Installed Base and Compatibility: Innovation, Product Preannouncements, and Predation

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A good is often more valuable to any user, the more others use compatible goods. We show that this effect may inhibit innovation. If an installed base exists and transition to a new standard must be gradual, early adopters bear a disproportionate share of transient incompatibility costs. This can cause "excess inertia." The installed base, however, is "stranded" if the new standard is adopted: this may create "excess momentum." These dynamic effects have strategic implications.

When compatibility is important, an installed base of durable goods or training may affect the likelihood and desirability of innovation. In this paper we analyze the private and social incentives for the adoption of a new technology that is incompatible with the installed base.

The benefits from compatibility create demand-side economies of scale: there are benefits to doing what others do. These benefits make standardization a central issue in many important industries. There are three main sources of these benefits. The first is *interchangeability of complementary products* such as computer software, VCR tapes, phonographic records, cassette tapes, and camera lenses. The second is *ease of communication* (between people or between people and machines). The most important example is that of telecommunications networks: the value to each telephone subscriber depends on the number of other people on the network. Other examples include standardized typewriter keyboards or machinery (this makes learned skills more widely usable), weights and measures, and, of course, language itself. The third is *cost savings*: standardization, especially interchangeability of parts, facilitates mass production.[1]

In the presence of compatibility benefits, a user who switches to a new, superior technology cannot obtain its full benefit unless other current users also switch and new users adopt the new technology. This creates the possibility of "excess inertia": a socially excessive reluctance to switch to a superior new standard when important network externalities are present in the current one.

In an earlier paper (1985), we examined this problem in a model in which all users have the opportunity to adopt the new technology at essentially the same time, that is, payoffs depend only on *who* switches, not on *when* they switch. We found that symmetric excess inertia (a Pareto-superior new technology not being adopted) could not occur with complete information,[2] although it could occur with incomplete information.[3]

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[1]This categorization is not exhaustive. For example, servicing of automobiles is cheaper and easier to obtain for common models because they are more familiar to mechanics and because spare parts are more widely available. (See our 1985 paper and Michael Katz and Carl Shapiro, 1985, for other examples.)

[2]The intuition for this result can be obtained by considering a sequence of N decision makers contemplating switching, and using a backwards induction argument. If everyone else has switched, the Nth decision maker will choose to switch. But then the $(N-1)$st decision maker can be certain that it will be followed in a switch by the Nth decision maker if *its* predecessors have all switched. Thus it too will find it optimal to switch, and so on. (See our 1985 paper, Sec. 2.)

[3]With incomplete information about the benefit of the network externalities to others, no firm can be sure

In practice, however, not all users have the same opportunities at a given time: when innovation is unexpected, new users have an option that was unavailable to previous users, and, moreover, those (the installed base) who had previously adopted the old technology may be at least somewhat *committed*. As a result, if the technology is adopted, it will take time for its network to grow.

These delays in building a network on the new standard can create inefficiencies. An early adopter of the new technology creates at least transient incompatibility. While this is a social cost of the innovation, the private costs and benefits may not accurately reflect the social ones. In our earlier paper (1985), any permanent incompatibility was important, but, since we ignored interim payoffs, any *transient* incompatibility did not matter. The two models we analyze here, on the contrary, emphasize that effect.

In the first model, we assume that the network on the new technology is built up of new users, and that old users who switch do not significantly contribute to it. In our second model, we assume by contrast that new users are negligible, and that the new network is built up through old users switching. The delays in building a substantial new network are caused in the first case by the time it takes for enough new users to arrive, and in the second by the time it takes for old users to switch. Before going to the formal treatment, we informally discuss the two models.

A Model with New Users. First, we consider the case in which the new network must be built up through adoption by new users. This is a reasonable assumption if old users switch slowly, compared to the arrival rate of new users. We suppose that there is a continual stream of (infinitesimal) new users. We examine what determines whether a new (and unexpected) technology gets adopted and emerges as the new standard.

The following examples may illustrate what we have in mind: there was a large installed base of "Standard 8mm" movie cameras and projectors when "Super 8" was introduced; the "QWERTY" keyboard was ubiquitious by the time the Dvorak keyboard became available (see Paul David, 1985); and the motor car was invented at a time when there was a substantial installed base of horse-drawn carriages and streetcars.

As we show in Section I, the presence of the installed base causes a disparity between the social incentives for the adoption of the new technology and the private incentives facing individual decision makers. There are two externalities. *First*, adoption of the new technology affects the users of the old technology. Their network ceases to grow, and may even shrink as some current users abandon their old equipment for newer equipment that uses the new technology. For instance, when Super 8 was introduced, recent buyers of Standard 8 equipment found that Standard 8 film became harder to obtain, and delays in processing grew. They suffered a loss, therefore, from the introduction of Super 8—especially relative to the benefits they had expected. This loss was not taken into account by the sellers or the buyers of the new Super 8 technology. *Second*, an early adopter of the new technology enhances its appeal to later users (and reduces the appeal of the old). In general, he or she does not appropriately take this into account.

In our model we consider the game between users who arrive at different times. Each decides which technology to adopt, given what others have done. The equilibrium outcome depends on the size of the installed base when the new technology is introduced, how quickly the network benefits of the new technology are realized, and the relative superiority of the new technology. The parameter space representing these attributes can be divided into three regions: In the first, the unique perfect Nash equilibrium is that the new technology is adopted; in the second, it is that it is not adopted; and in the third, both these outcomes are equilibria.[4]

that it would be followed in a switch to the new technology. This uncertainty can lead all the firms to remain with the status quo even when in fact they all favor switching, because they are unwilling to risk switching without being followed.

[4] The multiple equilibria arise from the fact that the outcome may depend on new adopters' expectations about what other adopters will do. If each user expects everyone (no one) else to adopt he will usually also

Because there are unique equilibria in some regions, we can illustrate unambiguously how the two externalities discussed above can lead to inefficient technology choice. Suppose, for example, that the new technology is far superior to the old in the long run (i.e., once the network is large), but that it would take a long time for the network to become established. Early adopters of the new technology would bear a disproportionate share of the transient incompatibility costs. They may be unwilling to do this. In that case, the unique equilibrium is that the new technology is not adopted, despite the long-run benefits. This is more likely to occur if the installed base is large, or if the new technology is unattractive when it has only a few users. Thus the installed base may cause excess inertia. The Dvorak keyboard's failure to displace the less efficient QWERTY keyboard may be an example of this.[5] Once the first potential adopters decide not to adopt the new technology, of course, the excess inertia only becomes worse.

Excess momentum—the inefficient adoption of a new technology—can also arise. Suppose that the new technology offers the first potential adopter an advantage over the current technology. He (or she) may be willing to adopt the new technology even though it will be a long time before the network is established. Once he adopts it, the new technology becomes even more attractive for later users, and the unique equilibrium may be that it is adopted. Excess momentum may result, because of the "stranding" (or "orphaning") externality, which hurts the users comprising the installed base.

Because the size of the installed base may critically affect adoption, it may constitute a *barrier to entry*. Not only does the presence of a barrier affect efficiency, but firms will have an incentive to take actions to buttress it. One such action that has been alleged in antitrust litigation is the announcement of future availability of a new product.[6] Defendants have been charged with making a "premature announcement" or a "predatory preannouncement" in order to discourage existing customers from switching to another supplier and to encourage those intending to buy soon to wait, and thus not become part of the "installed base." No formal models have been developed to deal with this question. However, several authors have claimed that preannouncements cannot be anticompetitive. For example:

> In general, there is no reason to inhibit the time when a firm announces or brings products to the marketplace. Customers will be the final arbiter of the product's quality and the firm's reputation . . . . Advance announcements of truthful information about products cannot be anticompetitive. Indeed, such announcement is procompetitive; competition thrives when information is good.
>
> [Franklin Fisher, John McGowan, and Joen Greenwood, p. 289][7]

However, when there are significant network externalities, the timing of the announcement of a new incompatible product can critically determine whether the new product supersedes the existing technology. In that case, because of the externalities arising from the installed base, a preannouncement can sometimes secure the success of a new technology that is socially not worth adopting, and that would not have been adopted absent the preannouncement.

The intuition for this result is the following: With a preannouncement, two effects favor the new technology. First, if some users decide to wait for it, the network benefits

adopt (not adopt). Imposing rationality on these expectations sometimes leads to a unique equilibrium, but not always. Where multiple equilibria exist, which equilibrium prevails may depend on which is more "focal" (see Thomas Schelling, 1960, for a discussion of this). The incentive to make an outcome more focal than another may lead to large investments in advertising and to "introductory" pricing.

[5] See David for the history of the typewriter keyboard.

[6] See Franklin Fisher, John McGowan and Joen Greenwood (1983) for a discussion of "predatory preannouncements" in the IBM case.

[7] Similarly, Robin Landis and Ronald Rolfe state: "...the welfare of consumers can only be increased by having additional correct information that is relevant to their purchasing decision" (1985, p. 140).

when the new technology is introduced (and adopted by those users) will be larger than otherwise. Second, the installed base on the old technology will be reduced by the number of users who wait. In some cases, the unique equilibrium without a preannouncement is that the new technology is not adopted, while with a preannouncement it is adopted. Of course, the potential users who decide to wait are indeed well-informed "arbiters of the product's quality" and their welfare is increased, but they are not the only ones who matter. Their adoption of the new technology affects both the users in the installed base and later adopters who might have preferred the old technology to the new. Thus, the preannouncement may reduce welfare.

Another strategic action that can exploit the installed-base effect is predatory pricing. An incumbent monopolist supplying the old technology may face a threat of competitive entry by a new technology. One weapon he can deploy against this is to engage in temporary price reductions, thus keeping the competition at bay, until his proprietary technology has so large an installed base that incompatible competitive entry becomes impossible. Because of the installed-base effect, predation can prevent future entry.

A Model without New Users. In our second model, we suppose that there are no new users: the network on the new technology must be built up through the switching of users from the old technology. By switching, a user encourages others to switch in two ways: the new network is made more attractive; the old less so. In our model, we assume that there are just two users, and that once one has switched the other will surely want to follow.

Where the users are firms, each firm's eagerness to switch will depend, inter alia, on the condition of its current equipment (does it need replacing anyway?), how well its current product line is doing (does the firm have other reasons to change the products it is offering?), whether it is already planning to add new capacity, etc. Looking forward the firm will thus be uncertain about when it will be advantageous for it (and for its rivals) to switch. We model this uncertainty about unpredictable eagerness to switch by supposing that "opportunities to switch" for each firm arrive randomly over time. (In particular, we assume that these opportunities follow a Poisson arrival process.) When such an opportunity occurs, the firm has a choice: it can switch now, or it can wait until its rival has an opportunity to switch, hope its rival switches at that opportunity, and then switch itself at *its* next opportunity.

In equilibrium, the firms may switch too reluctantly (excess inertia), too eagerly (excess momentum), or efficiently. The possible inefficiencies arise from two externalities in the model. First, when a firm switches, its rival loses some network benefits while they are using incompatible technologies, and the switching firm ignores this in its calculations.[8] Second, even if users unanimously favor a switch, each user may prefer the other to switch first.[9] As a result, switching may be delayed.

Adoption decisions will in general depend on prices. However, since we focus on the effects of the network externalities, we treat price as exogenous and suppress it. This is appropriate if the technologies are competitively supplied: W. Brian Arthur (1983) calls this "unsponsored technology." Michael Katz and Carl Shapiro (1986) discuss the effects of sponsorship. We consider price explicitly only when it has a strategic role, namely in our discussion of preannouncements and predation.

The paper is organized as follows: Section I presents the model with new users. Section II presents the model with no new users and a Poisson arrival process of switching opportunities.

I. A Model with New Users

In this section we study a model in which potential users arrive over time. Before time

[8] Indeed, this harm to the rival may provide an added incentive to switch if structural conditions are such that predation is possible.

[9] We call this the *penguin effect*. Penguins who must enter the water to find food often delay doing so because they fear the presence of predators. Each would prefer some other penguin to test the waters first.

T^*, only technology U is available. At T^*, a new technology, V, becomes available. Until we discuss preannouncements, we assume that the new technology is unanticipated. Those who adopted U before T^* do not switch, while subsequent users can choose which technology to adopt.

For simplicity, we suppose that users are infinitesimal and arrive continuously over time with arrival rate $n(t) \geq 0$ (i.e., we do not study shrinking markets). Write $N(t) = \int_0^t n(t')dt'$. Denote by $u(x)$ a user's flow of benefits from technology U when the size of the U network is x (i.e., when the set of users of technology U has measure x). The presence of network externalities implies that $u'(x) > 0$. For reasons that will become clear when we discuss equilibrium, we focus on two extreme possibilities. If everyone from T^* onwards adopts the new technology V, we call this the *adoption* outcome. If nobody adopts V, we call it *nonadoption*.

In the case of nonadoption of V, a user who adopts U at time T gets a present-value payoff of

$$(1) \quad \bar{u}(T) \equiv \int_T^\infty u(N(t))e^{-r(t-T)}dt,$$

where r is his or her discount rate.[10]

Periodically we will construct examples using the linear case:

$n(t) = 1;\ N(t) = t$

$u(x) = a + bx$ (so $u(t) = a + bt$).

Here a represents the "network-independent" benefits: the value to a user if there are no other users in the network. At time t, the network has grown to size t, giving rise to network-generated benefits of bt. For this case, we have

$$(2) \quad \bar{u}(T) = \int_T^\infty (a+bt)e^{-r(t-T)}dt$$

$$= \frac{a}{r} + b\int_0^\infty (\tau + T)e^{-r\tau}d\tau$$

$$= (a+bT)/r + (b/r^2).$$

This has an appealing interpretation. The user who adopts the technology at time T join a network of size T, and so gets an initial benefit flow $(a+bT)$. The net present value of benefits if the network size remains unchanged is $(a+bT)/r$, which is the first term of the expression. Naturally, this is increasing in a, b, and T and decreasing in r. The second term, b/r^2, gives the benefit to the adopter at time T from the *future* growth in the network.[11] This term is increasing in b, the rate of network growth.

Similarly, we define the net present value of benefits to a user who adopts the old technology at time T *and is the last user to adopt it*. This is

$$\tilde{u}(T) \equiv u(N(T))\int_T^\infty e^{-r(t-T)}dt$$

$$= u(N(T))/r.$$

In the linear case this is $(a+bT)/r$.

We define similar functions for the new technology V. Note, however, that when V is introduced, U already has an installed base of size $N(T^*)$. Therefore, if all new adopters after time T^* use V (and no current users of U switch), the benefit flow at time $t \geq T^*$ from using V is $v(N(T) - N(T^*))$. The analogous expression to (1) is

$$(3) \quad \bar{v}(T) = \int_T^\infty v(N(t) - N(T^*)) \times e^{-r(t-T)}dt \quad \text{for } T \geq T^*.$$

[10] Consumers' surplus is thus $\bar{u}(T)$ minus the price of technology U at time T. If we assume that price is constant over time and across technologies, then prices are common to most comparisons and can be ignored. While this is not realistic, it considerably simplifies notation and involves no loss of insight. The only comparison for which price is relevant is when the owner of a U machine considers scrapping it to buy a V machine. We assume that the price is high enough that this will not happen.

[11] Each unit of time the network grows by b. The net present value of benefits from this increase in the network size (evaluated at the time the growth occurs) is b/r. Thus the growth gives rise to a benefit stream of b/r per unit of time, which has a present value of $(b/r)/r = b/r^2$. It is this component of $\bar{u}(T)$ that is in jeopardy from the introduction of new technology.

In the linear case we suppose that

$$v(x) = c + dx = c + d(t - T^*).$$

Thus V can be superior to U in either of two ways: It can offer a higher *network-independent* benefit ($c > a$), or it can have higher *network-generated* benefits ($d > b$). In this linear case we have

$$\bar{v}(T) = \int_T^\infty [c + d(t - T^*)]\, e^{-r(t-T)} dt$$

$$= \frac{c + d(T - T^*)}{r} + \frac{d}{r^2} \text{ for } T \geq T^*.$$

The interpretation here is the same as for (2). Also $\tilde{v}(T)$ is given by the first term of $\bar{v}(T)$ as before.

A. *Equilibrium*

A strategy for the user who arrives at time $t \geq T^*$ consists of a choice of U or V as a function of what has happened before t, that is, the choices of those users who arrived between T^* and t. A Nash equilibrium specifies a strategy for each player that is optimal for him given the strategies of others. We now examine the Nash equilibria of the game and ask whether they are efficient.

In this game, there is a *bandwagon effect*: if a set of users adopts one technology, then that same choice thereby becomes more attractive to all other users. Accordingly, we focus on the two extreme possible outcomes: adoption and nonadoption. (Except for knife-edge cases, these are the only equilibria.)

Adoption is a subgame-perfect Nash equilibrium if $\bar{v}(T^*) \geq \tilde{u}(T^*)$. For then, if the first user to choose expects everyone else to adopt V, it is optimal for him to do likewise; and subsequent adopters then find the comparison all the more favorable to V. Moreover, because users are infinitesimal, any deviation from equilibrium by a single user will not affect the calculations of subsequent users, so the Nash equilibrium is indeed subgame perfect.[12]

[12] If we had a finite set of users, it could be that this Nash equilibrium is not perfect. If users are not infinitesimal, they may be able to affect later users' decisions. For a discussion of this strategic bandwagon power, see our earlier paper (1985).

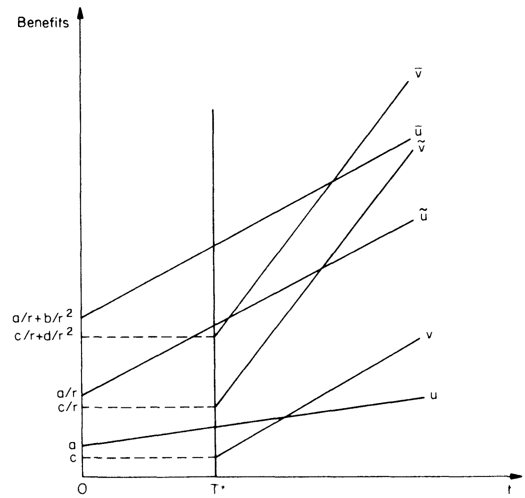

FIGURE 1: THE LINEAR EXAMPLE

If $\bar{v}(T^*) < \tilde{u}(T^*)$, on the other hand, then it is a dominant strategy for all users close enough to T^* to choose U. Once they have done so, the installed base on U is all the larger and so later users will also adopt U. Figure 1 illustrates this in the linear case with $d > b$ and $a > c > 0$. When a few users just after T^* adopt U, the $\bar{v}(t)$ curve shifts horizontally to the right. Consequently, $\tilde{u}(T) - \bar{v}(T)$ is even larger for $T > T^*$ than at T^*. In this case, then, nonadoption is the unique equilibrium.

Similarly, if $\bar{u}(T^*) \geq \tilde{v}(T^*)$ then nonadoption is a (subgame-perfect) Nash equilibrium, because users near T^* will prefer U if they expect later users to adopt U, and later users will then find U all the more attractive. If $\bar{u}(T^*) < \tilde{v}(T^*)$, then it is a dominant strategy for early choosers to choose V, and once the bandwagon is rolling this dominance can only be strengthened: adoption is the unique equilibrium.[13]

[13] There is another case in which adoption is the unique equilibrium. Suppose that users are discrete rather than infinitesimal, and that (*i*) $\bar{v}(t) > \bar{u}(t)$ for all t, and (*ii*) $\tilde{v}(t) > \bar{u}(t)$ for all $t \geq T'$ for some T'. Then if all users between T^* and T' adopt V, it becomes a dominant strategy for later users to adopt V. Knowing this, it is optimal for the last user before T' to choose V if all previous users did so. Continuing by backwards induction in the usual way, we see that adoption is the unique perfect equilibrium. This is similar to Proposition 1 of our earlier paper (1985).

Since generally $\bar{u}(T^*) > \tilde{u}(T^*)$ and $\bar{v}(T^*) > \tilde{v}(T^*)$, at least one of the conditions, $\bar{u}(T^*) \geq \tilde{v}(T^*)$ or $\bar{v}(T^*) \geq \tilde{u}(T^*)$, must hold. So an equilibrium always exists in our model. However, the conditions are not mutually exclusive. When they hold simultaneously, then both adoption and nonadoption are equilibria: because the network externality makes it desirable to do what others are going to do, users' expectations drive the equilibrium.

The above results can be summed up in

PROPOSITION 1: *Adoption is a perfect Nash equilibrium if and only if $\bar{v}(T^*) \geq \tilde{u}(T^*)$. Nonadoption is a perfect Nash equilibrium if and only if $\bar{u}(T^*) \geq \tilde{v}(T^*)$. At least one of these conditions must hold, so equilibrium exists. They may hold simultaneously, in which case there will be multiple equilibria. If just one holds, we have a unique equilibrium.*

B. *Efficiency*

There are both positive and negative welfare effects from the adoption of the new technology. If V is adopted, each user for whom $\bar{v}(T) > \bar{u}(T)$ (typically one who arrives well after T^*) gains $\bar{v}(T) - \bar{u}(T)$. However, there are two groups of losers. First, early adopters lose $\bar{u}(T) - \bar{v}(T)$ if they adopt V. Second, users who are stuck with old installed-base technology suffer a loss at the time that V is adopted. Evaluated at T^* that loss is equal to $\bar{u}(T^*) - \tilde{u}(T^*)$ for each user in the installed base. This is the present value of the loss to U users resulting from the fact that the U network ceases to grow after T^*. In the linear case that is equal to b/r^2 for each user, or a total of bT^*/r^2.

The present value of the net gain in welfare from the adoption of V is

$$G \equiv \int_{T^*}^{\infty} [\bar{v}(t) - \bar{u}(t)] e^{-r(t-T^*)} dt - bT^*/r^2.$$

The first term represents the gain (loss) to users who arrive after T^*, while the second term is the loss to the installed base. Rewriting,

$$(4) \quad G = \int_{T^*}^{\infty} \left[\frac{c + d(t - T^*)}{r} + \frac{d}{r^2} - \frac{a + bt}{r} - \frac{b}{r^2} \right] e^{-r(t-T^*)} dt - \frac{bT^*}{r^2}$$

$$= \int_{0}^{\infty} \left(\frac{d\tau}{r} - \frac{b}{r}(\tau + T^*) \right) e^{-r\tau} d\tau + \frac{d-b}{r^3} - \frac{bT^*}{r^2} + \frac{c-a}{r^2}$$

$$= \frac{2(d-b)}{r^3} - \frac{2bT^*}{r^2} + \frac{c-a}{r^2}$$

$$= [2(d-b) - 2rbT^* + r(c-a)]/r^3.$$

Thus $G > 0$ if and only if $2(d-b) - 2rbT^* + r(c-a) > 0$.

We now compare this efficiency condition with equilibrium conditions. Adoption is an equilibrium if $\bar{v}(T^*) \geq \tilde{u}(T^*)$, which in the linear case reduces to

$$(5) \qquad r(c-a) - rbT^* \geq -d.$$

Adoption is the unique equilibrium if $\tilde{v}(T^*) > \bar{u}(T^*)$, which reduces to

$$(6) \qquad r(c-a) - rbT^* > b.$$

From (4), (5), and (6) we see that $(c-a, bT^*)$ space can be divided as in Figure 2. Depending on how d compares with $b/2$ and with $2b$, we have three cases.

Case 1: $2(d-b) > d$ (i.e., $d > 2b$). The $G = 0$ curve intersects the vertical axis below $(-d/r)$. This creates a region (region A) in which switching is efficient but is not an equilibrium: clear-cut excess inertia. In this region, $(c-a)$ is sufficiently negative to put off early potential adopters of V, but is not so negative as to make a switch socially inefficient.

Case 2: $(-d/r) < -2(d-b)/r < b/r$ (i.e., $b/2 < d < 2b$). There is no unique-equilibrium excess inertia (region A vanishes), but it is possible that nonadoption is

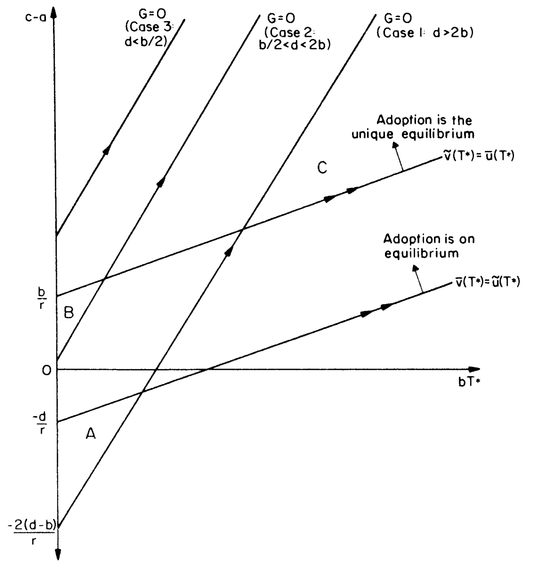

FIGURE 2: EFFICIENCY AND EQUILIBRIUM IN THE LINEAR CASE

an equilibrium even though adoption would be efficient. This occurs in region *B*.

Case 3: $-2(d-b)/r > b/r$ (i.e., $d < b/2$). There is *never* excess inertia (even region *B* vanishes): if adoption is efficient, then it is the unique equilibrium.

We also see from Figure 2 that there is always the possibility of excess momentum (region *C*): adoption is inefficient but is the unique equilibrium. This occurs when both bT^* (the installed base) and $(c-a)$ (the network-independent advantage of the new technology) are large. Then, *V* is adopted, and the installed base is inefficiently "stranded."

PROPOSITION 2: *In the linear case,*

(*i*) *If* $d > 2b$, *then there is a region in which adoption would be efficient but is not an equilibrium. There is excess inertia.*

(*ii*) *If* $b/2 < d < 2b$, *then adoption is an equilibrium wherever it is efficient. However, it need not be the unique equilibrium. There may be excess inertia.*

(*iii*) *If* $d < b/2$, *then adoption is the unique equilibrium whenever it is efficient. There cannot be excess inertia.*

(*iv*) *If the installed base and the network-independent superiority of V are both large, then there is unambiguous excess momentum: adoption is inefficient but it is the unique equilibrium.*

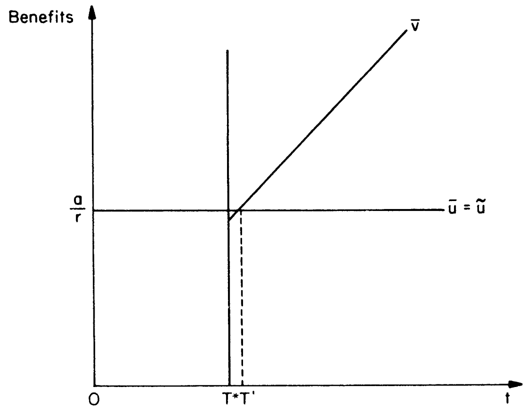

FIGURE 3: AN EXAMPLE OF EXCESS INERTIA

Although this analysis applies only to the linear case, it is instructive. It suggests that clear-cut excess inertia (inefficient nonadoption being the unique equilibrium) may be exceptional,[14,15] but it can arise. An extreme case is presented in Figure 3. Here there are no network benefits to the existing technology: $\bar{u} \equiv \tilde{u}$. Furthermore, the first potential user of the new technology *V* has only a slight preference for the old technology *U* ($\bar{v}(T^*) < \tilde{u}(T^*)$). However, even this slight preference causes him to adopt the old technology. All later users face the same

[14]The intuition for this result is the following. For it to be certain that the innovation will fail, it must be the case that $\bar{v}(T^*) < \tilde{u}(T^*)$, i.e., $rbT^* > d + r(c-a)$. This means that *d* cannot be too large. This can be seen by referring to Figure 1: as *d* grows so does $\bar{v}(T^*)$, eventually leaving the range where nonadoption is the unique equilibrium. However if *d* is small, the advantage of the new technology over the old is reaped only in the distant future, where discounting renders it less valuable. Of course, a higher value of *d* is possible (while still maintaining the inequality $\bar{v}(T^*) < \tilde{u}(T^*)$) if either *r* or T^* is large. However, if T^* is large, the loss to the installed base is also large, while if *r* is large, the benefits from the new technology (which are reaped only in the future) are also correspondingly less valuable.

[15]In our earlier paper (1986), we reach a similar conclusion in a static model in which users have different preferences over *U* and *V*.

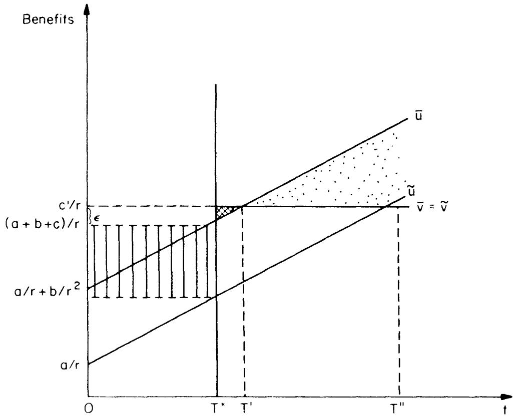

FIGURE 4: AN EXAMPLE OF EXCESS MOMENTUM

choice and make the same decision. Thus, V is not adopted although it would clearly be welfare enhancing.

"Excess momentum" can also arise. For example, consider the linear case and suppose that $c \equiv [a + bT^* + (b/r) + r\varepsilon]$ and $d = 0$. In that case $\bar{v}(t) = \tilde{v}(t) = c/r$, $\bar{u}(T^*) = ((a + bT^*)/r) + (b/r^2)$ and $\tilde{v}(T^*) - \bar{u}(T^*) = \varepsilon$. Thus for any $\varepsilon > 0$, the unique perfect equilibrium is that V is adopted. The situation is illustrated in Figure 4. The (undiscounted) gain to adopters from adoption of V is the shaded triangle (the discounted gain is even smaller). The loss to the installed base from the adoption is the shaded rectangle. There is also a loss to later adopters (dotted region). Since the shaded triangle can be made arbitrarily small (by shrinking ε) there obviously can be excess momentum. Indeed, it is possible that the losses are quite large and the gains minuscule, and yet V is adopted!

C. *Anticompetitive Behavior: Product Preannouncements and Predatory Pricing*

1. *Product Preannouncements*. So far, we have assumed that the new technology V becomes available unexpectedly. However, if potential users learn in advance (via a "product preannouncement," say) that V will become available, they may wait for it rather than adopt U immediately. But then V's installed base will start off much larger than otherwise. It is therefore possible that a technology V will be adopted with such a product preannouncement that would not have been adopted otherwise. Without the preannouncement, the old technology might have developed an unstoppable momentum, whereas the preannouncement can prevent this "bandwagon effect."

Below, we provide conditions under which nonadoption is the unique equilibrium with no preannouncement, but adoption is an equilibrium with the preannouncement. Furthermore, if we modify the model slightly so that users are discrete rather than infinitesimal, then adoption is the *unique* equilibrium with the preannouncement. We also give an example in which the preannouncement reduces welfare.

Suppose that a preannouncement is made at $T^* - \tau$ for a new technology V that will become available at T^*. Assume that users in the interval $[T^* - \tau, T^*]$ who wish to do so can prepurchase technology V. (In practice, popular new products often have delivery lags and it is desirable to order in advance.) For simplicity, we assume that $n(t)$ is constant. Then if all potential users in the interval $[T^* - \tau, T^*]$ adopt V, and all later users also adopt V, the net present value of adopting V at $t \geq T^*$ is $\tilde{v}(t + \tau)$. (This is the value it would have been at $T^* + \tau$ with adoption but without the preannouncement.) We can show

PROPOSITION 3: *If (i) $\bar{v}(T^*) < \tilde{u}(T^*)$ and (ii) $\tilde{v}(T^* + \tau - t')e^{-rt'} > \bar{u}(T^* - t')$ for all $t' \in [0, \tau]$, then*

(a) *Without the preannouncement, nonadoption is the unique equilibrium;*

(b) *With the preannouncement, adoption is an equilibrium.*

(c) *If, in addition, users are discrete, then with the preannouncement, adoption is the unique equilibrium.*

Assumptions (i) and (ii) are illustrated in Figure 5. When all the potential users between $(T^* - \tau)$ and T^* adopt V, the $\bar{v}$ and $\tilde{v}$ curves are "shifted to the left" by τ. The outlook for a potential user at $T^* + t$ absent the preannouncement is the same as the outlook of a potential user at $T^* + \tau + t$ with the preannouncement.

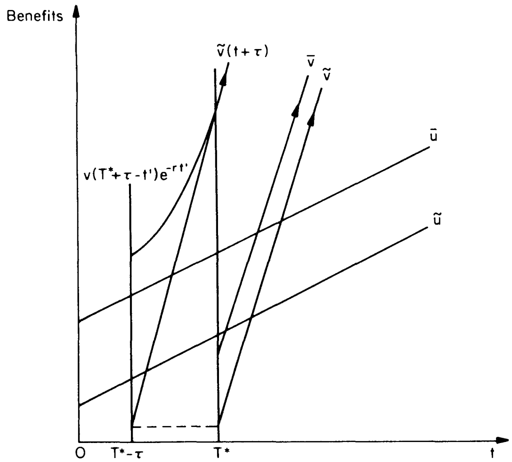

FIGURE 5: THE EFFECT OF A PREANNOUNCEMENT ON ADOPTION

PROOF OF PROPOSITION 3:

Assumption (*i*) implies (a) and assumption (*ii*) implies (b), both by Proposition 1. The proof of (c) uses the backwards induction argument of Proposition 1 of our earlier paper (1985) (see also fn. 2 above). Briefly, the argument is as follows: If all users from $T^* - \tau$ to T^* adopt V, then so will all later users. So consider the user who arrives "just before" T^*. If all prior users have adopted V, then so will he (since V will then be adopted by all later users). The backwards induction argument now applies the same reasoning to the previous arrival, and so on backwards.

Thus preannouncements can be powerful. We now show that they may be harmful.

PROPOSITION 4: *The preannouncement may reduce welfare, even though the conditions of Proposition* 3 *hold.*

PROOF:

We construct a linear example as follows: First, assume that $b < r$. Let $\tau \equiv \inf\ \{t'\colon \bar{u}(T^* - t') < \tilde{u}(T^*) - \varepsilon\}$ for some (arbitrarily small) ε. Second, let

$$v(x) = \begin{cases} 0 & \text{if} \quad x \leq \tau; \\ c' & \text{if} \quad x > \tau \end{cases}$$

(The new technology is valueless if the network size is less than τ and generates a benefit flow c' otherwise.) Now set c' so that $(c'/r)e^{-r\tau} > \bar{u}(T^* - \tau)$. Then $(c'/r)e^{-rt'} > \bar{u}(T^* - t')$ for all $t' \leq \tau$. Thus the conditions of Proposition 3 are satisfied. Notice that because u is linear, this construction can be carried out for any T^*. One can check that the welfare gain (evaluated at T^*) to adopters of the new technology is bounded above and is independent of T^*. However, the welfare loss to the installed base is $T^*[\bar{u}(T^* - \tau) - \tilde{u}(T^* - \tau)] = T^*b/r^2$, which can be made arbitrarily large by increasing T^*.

We have argued that a preannouncement may reduce welfare. Dominant firms have often faced antitrust charges of "anticompetitive" product preannouncements. (See fn. 6 above.) In the above analysis we have made pricing exogenous, and so our model does not yet show that the welfare-reducing preannouncements can be anticompetitive. However, it is a simple matter to complete the argument.

Suppose that the old technology U is provided competitively and that the u function represents consumers' benefits, given competitive pricing. Suppose further that the new technology V is provided by a monopolist and that the v function represents the benefit to consumers when the monopolist prices so as to maximize profits assuming that his proprietary V technology will be adopted. Under the assumptions of the example, absent a preannouncement, the monopolist's product will fail to be adopted. Of course, the monopolist might be able to induce adoption by offering a discount until V has become widely enough adopted. However, the preannouncement achieves the same result costlessly. Competition is destroyed and welfare may also be reduced.

The preannouncement is likely to be most effective where the current technology could otherwise greatly increase its network value in a short time between announcement time and introduction. Then the preemptive effect of the preannouncement will be crucial. So, especially when targeted against a fledgling technology, the preannouncement may well be anticompetitive.

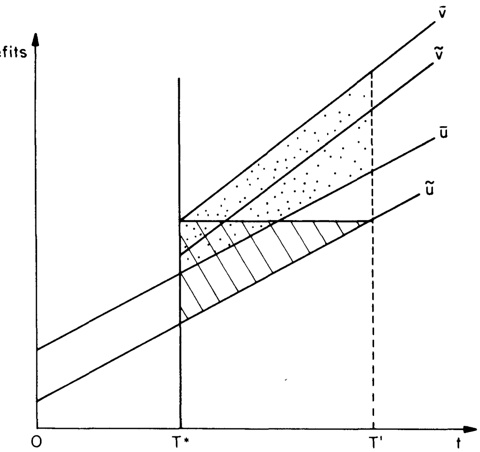

FIGURE 6: THE COST OF PREDATION

2. *Predatory and Strategic Pricing*. We consider the case in which the existing technology is provided by a monopolistic incumbent. We show below that if technology V is introduced, it may be both feasible and profitable for the incumbent to prevent the adoption of V by temporarily charging less than the monopoly price. By doing so, it can continue to build up its installed base and achieve an insurmountable lead, whereas absent such strategic pricing, V would be adopted. This strategic pricing is analogous to "penetration pricing" as analyzed by Katz and Shapiro (1986).

Suppose that when the incumbent sets its profit-maximizing prices over time (assuming no new technology), the flow of net benefits to users is given by the u function. Suppose further that the new technology V will be competitively supplied and that the v function represents benefits net of the competitive price. Finally, suppose that u and v are as shown in Figure 6.

Since $\tilde{v}(T^*) > \bar{u}(T^*)$, adoption is the unique equilibrium absent strategic pricing. But the incumbent can induce the user who arrives at T^* to stay with U by reducing the price of U by (just over) $\tilde{v}(T^*) - \tilde{u}(T^*)$. Then that user would prefer being the last user on U to being the first user of V, even if all later users adopt V. If the incumbent provides such a discount to all the users who arrive between T^* and T', it will then become impossible for V to enter (since $\tilde{v}(T') < \tilde{u}(T')$), *even if the incumbent then prices without regard to entry.*

The (undiscounted) cost to the incumbent of this strategy is given by the shaded area. Depending on the parameters of the model, the benefits may well exceed the costs, although in the short run the monopolist sacrifices profits. The private costs of pricing strategically are not the same as the social costs. The cost to the monopolist occurs through price reductions which are merely transfers to users. The social costs are the costs to users who arrive after T^* from the fact that the new technology is not adopted. The social benefit is that the installed base is protected against "stranding." Thus the welfare effects are ambiguous.

The sole purpose of the incumbent's pricing policy is to drive its rivals out of the industry and it may involve a short-run sacrifice of profits. Moreover, the monopolist can raise its price once the rivals have left the industry, without inducing reentry, even if there are no entry or exit costs. This is because if the incumbent fights off entry until T', it thereafter has an insurmountable advantage of installed base. If, in addition, welfare is reduced by the action, this is a classic case of predatory pricing.

Two leading tests for diagnosing predatory pricing may miss this kind of predation, however. The test proposed by Philip Areeda and Donald Turner (1975), which diagnoses predation if the firm prices below average variable cost, can yield a false negative: if the network benefits of installed base are sufficient, this kind of predation does not require pricing below the incumbent's, *or the entrants'*, average variable cost.

Janusz Ordover and Robert Willig's (1981) test asks whether the firm's action would have been optimal if the entrant faced no reentry costs. If so, then the action is deemed not to be predatory. Reentry costs are defined as "the cost that a firm that has exited a market must incur to resume production" (p. 12). Here, however, "reentry costs" are not the point. The opportunity to supplant the monopolist is only available until time T'. Through its predatory action, however, the incumbent closes this window of opportunity.[16] This evanescence of opportunity is assumed away in the Ordover-Willig test. Thus this test may also yield a false negative.

Thus we see that, on the one hand, standard tests may miss this kind of predation. On the other hand, if the stranding externality is important enough, the strategic pricing may be welfare enhancing. Because of this, it would be extremely difficult (if not impossible) to frame a legal rule that would make the correct diagnosis in all cases. What our analysis suggests, however, is that a greater than usual degree of caution is required in cases where "a window of opportunity" is important.

II. A Model without New Users

In this model, two agents, 1 and 2, are initially using a preestablished standard or technology, U. Another technology, V, is available; however, each agent has only occasional chances to switch. To be precise, each agent encounters switching opportunities randomly in a Poisson process with rate $\lambda > 0$.

An agent with a chance to switch faces the following choice. If he (or she) switches, then he knows that the other agent will not immediately be able to switch, so that they will be incompatible for a while. If he does not switch, then the other may or may not choose to switch at his next opportunity. We will consider agents' private incentives to switch or not to switch, and the nature of the externalities involved.

We write $u(k)$ for each agent's flow of net payoff if he is on standard U alone ($k=1$), or together with the other agent ($k=2$). Likewise, we define $v(k)$. Notice that this assumes that the firms' payoffs are symmetric.

As above, we interpret the two "agents" as *users* of the technology. If one of them switches, they become incompatible (because the other cannot immediately switch). In this interpretation, "installed base" is the non-switcher. It is natural to assume that network externalities are positive:[17]

$$(7) \qquad u(1) < u(2)$$

$$(8) \qquad v(1) < v(2).$$

For notational convenience, we normalize $u(2)$ at 0.

A. *Efficiency*

It should be clear that the efficient rule is either never to switch, or to switch as soon as possible. Which is better?

Suppose that agent 1 has a switching opportunity at a time we call $t=0$. Let $\tilde{t}$ be the (random) next switching opportunity for agent 2. Then the social value of switching is

$$(9) \qquad \int_0^{\tilde{t}}[v(1)+u(1)]e^{-rt}dt+\int_{\tilde{t}}^{\infty}2v(2)e^{-rt}dt$$

$$(10) \qquad =[v(1)+u(1)]((1-e^{-r\tilde{t}})/r) + 2v(2)(e^{-r\tilde{t}}/r).$$

It is well-known that

$$(11) \qquad E(e^{-r\tilde{t}})=\lambda/(r+\lambda).$$

[16] As time passes and the installed base grows, the barriers to entry rise and the incumbent becomes more protected. In our setting this is due to the benefits from compatibility; more generally, the same will be true where brand recognition or a product's reputation are important in determining consumer choice. Learning by doing will have a similar effect.

[17] In a second interpretation, our two agents are competing *suppliers* of a durable good embodying technology U or V. Buyers are concerned with network externalities: in particular, with compatibility with the installed base of equipment. If this network effect is strong enough, it may be the case that

$$(a) \qquad u(1) > u(2).$$

Also, if the installed-base effect is *not* so strong, so that buyers begin to buy the new technology as soon as it is available, there may be a *first-mover advantage*:

$$(b) \qquad v(1) > v(2).$$

Both (a) and (b) are influenced by buyers' expectations of whether the new technology will succeed, and by the relative sizes of the two suppliers.

Thus the expected social value of switching is

$$\frac{v(1)+u(1)}{r+\lambda}+\frac{2v(2)(\lambda/r)}{r+\lambda}. \tag{12}$$

In other words, we get

PROPOSITION 5: *Switching is socially efficient if and only if*

$$v(1)+u(1)+\lambda\frac{2v(2)}{r}\geq 0. \tag{13}$$

Equation (13) has a straightforward interpretation. Suppose a firm switches. The net social benefit has two components. The immediate change in benefit flow is $v(1)+u(1)-2u(2)$, or $v(1)+u(1)$. In addition, there is an instantaneous probability λ of achieving a joint switch which is worth $v(2)/r$. The qualitative properties of (13) are not surprising. For example, if $v(2)<0$ then, by assumption, $v(1)<0$. Since in any case $u(1)<0$, switching is not efficient. If $v(2)>0$ then switching is more desirable as λ increases (less time is spent incompatibly in transition) or as r decreases (transition effects are less important).

B. *Equilibrium*

As in Section I, our chief concern is to investigate when equilibrium will be efficient, when there will be excess inertia, and when there will be excess momentum.

We ask first in what circumstances a user will be willing to switch first. As we will see, the answer depends on whether he expects that the other would be willing to switch first.

LEMMA 1: *A user will be prepared to switch first when he believes that the other user would switch first, if and only if*

$$(\lambda+r)v(1)+\lambda[v(2)-u(1)]\geq 0. \tag{14}$$

PROOF:

Since we assume $v(2)>u(1)$, a user who switches first will always be followed as soon as possible. Therefore we can use the method of (10)–(12) to show that the payoff to switching first is

$$(r+\lambda)^{-1}[v(1)+(\lambda/r)v(2)]. \tag{15}$$

The payoff to waiting is a flow of 0 until the other user switches, then a flow of $u(1)$ until it is possible to follow. The value of this is

$$\frac{\lambda}{(r+\lambda)}\frac{1}{(r+\lambda)}[u(1)+(\lambda/r)v(2)]. \tag{16}$$

Comparing (15) and (16) yields (14).

LEMMA 2: *When a user believes that the other will never switch first, he will switch first, if and only if*

$$rv(1)+\lambda v(2)\geq 0. \tag{17}$$

PROOF:

If he does not switch, he gets zero forever. If he does, he gets $v(1)$ until the other user follows. By the method of (10)–(12), the present value of this is

$$\frac{v(1)}{r}\frac{r}{r+\lambda}+\frac{v(2)}{r}\frac{\lambda}{r+\lambda}.$$

Condition (17) follows immediately.

LEMMA 3: *If both* (14) *and* (17) *hold, then a user will switch first whatever his beliefs about whether the other would do so. If neither* (14) *nor* (17) *holds, then a user will never switch first, whatever his beliefs about the other's willingness to do so.*

PROOF:

Suppose that agent 1 regards the time at which agent 2 will switch (if 1 does not switch first) as a random variable $\tilde{s}$. We write $\tilde{s}=\infty$ if 2 never switches first. If 1 does not switch first, then he gets a flow $u(2)\equiv 0$ until the random time $\tilde{s}$, at which point his present discounted value becomes

$$E\left\{\int_0^{\tilde{t}}u(1)e^{-rt}dt+\int_{\tilde{t}}^{\infty}v(2)e^{-rt}dt\right\} \\ =(r+\lambda)^{-1}(u(1)+(\lambda/r)v(2)) \tag{18}$$

where $\tilde{t}$ is the (random) elapsed time after $\tilde{s}$ before agent 1 has his next switching opportunity. Thus, at time 0, the expected present value of the "wait" strategy is

$$(19)\quad E[e^{-r\tilde{s}}](r+\lambda)^{-1}(u(1)+(\lambda/r)v(2)).$$

Finally, we note that $\tilde{s}$ cannot occur before agent 2's first switching opportunity, so that, by (11),

$$(20)\qquad 0 \le E[e^{-r\tilde{s}}] \le \lambda/(r+\lambda).$$

Using (20) and comparing (15) and (18), we see that (14) and (17) together make switching optimal whatever a user's expectations. The proof of the other half of the lemma is similar.

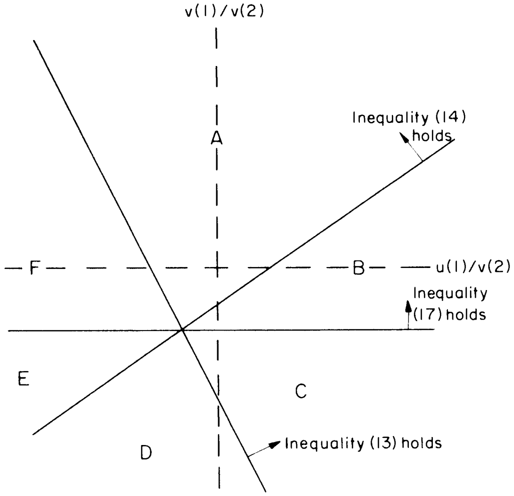

FIGURE 7: EFFICIENCY AND EQUILIBRIUM

From the lemmas, we see that (given r and λ) the space of possible values of $u(1)/v(2)$ and $v(1)/v(2)$ divides into four regions, according to whether (14) and/or (17) holds. Adding the efficiency condition (13) to the picture yields Figure 7. We label the resulting six regions of the parameter space A to F. Switching is efficient in regions A, B, C; inefficient in regions D, E, F. What does equilibrium look like?

In region A, (14) and (17) both hold. By Lemma 3, a user will switch as soon as possible, *whatever* he thinks the other would do (switch first, or wait). In this region, therefore, there is a unique (and efficient) perfect equilibrium: switching occurs as soon as possible.

In region B, (17) holds but (14) fails. This means that a user will switch first if he thinks the other would not, but would wait if he thinks the other would switch first. In this region, therefore, there are three perfect equilibria. In the first, user 1 is expected to (and will) switch as soon as he can, and user 2 will only follow. In the second, the roles are reversed. In the third equilibrium, each user plays a mixed strategy: he is just likely enough to switch first to make the other indifferent between switching first and waiting.

In each of these equilibria, switching occurs eventually, but is (on average) delayed. Fortunately, if r is large relative to λ (the case where delay matters), region B is small: (14) and (17) almost coincide.

In region C, both (14) and (17) fail. This means that neither user will switch first, whatever his beliefs about the other's willingness to switch first. Therefore switching never occurs, although it would be efficient to switch. This is the clearest kind of excess inertia. From (14) and (17), we see that this outcome is most likely when $v(1)$ is small and $u(1)$ is not too small.

In region D, (14) and (17) both fail: there will be no switching. Region D differs from region C in that this outcome is efficient in D.

In region E, (14) holds but (17) fails. So a user will switch first if and only if he thinks the other would do so. There are two pure-strategy equilibria. In one, there is no switching, and this is efficient. In the other, each user will switch at his first chance. However, this is only because if he does not switch he believes he will have to follow the other's switch. Such a *preemption equilibrium*[18] can

[18] If switching opportunities are observable, we can argue against the preemption equilibrium as follows. If 2 expects 1 to switch first, but observes him refraining from doing so, we might expect him to infer that 1 will not switch first, rather than inferring that 1 will *now*

arise even if $v(2)$, as well as $u(1)$ and $v(1)$, is negative.

In region F, (14) and (17) both hold: switching will occur as soon as possible, although it is inefficient. This is a clear case of excess momentum.

What causes these inefficiencies? The fact that there will be a period of incompatibility is not itself the source of an externality, but the difference between $v(1)$ and $u(1)$ is. In switching, a user calculates whether it is worth suffering $v(1)$ for a while in order to achieve $v(2)$ later; for efficiency, he should ask about suffering $[v(1)+u(1)]/2$. If $v(1) > u(1)$, then a user will be too ready to initiate a switch; if $v(1) < u(1)$, he will be too reluctant.

Second, there is the penguin effect (see fn. 9). Even though the users might *both* wish for a joint switch *whoever* goes first, it may still be that each would prefer the other to go first. This leads to the kind of excess inertia that occurs in region B. Conversely, it is possible that neither user wants a switch, but each prefers to switch first rather than second: this leads to preemption equilibrium.

III. Conclusions and Possible Extensions

There can be excess inertia, even with complete information, when we allow for the presence of an installed base. There are two externalities in a user's adoption decision: the stranding effect on the installed base, and an effect on the options available to later adopters. Since our previous model (in our 1985 paper) is essentially "timeless," the installed-base externality is absent. In that setting, identical adopters always reach the efficient outcome. In the present paper, installed-base users are somewhat tied to the old technology; this creates a bias against the new (perhaps superior) technology. Another inefficiency arises from the penguin effect.

The biases we identify can be turned to anticompetitive uses. We analyzed two: anticompetitive product preannouncements, and predatory pricing. First, product preannouncements may prevent a bandwagon from gaining momentum. Second, an incumbent firm may be able to deter entry by a credible threat of temporary price cuts in response to entry. This is so even when there are no reentry costs.

There are a number of ways in which the models could be generalized and extended. In the model with new users, we assumed that users live forever and products do not depreciate. Realistically, an installed base, once stranded, will shrink. The welfare cost of excess momentum will then be lower than in our model.

We could also examine the effect of a nonconstant arrival rate of new users. We would expect that if there is an unusual upturn in demand, perhaps because of a baby boom or an economic recovery, an innovation could gain a substantial network relatively quickly. Innovations may therefore be concentrated in such periods. Similarly, the destruction of installed base by war may clear the decks for innovation.

In the second model, the most interesting extensions would make the users asymmetric, either in the frequency with which they consider switching or in the value they attach to compatibility. Large firms plausibly care less about compatibility with small rivals than vice versa, and we therefore expect them to be de facto standard setters. Likewise, an agent who only rarely has a chance to switch may find his more flexible rival waiting for him to do so.

Another line of inquiry would consider multiple users in the second model. With equal-sized users, the first switcher sacrifices more in network benefits if there are many users. His strategic bandwagon power is also likely to be less. One might expect, therefore, that excess inertia will be a more serious problem in this case. This extension would form a close link with our earlier paper (1985). It would be equivalent to allowing stochastic decision lags, random order of

switch as soon as possible. If 1 believes that 2 would update as we suggest, then he can stop 2 from switching by refraining himself. Thus, for preemption to be a perfect equilibrium, updating after an unexpected failure to switch must take the form "I'm surprised you didn't switch; but I still expect you to switch at your next chance."

moves, and interim payoffs in that model. We believe that these are promising directions for further investigation.

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