present value of firm i's profits is zero. These prices depend on which technology the current period's oldsters have adopted, the value of each technology to current youngsters, and each firm's marginal cost. There are no profitable deviations from these prices, and so the prices constitute a Markov perfect Nash equilibrium.

The extent to which firm B can set price below marginal cost in period t depends on the price firm B will be able to charge in future periods, given adoption of B by current youngsters. In any period k $(k > t)$, the existence of firm A disciplines firm B's price. Firm A can always offer technology A at marginal cost in an attempt to win consumers back.[22] If, during period k, oldsters have adopted B, then youngsters would obtain the following surplus by adopting A when A is sold at marginal cost:[23]

$$S = (1 + \delta) \left[a + f(N) \right] - c_A. \tag{6}$$

Therefore, firm B must price in such a way that youngsters get this much surplus from adopting B. Thus firm B sets price

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\begin{aligned}
p_k^B &= (1 + \delta) \left[b + f(2N) \right] - S \\
&= (1 + \delta) \left[b - a + f(2N) - f(N) \right] + c_A.
\end{aligned}
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Since firm B incurs marginal cost c_B, the surplus it appropriates during each period k is

$$N \left\{ (1 + \delta) \left[b - a + f(2N) - f(N) \right] + c_A - c_B \right\}. \tag{7}$$

Note that $N[(1 + \delta)(b - a) + c_A - c_B]$ is exactly the total additional stand-alone

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[22] Marginal cost is the price for which the present value of firm A's profits is zero. Firm A cannot lower price below marginal cost because it can never hope to make up the loss: Firm B will always be at least as strong a competitor as A because of its higher quality-cost margin.

[23] Here I consider the one-period deviation from the equilibrium path, in which firm A's price is equal to marginal cost and firm B's price is high enough that youngsters adopt A. In the following period, firms revert to equilibrium behavior, wherein that period's youngsters adopt B.

benefit generated by adoption of B; the firm appropriates all of this surplus, plus some of the surplus generated by the network effect itself.

The profit firm B earns in any period k after inducing adoption is $\pi_k^B = N\left(p_k^B - c_B\right)$, where p_k^B is as above. The present value of firm B's profits after inducing adoption is

$$\pi = \sum_{i=1}^{\infty} \delta^i N \left(p_k^B - c_B\right) \tag{8}$$

$$= \frac{N}{1-\delta} \left\{ (1+\delta)\left[b - a + f(2N) - f(N)\right] + c_A - c_B \right\}. \tag{9}$$

This is the most firm B is willing to sacrifice during period t to induce adoption. The maximum discount (below marginal cost) that firm B would give to each youngster in period t is $\frac{\pi}{N}$. That is, the lowest price B is willing to offer during period t is $p_t^B = c_B - \frac{\pi}{N}$. This price may be negative. We could interpret a negative price to mean that firm B gives away complementary goods or services with the purchase of B.[24]

Youngsters in period t will adopt B if the maximally discounted price for B gives them more surplus than A when priced at marginal cost.[25] This condition simplifies to

$$(1+\delta)(b-a) > p_t^B - c_A + f(2N) - f(N). \tag{10}$$

As in the previous section, it is socially optimal for youngsters to adopt B if

$$(1+\delta)(b-a) > c_B - c_A + (1-\delta)F_s \tag{11}$$

where $F_s = 2\left[f(2N) - f(N)\right]$. It is straightforward to show that the right-hand side of (10) is less than the right-hand side of (11). This implies that firm B can always

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[24] For instance, the producer of a new video game console may include a number of video game titles with the console. In Section 5, I discuss the implications if firm B is constrained to offer nonnegative prices.

[25] Here I am comparing youngsters' surplus when they adopt B in equilibrium to that when they adopt A in equilibrium. Thus, if current youngsters adopt A, they expect that the following period's youngsters will do the same.

induce adoption when it is socially optimal, and may be able to induce adoption when it is not socially optimal. The firm appropriates all of the additional stand-alone benefit, plus more than enough of the network benefit to compensate current youngsters for their switching cost. However, the firm does not have to compensate current oldsters for their loss of network benefit. Thus, there may be overadoption of B, but there is never underadoption.[26] A higher discount factor raises the present value of the future stand-alone benefit of switching; for δ sufficiently high, this present value outweighs the cost of switching, implying that adoption of B is socially optimal. This contrasts with the open-standards case, in which there is potential *underadoption* when δ is high. There, when the present value of the future stand-alone benefit is high, there may be underadoption because current consumers do not take the future stand-alone benefit into account in making their adoption choice.

In the open-standards case, a very strong network effect implies that B will not be adopted and that this will be socially optimal. In the proprietary case, if there is a stronger network effect, there is more surplus for the firm to appropriate in future periods. This makes it easier for the firm to induce adoption but does not affect social welfare. If the network effect is strong enough, the firm will induce adoption of B. However, because of the switching costs arising from the strong network effect, adoption of B will not be socially optimal.

When consumer preferences are heterogeneous, it may be profit-maximizing for firm B to induce adoption by all youngsters or just H-types. There are thus more pricing strategies to consider, and as in Section 3, there are different degrees of under- or overadoption. When both consumer types adopt B, firm B will not be able to appropriate all of the additional stand-alone surplus generated by adoption of B. If firm B would like all consumers to adopt B, it will give one consumer type exactly the amount of surplus that they would obtain from adopting A, and the other type will get a greater surplus than if they adopted A (assuming that the firm is not

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[26]The intuition here is similar to that of the second-mover advantage in Katz and Shapiro (1986).

able to price discriminate). The greater the degree of heterogeneity, the less surplus firm B will be able to capture. If heterogeneity is high enough, in the sense that $|(b_H - a_H) - (b_L - a_L)|$ is large, underadoption is possible. In order for there to be underadoption, two other conditions must be met. First, the discount rate must be sufficiently high; for a low discount rate, the present value of the future surplus generated by adoption of B is small, and so adoption of B is not socially optimal. Second, B cannot be too superior to A, in the sense that $\min\{b_H - a_H, b_L - a_L\}$ must be relatively small; otherwise, all consumers will adopt B and this will be socially optimal.

Proposition 3 *When technologies are proprietary, there is underadoption of new technology if consumer heterogeneity is sufficiently high, the degree of superiority of B over A is not too great, and δ is sufficiently low.*

On the other hand, if consumers adopt B, the firm still appropriates part of the network benefit in later periods. Firm B appropriates more of this benefit if either the discount factor is larger or if the network benefit is stronger. However, for a strong enough network benefit, the switching cost is so high that it is not socially optimal for consumers to adopt B. There is then overadoption of B.

Proposition 4 *When technologies are proprietary, there is overadoption of new technology if δ is sufficiently high and the network effect is sufficiently strong.*

As in the open-standards case, either kind of inefficiency is possible, but the inefficiencies arise under different circumstances and for different reasons. The results here depend not on how much additional benefit adoption of B confers, but how much of this additional benefit, and how much of the network benefit, firm B can appropriate.

It is very reasonable to think that the results here are robust to other specifications that capture the same essential characteristics. It is intuitively clear that some form of consumer heterogeneity limits a monopolist's ability to extract surplus, and that

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the presence of a network effect increases the firm's ability to extract surplus after establishing a standard. The effect of discounting is also intuitively clear. Thus we would expect the same qualitative results to arise from any model that incorporates these effects.

5   Persistence of inferior standards

So far, this paper has demonstrated the theoretical possibility of over- or underadoption of new technology. Overadoption can generally be attributed either to the value of the new technology to current consumers or to the efforts of a firm to encourage adoption. Both of these effects are captured in the model. I now consider some realistic complications to the model that tend toward underadoption. Essentially, there may be practical constraints on the firm's ability to extract future surplus and transfer it to current consumers.

- *Nonnegative pricing.* As mentioned above, the price that firm B would have to set in order to induce consumers in period t to adopt B may be negative. A negative price may be infeasible because of consumers' ability to "buy" an unlimited amount of the product. Mechanisms to transfer surplus to consumers, other than the price itself, may be costly for the firm. For example, if the firm gives consumers a rebate in the form of a complementary good, the firm may incur a transaction cost. It may be difficult to give all consumers a non-cash rebate that all consumers value equally; if there is a great deal of heterogeneity in consumers' willingness to pay for the rebate, the cost of the rebate to the firm may exceed some consumers' valuation of it. Or the firm may simply face a liquidity constraint that prevents it from transferring enough of the surplus from future periods. These possibilities could be modeled through a constraint on price. Alternatively, the cost to the firm of transferring surplus could be the value received by consumers multiplied by some factor greater than one.

- *Limited intellectual property rights.* Presumably, firm B's monopoly on its technology would be protected by a patent. The patent would of course expire eventually, and the effective length of patent protection could be severely limited by the ability of competing firms to reverse-engineer the technology. Any competition from other firms in the form of a compatible technology would limit the surplus that firm B could extract from consumers. More generally, if the firm faces the possibility of hazard that will limit the amount of time during which it can extract surplus, this can be reflected in a firm discount factor, δ_f, that is lower than consumers' discount factor, δ_c. Both δ_f and δ_c would incorporate the probability that a disruptive technology will arrive in any given time period, but δ_f would also incorporate the probability of firm hazard in any given time period.

If these complications are incorporated into the model, the effects are quite clear. Both limit the ability of firm B to induce adoption of its technology, but neither has any effect on social welfare. Given the results of the model and these additional considerations, it is quite reasonable to believe that an inferior standard can persist in the market indefinitely. To be precise, given the presence of one technological standard, another standard is superior if, considering the welfare of all current and future consumers, there would be a net gain if the current generation adopted the new standard. However, even if it is common knowledge that the new standard is superior in this sense, consumers will not necessarily adopt it. An inferior open standard can also persist, albeit for different reasons.

A natural question to ask is whether there have been actual cases of persistence of inferior standards. An often cited example is the QWERTY keyboard (and the presumed superior counterpart, the Dvorak keyboard[27]). Liebowitz and Margolis (1990) cast doubt on the claim that the Dvorak keyboard was in fact greatly superior to the QWERTY keyboard. They demonstrate that Dvorak's own studies in support

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[27]Dvorak held the original patent on the keyboard, but it is now in the public domain.

of his keyboard were flawed, but this simply invalidates the results of those studies. It does not address the fundamental question of which keyboard is superior. There is a wealth of anecdotal evidence that the Dvorak keyboard is in fact significantly better than the QWERTY keyboard.[28] It may well be that the future benefits of the keyboard would outweigh the switching cost, but that the switch is not made for exactly the reasons outlined in this paper.

The use of metric rather than English measurement is another example. Liebowitz and Margolis (1999, pp. 129-130) criticize this example as well: "The costs of switching to metric measuring systems are nontrivial, and most Americans do not think that they outweigh the benefits... the failure to establish the metric system in the United States is a rational response to individual choices—not an indicator of a problem." This paper fully supports this statement, right up to the dash. It is a rational response of current consumers to their individual choices, but it may be a problem in the sense that the unregulated market does not necessarily lead to the best outcome.

As for proprietary standards, it could be that the Macintosh is superior in the stand-alone sense—that the PC is superior only insofar as it has more associated software applications—but that it has never been widely adopted because of Apple's imperfect ability to appropriate future surplus. More importantly, if a firm foresees difficulty in sponsoring a new standard, it will be hesitant to develop the standard in the first place. There is no way to know how many potential standards have been kept out of the market.

On the other hand, this paper is not trying to argue that this is a pervasive problem. It is true that markets have overcome supposed lock-in many times; greatly superior standards do find their way into the market. Marginally superior standards should not be adopted if the benefits do not outweigh the switching costs. The point of this paper has been to demonstrate that inefficient standard adoption is possible, given a reasonable economic model. The model here captures several characteristics

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[28]See, for example, Thompson (2002), www.mwbrooks.com/dvorak/index.html, www.thisistrue.com/dvorak.html, or www.howstuffworks.com/question458.htm.

that we observe in actual markets involving a technological standard: there are successive generations of consumers; there are network effects among users for a durable good; consumer preferences are heterogeneous; and consumers can overcome the static coordination problems that can generate inefficiencies, perhaps because firms can act as coordinating devices. The results here depend on these characteristics, but not on the specific manner in which they are modeled. Given any kind of network effect among users, there are costs incurred when consumers adopt a new standard. Given any kind of heterogeneity in consumer preferences, a firm cannot extract all of the surplus from all consumers. Considering these effects, inefficient adoption of a technological standard is a reasonable possibility.

6   Conclusion

When a technological standard is in place and a new, superior technology arrives, consumers' private adoption incentives can be socially inefficient. In deciding whether to adopt the new technology, today's consumers do not consider the costs imposed on past consumers or the benefits accruing to future consumers. Because of these effects, markets can exhibit excess inertia or excess momentum; the market may become locked in to an inferior standard, or consumers may rush to adopt a standard that is not sufficiently superior to justify switching. When a firm owns the new standard, the same potential inefficiencies arise, but for different reasons. A firm may not be able to induce adoption when it is socially optimal because the firm cannot appropriate enough of the additional future benefit the standard offers. On the other hand, a firm may be able to induce adoption when it is socially inefficient because the firm can appropriate some of the surplus arising from the network effect itself, which does not depend on which standard is used. Furthermore, additional considerations beyond the scope of the model clearly tend toward underadoption of new technologies. While this is probably not a pervasive problem, it is certainly a possibility.

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7 Appendix

7.1 Proof of Propositions 1 and 2

In period t, oldsters of both types have adopted technology A. I consider three adoption choices for youngsters in period t: all adopt A; all adopt B; or H-types adopt B while L-types adopt A. I will compare, pairwise, the private and social incentives for each adoption scheme. For other possible adoption schemes—L-types adopt B and H-types adopt A, or one type adopts no technology—the potential for divergence between the private and social optimum is qualitatively the same.

If all period t youngsters adopt A, the respective utilities for L and H types are $(1 + \delta) a_L - c_A + (1 + \delta) f (2N)$ and $(1 + \delta) a_H - c_A + (1 + \delta) f (2N)$. If all youngsters adopt B, these utilities are $(1 + \delta) b_L - c_B + f (N) + \delta f (2N)$ and $(1 + \delta) b_H - c_B + f (N) + \delta f (2N)$. All youngsters prefer adopting B to adopting A if both of the following inequalities hold:

$$(1 + \delta) (b_L - a_L) - (c_B - c_A) \; > \; F_p \tag{12}$$

$$(1 + \delta) (b_H - a_H) - (c_B - c_A) \; > \; F_p \tag{13}$$

where $F_p = f (2N) - f (N)$. The social benefit of youngsters' adoption of B rather than A is $\frac{N}{1-\delta}\{\alpha (1 + \delta) (b_L - a_L) + \beta (1 + \delta) (b_H - a_H) - (c_B - c_A)\}$. The social cost is F_s, where $F_s = 2N[f (2N) - f (N)]$. It is then socially preferred for youngsters to adopt B if and only if

$$\frac{1}{1 - \delta} \{\alpha (1 + \delta) (b_L - a_L) + \beta (1 + \delta) (b_H - a_H) - (c_B - c_A)\} > F_s. \tag{14}$$

The left hand side of this inequality increases without bound as δ approaches 1, but this is not the case in the private adoption incentives. For sufficiently large δ, adoption of B is socially preferred regardless of the values of other parameters. Next, note that $\alpha (1 + \delta) (b_L - a_L) + \beta (1 + \delta) (b_H - a_H) - (c_B - c_A) \leq \min\{(1 + \delta) (b_L - a_L)$

$- \left(c_B - c_A\right), \left(1 + \delta\right)\left(b_H - a_H\right) - \left(c_B - c_A\right)\}$. Also, $F_s > F_p$ always. Therefore, if (12) and (13) both hold and, holding all other parameters fixed, δ is sufficiently close to zero, (14) is violated. However, if $b_H - a_H$ or $b_L - a_L$ is sufficiently large relative to the network effect, (12), (13) and (14) all hold, and all the conditions are violated if $b_H - a_H$ and $b_L - a_L$ are sufficiently small. An inefficient outcome arises only if the additional stand-alone benefit of B and the network benefit are relatively close together.

Now, if H-types adopt B and L-types adopt A, the respective utilities of L-types and H-types are $\left(1 + \delta\right) a_L - c_A + f\left[\left(1 + \alpha\right) N\right] + \delta f\left(2\alpha N\right)$ and $\left(1 + \delta\right) b_H - c_B + f\left(\beta N\right) + \delta f\left(2\beta N\right).$ Note that L-types never prefer this outcome; if L-types adopt A, they would always prefer that H-types adopt A also. The split adoption can only result if H-types have such a strong preference for B that they will adopt it no matter what the L-types do, and that given this, L-types would rather adopt A than B. This would be the case if $b_H - a_H >> b_L - a_L$, α is large, and δ is small. Then L-types would want to adopt the same technology as the past generation to take full advantage of the network benefit, and H-types' preferences would be dominated by the large stand-alone value of B. The key condition for youngsters to split in this fashion rather than all adopting A is

$$\left(1 + \delta\right)\left(b_H - a_H\right) - \left(c_B - c_A\right) >$$

$$\left(1 + \delta\right) f\left(2N\right) - \left[f\left(\beta N\right) + \delta f\left(2\beta N\right)\right]. \tag{15}$$

This is the condition for H-types; there is also a condition for L-types, but it is not relevant for the welfare comparison. The social benefit, relative to all adopting A, is $SB = \frac{\beta N}{1 - \delta}\left[\left(1 + \delta\right)\left(b_H - a_H\right) - \left(c_B - c_A\right)\right]$, the additional stand-alone benefit to H-types. The social cost is the loss of network benefit to both types of consumer for the current and future periods: summing this loss for both types of current oldsters,

current youngsters, and future youngsters, the total social cost is

$$
\begin{aligned}
SC = {}& N \{f(2N) - f[(1+\alpha)N]\} + \frac{N(1+\delta)f(2N)}{1-\delta} \\
& -\beta N [f(\beta N) + \delta f(2\beta N)] - \alpha N \{f[(1+\alpha)N] + \delta f(2\alpha N)\} \\
& -\frac{\delta \beta N(1+\delta)f(2\beta N)}{1-\delta} - \frac{\delta \alpha N(1+\delta)f(2\alpha N)}{1-\delta}.
\end{aligned}
\tag{16}
$$

First note that the conditions for split adoption to be privately and socially preferred match if the additional stand-alone benefit is either very large or very small relative to the network benefit. Now, consider the case when δ is small. As δ approaches zero, the private adoption condition becomes

$$
(b_H - a_H) - (c_B - c_A) > f(2N) - f(\beta N)
\tag{17}
$$

and the social condition becomes

$$
\begin{aligned}
(b_H - a_H) - (c_B - c_A) > {}& \frac{1}{\beta}\{f(2N) - f[(1+\alpha)N]\} \\
& - [f(\beta N) + \delta f(2\beta N)] \\
& - \frac{\alpha}{\beta}\{f[(1+\alpha)N_{t-1}] + \delta f(2\alpha N)\}.
\end{aligned}
\tag{18}
$$

The right hand side of (18) is larger than the right hand side of (17), which means that it is possible for (17) to be true but (18) to be false (there is potential overadoption).

Next consider the case when δ is close to 1. I transform the social condition so that the left hand side matches the private condition: $SB > SC \Leftrightarrow (1+\delta)(b_H - a_H) - (c_B - c_A) > \frac{1-\delta}{\beta N}SC$. As δ approaches 1, the left hand side does not change, but the right hand side becomes less than the right hand side of (17). This means that it is possible for (17) to be false but (18) to be true (there is potential underadoption).

I have compared the private and social incentives for this kind of split adoption to the incentives for uniform adoption of A. There is a similar comparison with uniform adoption of B, and with other adoption schemes in which different consumer types

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adopt different technologies.

7.2 Proof of Propositions 3 and 4

As in the open-technologies case, I make pairwise comparisons of the private and social incentives for three adoption schemes: all period-t youngsters adopt A; all adopt B; and H-types adopt B while L-types adopt A. As above, I omit the results for the remaining cases, but the qualitative results are the same.

First I compare uniform adoption of A to uniform adoption of B. If firm B induces adoption by all youngsters in period t, the price charged in period k ($k > t$) is $p^B = (1 + \delta)[b_L + f(2N)] - S$, where S is the surplus given to consumers to keep them from adopting A when it is offered at marginal cost. This must be sufficient to keep either type of consumer from adopting A alone and to keep all consumers from adopting A together. Thus, $S = \max\{S_1, S_2\}$, where $S_1 = (1 + \delta)[a_H - b_H + b_L + f(\beta N)] + - c_A$ and $S_2 = (1 + \delta)[a_L + f(N)] - c_A$. The total profit that firm B earns after period t is $\pi = \frac{\delta}{1-\delta} N (p^B - c_B)$. This is the maximum amount the firm is willing to give away in period t to induce adoption. The lowest price the firm can offer in period t is $p_t^B = c_B - \frac{\delta}{1-\delta}(p^B - c_B)$. The conditions for both types of consumer to adopt B rather than A are $(1 + \delta) b_H + (1 + \delta) f(2N) - p_t^B \geq (1 + \delta) a_H + (1 + \delta) f(2N) - c_A$ and $(1 + \delta) b_L + (1 + \delta) f(2N) - p_t^B \geq (1 + \delta) a_L + (1 + \delta) f(2N) - c_A$, or

$$p_t^B \leq (1 + \delta) \min\{b_H - a_H, b_L - a_L\} + c_A. \tag{19}$$

As in the open-technologies case, uniform adoption of B is socially preferred to uniform adoption of A if

$$\frac{1}{1-\delta}\{\alpha(1+\delta)(b_L - a_L) + \beta(1+\delta)(b_H - a_H) - (c_B - c_A)\} > F_s. \tag{20}$$

As δ approaches zero, p_t^B approaches c_B. Then (19) is clearly violated if $\min\{b_H - a_H,$

$b_L - a_L\}$ is sufficiently low. If, at the same time, $|(b_H - a_H) - (b_L - a_L)|$ is sufficiently large, (20) does hold, and uniform adoption of B is socially preferred but not induced by firm B. If δ is sufficiently high, then as the strength of the network effect increases, p_t^B decreases without bound. For a sufficiently strong network effect, (19) is true. However, a sufficiently strong network effect also tends to make (20) false. If we fix δ at any level such that $\delta < 1$ and increase the strength of the network effect, (20) is violated. Uniform adoption of A is socially preferred, but firm B prefers uniform adoption of B.

Next I look at the case where H-types adopt B and L-types adopt A. If H-types have adopted B in period t, the price of B in period k, $k > t$, is $p^B = (1 + \delta) b_H + (1 + \delta) f(2\beta N) - S$, where $S = (1 + \delta) \{a_H + f[(\alpha + \beta) N]\} - c_A$. The total profit that firm B earns after period t is $\pi = \frac{\beta N \delta}{1 - \delta} (p^B - c_B)$. The lowest price the firm can offer in period t is $p_t^B = c_B - \frac{\delta}{1 - \delta} (p^B - c_B)$. The condition for H types to adopt B rather than A is $(1 + \delta) b_H + f(\beta N) + \delta f(2\beta N) - p_t^B \geq (1 + \delta) a_H + (1 + \delta) f(2N) - c_A$, or $p_t^B \leq (1 + \delta)(b_H - a_H) + f(\beta N) + \delta f(2\beta N) - [(1 + \delta) f(2N) + c_A$. The social cost and benefit (in comparison to all consumers adopting A) are the same as in the open technologies case: $SB = \frac{\beta N}{1 - \delta}[(1 + \delta)(b_H - a_H) - (c_B - c_A)]$, and

$$
\begin{aligned}
SC = N \{f(2N) - f[(1 + \alpha) N]\} + \left(\frac{1}{1 - \delta}\right) N (1 + \delta) f(2N) \\
- \beta N [f(\beta N) + \delta f(2\beta N)] - \alpha N \{f[(1 + \alpha) N] + \delta f(2\alpha N)\} \\
- \left[\frac{\delta(1 + \delta)}{1 - \delta}\right] [\beta N f(2\beta N) - \alpha N f(2\alpha N)].
\end{aligned}
\tag{21}
$$

Consider the possibility of overadoption. If the conditions in Proposition 4 hold, clearly the firm is able to induce H-types to adopt B; if δ is sufficiently high and the network effect is sufficiently strong, p_t^B decreases without bound. Firm B clearly prefers this outcome to all consumers adopting A, in which case firm B earns zero profit. Given these same conditions, and given that the network benefit function exhibits decreasing returns to scale, SC above increases without bound. To see this

intuitively: there is a net loss of network benefit in every generation when consumers are split between technologies rather than all adopting A. When the conditions in Proposition 4 hold, firm B prefers inducing adoption by H-types to inducing no adoption of B, but it is socially preferred for all consumers to adopt A. The same basic argument follows if we consider adoption of B by L-types alone. If the conditions in Proposition 3 hold, a similar argument shows that it is socially preferred for one consumer type to adopt B, but firm B cannot induce either type to adopt B.

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