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Lock in and switch: Asymmetric information and new product diffusion

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Abstract Many new web-based services are introduced as free services. Depending on the seller's business model, some remain free in the long run, while others switch to pay mode at some point in time. I characterize the relation between buyers and a new service seller when the former are uncertain about the latter's business model and need to incur a one-time sunk cost before enjoying the new service. I derive a natural signaling equilibrium where the seller plays a "lock-in-and-switch" strategy, while buyers play a "wait-and-see" strategy. Specifically, a high-cost seller starts by pricing at zero and waits for a sufficient number of consumers to adopt the new service, at which point the seller switches to pay mode. In this gradual separation equilibrium, the signal is given not by the price level (which always starts at zero) but rather by the duration of the introductory offer. Finally, I show the equilibrium entails diffusion even though consumers are identical and equally aware of the new service's existence.

Keywords Diffusion · Asymmetric information

JEL Classification D11 · D21 · D82 · L11 · L12

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1 Introduction

The economic and social impact of the Internet can hardly be overstated. One of the many effects of the "information highway" is the wealth of new services that it allows for—sometimes web-based versions of existing services, sometimes entirely new services. Examples include web-based email, news, blogging, on-line radio and TV; and various types of organized information (dictionaries and encyclopedias, directions, restaurant reviews, financial information, and so forth).

Frequently, new services are offered for free. Examples include JumpTV, Vindigo, AvantGo and Google mail. However, a zero introductory price is not necessarily a permanent feature: at some point, Vindigo and JumpTV started charging for their services; AvantGo and Google mail are still free.[1]

The variety of pricing strategies reflects the variety of business models followed by new service suppliers. Sometimes revenues are primarily based on consumer subscription fees, in which case a zero introductory price is most likely a temporary offer. In other cases, revenues are primarily based on advertising or referral fees charged to third parties, in which case consumers can expect zero prices to be a permanent feature. In most cases, however, revenues are a combination of advertising and subscription revenue. In fact, it is common for sellers to offer two options, a free option and a pay option, with different levels of service and advertising included.

From a consumer's point of view, whether to start using one of these services is a difficult decision problem. A starting cost must normally be incurred: getting acquainted with how the service works, downloading software, perhaps making some complementary investment. Against this cost—typically a one-time sunk cost—potential adopters must weigh an uncertain benefit: perhaps the service will be offered for free indefinitely, perhaps the seller will start charging for it at some point in time.

In this paper, I characterize the strategic interaction between seller and buyers in a situation of asymmetric information. Consumers are uncertain about the seller's business model, a feature that I model by assuming the seller can be of two types: H and L. A type H seller, under complete information, would optimally set a strictly positive price—the seller's business model is to charge consumers. A type L seller, in turn, has marginal cost sufficiently negative that its optimal price is zero. The idea of a negative marginal cost captures the business model whereby sellers earn revenue from a third party either in the form of advertising or business referrals.

I consider a "natural" Bayesian equilibium and show that it involves gradual separation between the two seller types. For a period of time, sellers pool at a price of zero. Eventually, a high-cost seller type switches to its monopoly

[1] AvantGo offers a premium service for a fee. In Section 5, I consider the case when a seller's set of options extends beyond the choice of free and pay modes.

price. Until then, potential adopters gradually enter, by paying the necessary sunk cost and thus becoming "locked-in" to the seller.

In other words, the seller—in particular the high-cost seller—plays a "lock-in-and-switch" type of strategy: set prices at zero, wait while buyers gradually come in, then switch to pay mode. Buyers, in turn, play a "wait-and-see" strategy: wait while price is at zero and gradually update the belief that the seller's business model is one of charging third parties, not the buyers. In this semi-separating equilibrium, the signal is given not by the price level (which always starts at zero) but rather by the duration of the introductory offer.

Previous economic research has dealt with new product introduction under asymmetric information. This literature typically derives separation equilibria, whereby the introductory price indicates to consumers the firm's level of cost or quality. If the length of commitment to price is very short, however, than no pure separation equilibrium exists. I focus in the case of no commitment to prices by considering the extreme case of continuous time; and show that a "gradual separation" equilibrium exists, whereby sellers pool at zero price for a while and the high cost seller eventually switches to a positive price.

One of the interesting characteristics of the equilibrium I consider is diffusion. Specifically, even though all consumers are identical and equally aware of the existence of the new service, different consumers adopt the new service at different moments in time. In this sense, I provide an explanation for diffusion that differs from the traditional models based on word-of-mouth effects or consumer heterogeneity.

2 Model

The central players in my model are a seller and a continuum of consumers. I am interested in examining the case when the seller has no ability to commit to future prices. In order to do so, I consider the extreme case of continuous time and assume the seller must set $p(t)$ for all $t \in [0, \infty)$. I also assume that both seller and buyers discount the future according to an interest rate r.

All consumers have the same utility function. In order to start using the new service, a consumer must pay a sunk cost s/r, so that s represents the equivalent flow of cost the new consumer must commit to. Upon adoption, a consumer receives a surplus rate of $\mu(p)$ at each moment in time, where p is price at that moment in time. (I could consider a more complicated model including the decision of how much to consume of the service, but all that I need is the value of consumer surplus as a function of price.)

A central feature of the model is incomplete information: consumers are uncertain about the seller's business model.[2] I model this feature by assuming that the seller can be of two types: H and L. A type H seller has zero marginal

[2]By contrast, Hitsch (2006) , among others, considers the case when the seller is uncertain about demand.

cost. Given a set of consumers and complete information, an H seller would optimally set a strictly positive price—the seller's business model is to charge consumers. A type L seller, in turn, has marginal cost sufficiently negative that its optimal price is zero.[3] The idea of a negative marginal cost captures the business model whereby sellers earn revenue from a third party either in the form of advertising or business referrals. Note that an optimal price of zero is not a knife-edge situation as long as negative prices are not feasible. The assumption is then that the seller's cost is sufficiently negative that the optimal price (under complete information) would be negative.[4]

The seller's type is the seller's private information; consumers only know the distribution of types, holding a prior α that the seller is of type L. Let $\pi^\star$ be a type H seller's profit per consumer if it sets its (static, complete information) optimal price. (Notice that, since all consumers are identical, optimal price is independent of the number of consumers.) Let μ° be consumer surplus under zero price, and $\mu^\star$ consumer surplus when price equals seller H's optimal price. Both π and μ are measure as flows. I make a fundamental assumption regarding consumers' adoption cost in relation to consumer surplus:

Assumption 1 $0 < \mu^\star < s < \mu^\circ$.

In words, consumers derive a positive benefit from using the service, but not high enough always to justify adoption. Specifically, under complete information consumers would not buy from a high-cost seller, but they would from a low-cost seller. If this assumption is violated, then the problem is trivial. Specifically, if s is lower than $\mu^\star$ then the only equilibrium is for all potential adopters to adopt at time zero. If, on the other hand, s is greater than μ°, then the only equilibrium is for consumers never to adopt.

3 Diffusion equilibrium

My main result is that there exists a sensible equilibrium to the game presented in the previous section. In this equilibrium, a type H seller sets zero price for some time and then switches to its optimal static monopoly price. Consumers, in turn, gradually pay the "entry" cost required to benefit from the service. In other words, the seller plays a "lock-in and switch" strategy, whereas consumers play a "wait-and-see" strategy.

[3] Even if the optimal monopoly price is positive, there may be reasons why zero is a better pricing strategy. See Bawa and Shoemaker (2004), Shampanier et al. (2007).

[4] In some cases, negative prices are feasible and observed in equilibrium. For example, for a while PayPal paid consumers $10 for opening an account; and opentable.com (an online reservation and review site) sometimes provides dollar-off coupons for restaurants as a reward for using their service. The results in this paper follow through if there exists a finite lower bound to price, which may be negative. The important assumptions are that (1) the seller has no commitment to price beyond the current moment; and (2) the seller is unable to make a fixed transfer to the buyer.

In what follows, I first show that there exists a perfect bayesian equilibrium with the above features (Proposition 1). I then discuss other possible equilibria and argue by means of equilibrium refinements that my equilibrium is a sensible one (Proposition 2).

Proposition 1 *There exists a Bayesian equilibrium characterized by the following behavioral strategies. Let*

$$T = -\frac{(s-\mu^{\star})\,\ln\alpha}{(\mu^{\circ}-s)\,r}$$

where α is the initial belief the seller is of type L.

An L seller always sets zero price.

An H seller starts pricing at zero; for $t < T$ and conditional on having set zero price in the past, an H seller switches to monopoly price at time t with probability density

$$\theta(t) = -\frac{\ln\alpha}{T}\,\frac{\alpha^{t/T}}{\alpha-\alpha^{t/T}}$$

finally, for $t > T$ an H seller sets monopoly price.

For $t < T$ and conditional on having observed zero price in the past, a potential adopter enters with probability density

$$\lambda(t) = \frac{r\,\exp(r(t-T))}{1-\exp(r(t-T))}$$

For $t > T$, a potential adopter enters if and only if price is zero.

Proof of Proposition 1 In the equilibrium I consider, an L type seller always sets zero price. For the remainder of the proof, I focus on the H type seller and refer to it simply as seller.

In what follows, I derive a mixed-strategy equilibrium that leads to gradual separation. The seller switches to pay mode by time t with probability $F(t)$. Each consumer, in turn, adopts the new service by time t with probability $Q(t)$. Since there is a continuum of consumers of mass 1, $Q(t)$ is also the measure of consumers who adopt by time t.

By switching at time t, the seller expects a payoff of

$$\frac{1}{r}\,e^{-r\,t}\,Q(t)\,\pi^{\star}$$

During the period when the seller is indifferent, this must be constant in t. It follows that

$$Q(t) = Q(0)\,e^{r\,t} \tag{1}$$

Solving $Q(T) = 1$, where $Q(t)$ is given by Eq. 1, we get

$$Q(0) = e^{-rT}$$

and so

$$Q(t) = \exp(r(t - T)) \tag{2}$$

A consumer who plans to adopt at time t expects a discounted payoff of

$$\alpha\, e^{-rt}\, \frac{1}{r}\, (\mu^\circ - s) + (1-\alpha) \int_t^\infty e^{-rx} ((F(x) - F(t))(\mu^\star - s) + (1 - F(x))(\mu^\circ - s))\, dx$$

The first term represents the case when the seller is of type L, in which case the consumer enjoys zero price at all times after adoption. The second term corresponds to the case of an H type seller. With probability $F(t)$, the seller will have switched to pay mode by time t, in which case the consumer strictly prefers not to adopt. With probability $1 - F(t)$, price is still zero and the consumer adopts. At any time x subsequent to adoption, with probability $(F(x) - F(t))/(1 - F(t))$ the seller will have switched to pay mode, in which case the buyer receives a net flow of $\mu^\star - s$ (a negative flow); whereas, with probability $(1 - F(x))/(1 - F(t))$, the seller is still selling at zero price, yielding the consumer a positive utility flow of $\mu^\circ - s$.

During the period when consumers are indifferent concerning adoption time, this expression must be constant in time. Taking the derivative with respect to t and equating to zero we get

$$-\alpha\, e^{-rt}\, (\mu^\circ - s) - (1-\alpha)(1 - F(t))\, e^{-rt}\, (\mu^\circ - s) + (1-\alpha) \int_t^\infty e^{-xr}\, (s - \mu^\star)\, f(t)\, dx = 0$$

where $f(t)$ is the density function corresponding to $F(t)$. Simplifying, we get

$$(\mu^\circ - s)(1-\alpha)\, F(t) + (s - \mu^\star)(1-\alpha)\frac{1}{r}\, f(t) - (\mu^\circ - s) = 0$$

Solving with respect to $F(t)$, we get

$$F(t) = \frac{1}{1-\alpha} \left(1 - \exp\left(-\frac{\mu^\circ - s}{s - \mu^\star}\, r\, t\right)\right). \tag{3}$$

Equating $F(T) = 1$ and solving with respect to T we get

$$T = -\frac{(s - \mu^\star)\, \ln \alpha}{(\mu^\circ - s)\, r}$$

or

$$\frac{\ln \alpha}{T} = -\frac{\mu^\circ - s}{s - \mu^\star}\, r \tag{4}$$

Finally, substituting Eq. 4 in Eq. 3 and simplifying, we get

$$F(t) = \frac{1-\alpha^{\frac{t}{T}}}{1-\alpha} \tag{5}$$

The expressions in the proposition follow. Specifically, $\theta(t)$ is given by the derivative of $F(t)$ with respect to t divided by $1 - F(t)$; and $\lambda(t)$ is given by the derivative of $Q(t)$ with respect to t divided by $1 - Q(t)$. □

In order to better understand the nature of the equilibrium, Fig. 1 depicts the cumulative distribution functions of the seller and buyers' strategies. Specifically, $F(t)$ is the probability that an H type seller will have switched to pay mode by time t, whereas $Q(t)$ is the fraction of consumers who adopt by time t conditional on the service being offered for free up until then. The corresponding hazard rates,

$$\theta(t) \equiv \frac{f(t)}{1-F(t)}$$

and

$$\lambda(t) \equiv \frac{q(t)}{1-Q(t)}$$

are given by the expressions in the proposition. Notice that both the seller's and the buyers' hazard rates are increasing in t.

The equilibrium in Proposition 1 involves mixed strategies. I derive the equilibrium in the usual way: the seller's indifference condition implies an adoption path for buyers, and the buyers' indifference condition implies a price switch distribution. Specifically, in order for an H seller to be indifferent between switching to pay mode and continuing with zero price there must be a "promise" that by continuing with zero price the installed base will increase. Since the opportunity cost of keeping price at zero is greater the greater the installed base, the increase in installed base itself must be greater the greater

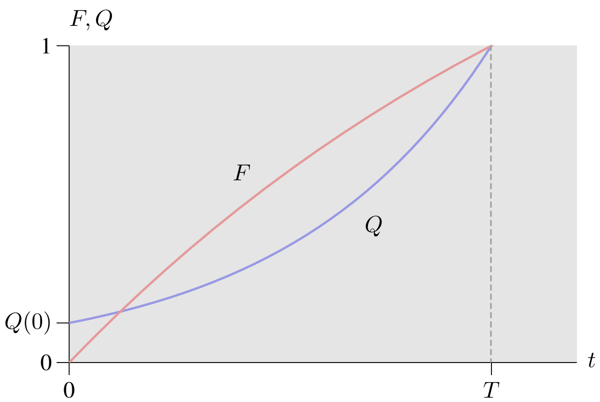

Fig. 1 Equilibrium cumulative distribution functions

the installed base. This implies an exponential growth path for Q, which is given by Eq. 2.

Conversely, in order for consumers to be indifferent between adopting now or at a future moment in time, F must be given by Eq. 3. (Or by Eq. 5), once I impose the boundary condition $F(T) = 1$.) The intuition for the expression of F is not immediately apparent. Note however that the hazard rate $\theta(t) \equiv f(t)/(1 - F(t))$, given in the text of Proposition 1, increases exponentially. This is intuitive as the value of $\theta(t)$ corresponds to the consumer's option value of waiting: by waiting for a period dt, there is a chance $\theta(t)$ that the seller will switch to pay mode, in which case the consumer will have optimally saved the sunk cost s/r. Now, the longer the service is offered for free the more convinced the consumer is that the seller's business model is one of zero price. In order to balance this increased value from adoption we must also increase the value of waiting—which we do by increasing θ.

Equilibrium properties and comparative statics It can be shown that F is concave and Q is convex (for $0 < t < T$), so the qualitative properties of Fig. 1 are general. Regarding the value of T, the comparative dynamics produce the expected results: T tends to zero as α tends to 1, and to infinity as α tends to zero. In words, if consumers initially believe that the seller's business model is to charge consumers (α close to zero) then consumers behave conservatively and an H type seller must keep price at zero for a long time in order to attract a significant measure of adopters. If, on the contrary, consumers believe that the seller's business model is to charge a third party, then an H type seller has an excellent opportunity for lock-in-and-switch: by setting price at zero for a relatively short period of time, many consumers will adopt, at which point the seller can profitably switch to pay mode.

Additional economically interesting comparative statics include that T is increasing in s and decreasing in μ°, $\mu^\star$. In words, the greater the cost of adopting the new service, the more cautious consumers are; and conversely, the greater the benefits from adoption, the quicker consumers are at adopting the new service. The comparative statics regarding the values of μ are not obvious because there are two effects to consider. First, the greater the difference $\mu^\circ - \mu^*$, the greater the option value from waiting. In this sense, an increase in μ° should lead consumes to wait for longer. However, there is an additional effect: the greater μ° is, the greater the opportunity cost from waiting. This latter effect dominates, so that the greater μ° is, the quicker consumers adopt the new service.

4 Equilibrium refinements and extensions

In this section I consider alternative equilibria to the one considered in Proposition 1. By means of equilibrium refinements, I also argue that the equilibrium I consider is a reasonable one. Next I consider possible model extensions and argue that the qualitative features of Proposition 1 are robust.

Alternative equilibria I can prove that there exists no equilibrium with separation at a time when $Q(t) < 1$. (In the equilibrium considered in Proposition 1 separation takes place exactly when $Q(t) = 1$, which happens at $t = T$.) Suppose such an equilibrium exists and let t' be the first moment in time when separation takes place. At that moment, if the price reveals the seller to be an L type then all remaining consumers (a positive measure) adopt the good instantly; whereas if the price reveals the seller to be an H type then no remaining consumer adopts the good. But this implies that a deviation by the H type, imitating the L type for an arbitrarily short period of time, would be profitable.

The above statement notwithstanding, the equilibrium I consider in Proposition 1 is hardly unique among the set of perfect Bayesian equilibria (PBE). In fact, the power of arbitrating off-the-equilibrium-path beliefs allows me to find a continuum of equilibria. In particular, consider equilibria of the same type as Proposition 1 where firms gradually separate from a pooling price $p > 0$ (as opposed to $p = 0$, the case considered in Proposition 1). If p is sufficiently low, then this constitutes a PBE. The indifference condition for an H seller is now given by

$$\int_0^t e^{-rx}\, Q(x)\, \pi_H(p)\, dx + \frac{1}{r}\, e^{-rt}\, Q(t)\, \pi_H(p_H^\star)$$

where $\pi_H(p)$ is profit flow per consumer for an H type when price is p. Solving for $Q(t)$, this yields

$$Q(t) = \exp\left(\frac{\pi_H(p_H^\star) - \pi_H(p)}{\pi_H(p_H^\star)}\, r\,(t - T)\right) \tag{6}$$

where T is given by $Q(T) = 1$.[5] The indifference condition for consumers can be derived in a way similar to Proposition 1, though the expressions are somewhat more complicated.

Although there are multiple gradual separation equilibria, I will next argue that pooling at zero is a natural equilibrium to select. To do so, I invoke an argument similar to the divine equilibrium refinement. This and other equilibrium refinements were developed for one-shot signaling games, not for continuous time games as the one in this paper. However, we can construct a "meta-game" as follows: the seller choses a gradual separation equilibrium by picking the introductory price p; consumers then update their belief that the seller is of type L; and the gradual separation equilibrium $\Gamma(p, \alpha)$ is played, where p is price and α the consumer's posterior that seller is an L type. Let $V_i(p, \alpha)$ be the seller's value of this game if the seller is of type i. Based on the analysis above, we conclude that V_i is increasing in α for both types; however, V_H is increasing in p, whereas V_L is decreasing in p.

Let $\mathcal{P}$ be the set of p values such that a gradual separation equilibrium $\Gamma(p, \alpha)$ exists (for all α). Consider the metagame $\mathcal{M}$ whereby consumers hold

[5] Note that, as expected, for $p = 0$ we get $\pi_H(p) = 0$ and Eq. 6 reduces to Eq. 2.

an initial prior α° that the seller is an L type and timing proceeds as follows: (1) the seller chooses p; (2) consumers choose beliefs α; (3) the equilibrium $\Gamma(p, \alpha)$ is played.

In this context, I say that an equilibrium (p, α°) of $\mathcal{M}$ fails the Cho and Kreps (1987) intuitive criterion if there exists a p' such that $V_L(p', 0) > V_L(p, \alpha^\circ)$; in words, if there exists a deviation price to which an L type would prefer to deviate even if it were taken for as an H type. Regarding the divinity refinement, I adapt the D1 criterion in Banks and Sobel (1987) as follows. Let $A_i(p')$ be the set of values of α such that $V_i(p', \alpha') \geq V_i(p, \alpha^\circ)$. In considering deviations from a proposed equilibrium (p, α°), divinity requires that, if $A_i(p')$ is strictly included in $A_j(p')$, then the posterior α should place infinitely greater weight on type j.

Proposition 2 *Every equilibrium (p, α°) survives the Cho–Kreps intuitive criterion. However, only the equilibrium corresponding to Proposition* 1 *survives the divinity criterion.*

Proof of Proposition 2 First note that $V_i(p, 0) = 0$: if consumers believe the seller to be an H type for sure, then no consumer adopts and the seller makes no sales, regardless of its type. This implies that the Cho–Kreps criterion has no bite. Second, define $\alpha_i(p)$ as the solution to $V_i(0, \alpha_i(p)) = V_i(p, \alpha^\circ)$. Since $V_i(p, \alpha)$ is increasing in α, we have $V_i(0, \alpha) \geq V_i(p, \alpha^\circ)$ if and only if $\alpha > \alpha_i(p)$. Since $V_H(p, \alpha)$ is increasing in p, whereas $V_L(p, \alpha)$ is decreasing in p, we conclude that $\alpha_L(p) < \alpha_H(p)$ for $p > 0$. It follows that $A_H(0)$ is strictly included in $A_L(0)$. This implies that a deviation from $p > 0$ to $p = 0$ should lead consumers to believe the seller to be an L type, which in turn makes this a profitable deviation (for both types). □

I next consider a series of possible extensions to the basic model and result.

Alternative sources of uncertainty The examples considered in the introduction, and other examples of new Internet services, suggest that the free-vs-pay dichotomy may be a bit simplistic. For example, even if consumers know that a seller will charge for its service, the consumer may not know the exact price that the seller will charge. In terms of my model, this would amount to considering more than two types, that is, different values of marginal cost that would lead to different optimal prices. Alternatively, the consumer may be uncertain about the demand elasticity, so that, even if cost is known, optimal price in not known.

Versioning As mentioned in the introduction, one common feature of many new services offered on the Internet is that they are offered in multiple versions. A particularly common pattern is to offer a free version, with limited capabilities and/or with ads, as well as a paid version, with full capabilities and no ads. For example, Eudora 7.1 is offered in three possible versions (paid mode, sponsored mode, light mode), each offering a different combination of price, advertising and convenience.[6] The basic pattern described in Proposition 1 still holds if there is residual uncertainty regarding the seller's business model. For example, if the seller earns revenues primarily through advertising, then we would expect the free version to be continuously updated and upgraded so as to attract eyeballs. If, by contrast, the seller earns revenues primarily through sales, then we would expect the free version to decrease in value by virtue of not being updated and upgraded. Anecdotal evidence suggests that both scenarios are possible, which in turn suggests that the kind of business-model uncertainty that my theory is based on holds even in the context of versioning.

Multiple consumer types One aspect in which my model is clearly not very realistic is that all consumers are identical. In fact, most models of new product adoption place considerable weight on adopter heterogeneity. For example, Van den Bulte and Joshi (2007) consider the case when consumers can be divided into two groups: *influentials* and *imitators*. One advantage of my assumption of homogeneous adopters is that it highlights the fact diffusion is due to the properties of the equilibrium, not the heterogeneity of adopters. Extending my model to the case of different adopter types would certainly make it more realistic and consistent with the previous literature. However, it would obfuscate the role played by business-model uncertainty in the diffused adoption of a new product.

Seller uncertainty about own type I made the extreme assumption that adopters know very little about the seller's type (only the prior distribution), whereas the seller knows its type perfectly. While information asymmetry seems reasonable (with the seller knowing its type better than consumers), the extreme form considered may be a little unreasonable. The argument can be made that successful online sellers such as Amazon, eBay and Google had an imperfect knowledge of what their business model would become as they first got under way. I conjecture that the central feature of Proposition 1 is robust to introducing some uncertainty on the seller's part. So long as there is information asymmetry there will be scope for a gradual separation equilibrium, where consumers gradually acquire the information possessed by the seller. However, the extension to the case when the seller also learns is beyond the scope of this paper.

5 Related work

There is a very extensive economics literature on the adoption of new goods. There is also a very extensive literature on the implications of asymmetric information between seller and buyers. In this section, I try to relate my model

[6] http://www.eudora.com/download/, visited on April 16, 2008.

to these literatures. I also consider alternative interpretations and extensions of my basic model.

Relation to the diffusion literature One interesting feature of my equilibrium is that it induces diffusion, that is, not all adopters start purchasing at the same time. At the risk of oversimplifying, the previous literature on new product diffusion can be summarized into two classes of theories. One is based on imperfect knowledge of product availability and some form of word-of-mouth communication whereby later adopters learn from earlier ones. The second one is based on adopter heterogeneity and a declining trend in adoption price: high valuation adopters buy earlier, low valuation adopters buy later.[7] In my model, diffusion results from the consumers' wait-and-see strategy, not from adopter heterogeneity. Naturally, my assumption of consumer homogeneity is not particularly realistic. Moreover, in a richer model that featured heterogeneous consumers I would expect the order of adoption to be monotonic in consumer type. However, even in that case an important portion of diffusion would be due to consumer uncertainty about the seller's business model.

An additional difference with respect to the diffusion story based on adopter heterogeneity is that the latter requires that price be declining over time. In my gradual separation equilibrium, however, expected price is *increasing* over time.

By proposing a new view on diffusion, my model also suggests new avenues for empirical implementation of diffusion models. An extensive literature on the estimation of the Bass (1969) model has considered various functional forms and econometric estimation techniques (see for example Narasimhan and Sen 1983; Venkatesan et al. 2004, and references therein). Other authors have investigated cross country differences in adoption patterns (see for example Talukdar et al. 2002). Proposition 1 and the implied comparative statics on T suggest some possible testable predictions, both in terms of the shape of diffusion and of its speed.

Finally, there is a literature that, based on a diffusion model of the Bass (1969) type, derives optimal pricing strategies. See Krishnan et al. (1999) and references therein. However, these papers do not consider the possibility of asymmetric information and signaling.[8] (Below I consider the relation of my paper to the signaling literature.)

Relation to the war-of-attrition literature The nature of the equilibrium of Proposition 1 is reminiscent of other applications of the war of attrition to the

[7] See Bass (1969) and Jensen (1982) for examples of the former approach; and Griliches (1957), David (1969), Davies (1979) for examples of the latter approach. See also Geroski (2000) for a good survey of this literature.

[8] Danaher (2002) considers optimal pricing strategies for a new subscription service. See Essegaier et al. (2002) for a related approach. One important difference with respect to my model is that these papers look at the case of recurrent fixed feeds (e.g., the monthly rental in a cell phone plan), whereas I consider the one-time sunk cost a consumer must incur before beginning to enjoy a new product or service.

problem of entry and exit. For example, Fudenberg and Tirole (1986) consider the case when entrants are uncertain about each other's costs. They show that, if there is an entrant type such that remaining active is a dominant strategy, then there exists a unique equilibrium (unlike the case of natural monopoly, when there exists a continuum of equilibria). Similarly to my Proposition 1, the equilibrium involves mixing by both players. Other authors consider the case of complete information and derive similar results.[9] My model differs in several ways. Unlike the previous literature, I consider an asymmetric game (instead of two firms, I have a firm and a continuum of consumers). In terms of the information structure, I consider a hybrid model, with private information on the seller's side and complete information on the consumer's side. Moreover, while my model has the structure of a war of attrition, the particular issues I deal with are somewhat different from the issues of interest in the previous literature.

Relation to the viscous demand and switching costs literature Radner (2003) and Radner and Richardson (2003) propose models of "viscous demand," the situation when demand adjusts slowly to changes in prices. Radner (2003) proposes an "attention budget" explanation for demand viscosity. As he puts it, "the (potential) consumer cannot be thinking every hour, or even every week, about which long-distance carrier to use. Rather, the consumer rethinks such decisions from time to time, regularly or at some random intervals." If different consumers do their rethinking at different moments of time, then the phenomenon of gradual response to price changes results naturally.

Suppose there is an incumbent firm (e.g., AT&T) committed to charging a fixed price p. Suppose that an entrant (e.g., MCI) moves in with a lower price, $p' < p$. If consumers are uncertain about the entrant's cost, then we have a situation similar to the adoption of a new service. Specifically, I may reinterpret the adoption of a new seller as a switch from an existing seller. My model then provides an alternative foundation for demand viscosity. Even if consumers have an infinite "attention budget," to use Radner's terminology, they do not switch immediately; rather, they play a "wait-and-see" strategy, as shown in Section 3, which in turn leads to gradual adjustment to a lower price set by an entrant—a viscous demand shift.

Continuing with the analogy between new product adoption and seller switching, my model is related to the switching cost literature (see, for example, Klemperer 1995). However, this literature typically does not consider the information asymmetry that is essential in my model.

Finally, a related series of papers have looked at price dynamics with customer loyalties that create demand inertia.[10] These papers, like Radner (2003) and Radner and Richardson (2003), take a reduced-form approach

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[9] (See for example Fudenberg and Tirole 1983; Ghemawat and Nalebuff 1985; Cabral 2004).

[10] See Rosenthal (1982, 1986), Chen and Rosenthal (1996).

to consumer behavior. By contrast, I explicitly model the optimal Bayesian behavior of potential consumers.

Relation to the "bait-and-switch" literature Sellers sometimes practice a form of false advertising known as "bait and switch." They advertise a certain good at a certain price, thus enticing consumers to visit their store. But when the consumer visits the seller, that is, when the consumer has paid a sunk search cost, then the seller tries to sell a different product at a different price. Various authors have shown how bait and switch can be an equilibrium strategy. However, they have not considered to role of time as I do in this paper.[11]

The equilibrium of my model shares some of the features of equilibrium bait and switch. Rational buyers know that, with some probability, they will regret having paid the sunk cost required before a purchase. This cost can be a search cost (bait and switch) or one of the investments listed in the Introduction (lock-in and switch). The reason for the regret is asymmetric information regarding the sellers inventory (bait and switch) or some aspect of the seller's business model (lock-in and switch).

A related line of research is that of ad-on pricing.[12]

Relation to the price signalling literature In a classic paper, Bagwell (1987) showed that, in a two-period model of asymmetric information about seller cost, there may exist an equilibrium where first period price signals the firm's cost and therefore expected second period price.[13] In Bagwell's model, consumers must pay a search cost before visiting a particular seller. In this sense, Bagwell's model addresses the issues considered in this paper: (1) buyers must pay a cost before beginning to enjoy the new service; and (2) buyers are uncertain about future price.

However, there are reasons to believe Bagwell's equilibrium may not exist in many real-world situations. In fact, if the first period is very short and negative prices are unfeasible, then no separating equilibrium exists. Intuitively, a high-cost seller would always want to mimic a low cost seller, thus attracting more consumers and then exploiting its enlarged base of captive consumers. If a money burning technology such as advertising is available, then a combination of price and money burning may achieve separation. But imperfect observability or other reasons may limit such a possibility.

In this paper, by considering a model of continuous time I implicitly make the extreme assumption that the seller cannot commit to prices. This implies that price signalling as in Bagwell's model is not feasible. Prices can still signal seller cost but only when such prices are maintained for a period of

[11] See Gerstner and Hess (1990), Lazear (1995), Wilkie et al. (1998). These papers are inconclusive as to the welfare effects of bait-and-switch, a (currently) illegal activity.

[12] See for example Ellison (2005).

[13] See also Bagwell and Riordan (1991), Judd and Riordan (1994). See Dawar and Sarvary (1997) for a (successful) test of some implications of price signaling theory. In addition to price, other variables, such as specialization, may be used as signals. See Kalra and Li (2008)

time. Continuous time also implies that there exist no equilibria with pure separation. Instead, I consider the possibility of semi-separating equilibria whereby types initially pool and gradually separate (according to the cdf F). Specifically, in my model separation is given by the time spent at zero price, rather than by the price level itself.

There also exists a literature on separation in dynamic models. The classical application of signalling and separation is Spence's job market signalling game, a two-stage game where workers first choose their education level and firms then make job offers. The Riley (1979) outcome of this game is a separating equilibrium whereby a low ability worker makes no investment and a high ability worker makes the lowest investment such that the low ability worker has no incentive to mimic. Noldecke and van Damme (1990) show that this separation equilibrium survives even if firms can make offers before workers finish their investment in education (and workers cannot commit not to accept interim offers). Swinkels (1999) however shows that, if job offers are not publicly observed, then the equilibrium involves either pooling or partial pooling. My result bears some relation to Swinkels (1999) in that it involves a semi-pooling, or semi-separating, equilibrium.

More recently, Janssen and Roy (2002), consider a dynamic model of a durable good with adverse selection. They show that the classical static-game lemons problem disappears when time is taken into account. In equilibrium, both price and the quality of the goods traded increase over time. Although my model is one of signalling, not screening, the equilibrium I consider shares some of the features of that in Janssen and Roy (2002), namely the role of time in achieving separation.

Relation to the learning curve and network effects literatures The equilibrium presented in Proposition 1 involves introductory pricing. Two of the most popular explanations for this pricing strategy are learning by doing and network externalities. In a two-period model, Spence (1981) and Fudenberg and Tirole (1983) have shown that learning curve effects imply that first period price may be lower than cost—and in fact lower than second period price.[14] This is very different from my model. In fact, I get introductory pricing even though there is no "physical" link between periods as in the case of a learning curve.

Regarding network effects, Cabral et al. (1999) show that it is remarkably difficult to obtain introductory prices in a setting where consumers are aware of the seller's cost and product quality levels. Their central result features increasing prices but a small number of strategic buyers, a situation that is unlikely to be found in the context of web-based services like the ones presented in the Introduction.

[14] See also Cabral and Riordan (1994).

6 Concluding remarks

In Section 5, I considered various possible extensions of my basic model. The important feature to maintain is that an appropriate generalization of Assumption 1 holds, that is, the set of possible seller types must be such that consumers would want to adopt if they knew the seller was of type L but not adopt if they knew the seller was of type H. If this is the case, then I conjecture that the qualitative nature of Proposition 1 holds in more general settings. The qualitative feature that is robust is that, in equilibrium, a type H seller pools with a type L seller for some period of time and then switches to its optimal complete information set of offerings.

Another fundamental assumption on which my analysis is founded is that firms cannot commit to future prices. In fact, the main difference between my results and Bagwell (1987), who also looks at new product introduction with asymmetric information, is precisely the seller's inability to commit to future prices.

Some Internet services suggest that there may be some degree of commitment on the seller's part. While promises are just cheap talk, dynamic reputational concerns may lend some credibility to announcements of this type. If commitment to future prices is feasible, then the natural equilibrium would involve immediate separation (as in Bagwell 1987). The idea is that the cost of promising zero prices in the future is lower (maybe even zero) for the low cost firm, but high for the high cost firm.

However, even if sellers can commit to keep their current offering free, such offer may be worth little if there is a significant rate of service improvement. By keeping those improvements inaccessible to the free version, the perceived or the real value of the free version is degraded, to the point that the seller may be effectively discontinuing the free option. So, ultimately I believe my assumption of inability to commit to future price or quality terms is realistic, and so are the qualitative features of the equilibrium I derive.

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