Innovative leadership: First-mover advantages in new product adoption*

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Summary. This paper analyzes innovation adoption when uncertainty about its profitability cannot be resolved immediately. Firms begin with a common estimate of the probability of high demand. If any adopts, all observe realized demand. An increase in the initial estimate can decrease the equilibrium number of initial adopters, because it results in higher updated estimates that can induce future adoption by additional firms that reduces the initial adoption payoff. Moreover, innovative leadership does not imply initial adoption because leadership implies a greater waiting payoff as well as a greater adoption payoff. Leadership does, however, still provide a higher expected payoff.

Keywords and Phrases: adoption, innovation, leadership, first-mover advantage

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1 Introduction

Many new products fail because the demand for them is not high enough to allow profitable production by at least one firm. Indeed, failures are more common than successes. Moreover, learning whether a new product is a success or not may take time if demand is stochastic and its distribution is unknown. If demand can be either high or low in any period and the true probability of high demand is unknown, then mean demand is learned only if sales are observed in a large enough number of periods. In this case, whether the new product succeeds, and if so how many firms can profit from it, is learned only if some firms take the risk of producing it for a long enough period of time.

This paper studies the nature of innovative leadership, in the form of a first-mover advantage, in the strategic adoption of an innovation subject to this type of uncertainty. It differs from previous studies (e.g., Reinganum [18], [19], Fudenberg and Tirole [5], Stenbacka and Tombak [22], and Hoppe [10]) in three major ways. First, profit is not only random, but its distribution is unknown. This implies that adoption does not instantaneously reveal whether the innovation is a success, so firms may cease production at any time after adopting, and need not adopt a success.[1]

Second, all information is public. If at least one firm produces, the state of demand realized in that period is observed by all firms, including those which did not adopt. Thus, there is a free-rider problem associated with adoption. Each firm has an incentive to "wait and see" because adoption by a rival provides the same information as its own adoption.

Finally, this is not a game of timing in which the objective is to determine the date at which each firm adopts. In this analysis, all firms adopt immediately for high enough probabilities of success. Conversely, adoption never occurs for low enough probabilities. There are no forces external to the industry that decrease the cost of, or increase the revenue from, adoption over time. Thus, the objective is to examine the implications of an exogenously-determined order of moves, not to endogenously determine the order of adoption. This paper, therefore, also contributes to the literature on first-mover advantages and disadvantages (e.g., see Gal-Or [6], [7]) by analyzing a problem where the entire sequence of moves is repeated (i.e., firms can adopt or not in more than one period). This provides interesting results on the intertemporal implications of being a first-mover.

The experience of the convenience food industry over the last few decades provides an excellent example of the type of industries and potential innovations with these characteristics. Firms in this industry

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[1] Jensen [11], [12], Balcer and Lippman [1], McCardle [15], and Bhattacharya, Chatterjee, and Samuelson [3] study decision-theoretic adoption models with stochastic profit. Benoit [2] studies a game-theoretic model in which uncertainty about the innovation is not resolved until a finite time after adoption, but there

have regularly introduced new products, many of which have been quickly dropped from the product line. For example, consider the decision to expend the resources required to open for business in the morning and offer an additional line of breakfast products. This innovation was not considered a sure thing at the time of initial adoption, and some convenience food firms still do not offer a breakfast menu. Moreover, whether it would succeed or not was certainly not learned instantaneously after the first day, or even month, of adoption. It took time for the adopters to learn if there was sufficient demand for convenience breakfasts to make this innovation profitable, and during this time their experiences could be observed by the waiters.[2] Also during this learning period, each adopter had to decide whether to continue producing or not, while each waiter had to decide whether to adopt or to continue to wait and observe. Finally, given the nature of this market, namely that breakfast can only be served at discrete time intervals, it is appropriate to assume these decisions occurred at discrete dates in time.

Hence, a model of a stochastic game with two production periods is analyzed (adding more periods would merely complicate the analysis and exposition without offering additional insights). It applies to any innovation without patent protection[3], but a new product interpretation is used because it seems the most natural. Each firm can produce or not in both periods. To begin production a one-time, lump-sum adoption cost must be paid (e.g., the cost of developing a convenience breakfast menu). All firms begin with the same, common knowledge initial estimate of the probability of high demand. If any firm adopts, all firms observe realized demand and revise the estimate accordingly in period two: up for good news (high demand), and down for bad news (low demand).

One interesting result is that an increase in the initial estimate of high demand can decrease the number of firms that initially adopt in the subgame perfect Nash equilibrium. The reason is that an increase in this estimate is necessarily accompanied by an increase in both updated estimates of high demand in period two. The increase in the updated estimates may induce adoption in period two by a firm which

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is no learning in the interim.

[2] The lack of patent protection distinguishes adoption studies from the more common patent races studies (see Reinganum [20] or Geroski [8] for surveys). See Gilbert and Newbery [9] for a discussion of reasons why patent protection may not exist.

[3] Admittedly, waiters do not have exactly the same information as adopters about their experience with the innovation. Nevertheless, the assumption that the adopters experience is common knowledge is not overly restrictive. Given the visible nature of operation in this market, it is easy to observe the flow of customers during any time of the day. Moreover, industries such as these have financial analysts and observers who routinely produce estimates of the viability of such new product innovations. How adopters and analysts might try to strategically manipulate their private information to their advantage is an interesting question, but also one that is beyond the scope of this paper.

otherwise would have waited. Adoption by an additional firm reduces the expected profit of any producer in period two, and thus decreases the incentive to adopt initially. This downward discontinuity in the initial adoption payoff can reduce the equilibrium number of adopters. This outcome is more likely for more risky innovations, greater competition (more firms), and lower adoption costs. Moreover, note that this cannot occur when adoption is assumed to instantaneously reveal whether the innovation is a success (as in the preceding studies above). In such a model, for any initial estimate, good news reveals the innovation is a success with absolute certainty, so all remaining firms adopt in the next period.

Intuition suggests that early adopters are the "most innovative" firms. However, empirical observation shows that innovative leadership changes over time. Early adopters of past innovations often are not early adopters of current innovations (see Davies [4], Mansfield [13], Nasbeth and Ray [17], Rogers [21], and Stoneman [23], [24]). In fact, this phenomenon also seems to occur globally (see, for example, McCulloch [16] for evidence the United States is losing its position as the global innovative leader). A second interesting result is that, when innovative leadership takes the form of sequential moves, the leader (first-mover) may rationally decide not to be an early adopter.

The logic of this result is somewhat unusual because it requires at least three firms. Assume that the firms move in the order given by their numbers (firm 1 moves first, and so on). A firm adopts if and only if its expected payoff exceeds that from waiting. The key is that innovative leadership can provide a larger waiting payoff as well as a larger adopting payoff. Suppose that if any one firm adopts initially and gets good news, then one of the waiters can adopt in period two (i.e., there are at least three firms, one initial adopter and two waiters). Then only the lowest-numbered waiter adopts and earns positive expected profit in period two. Hence, firm 1 has a positive waiting payoff, but all other firms have a zero waiting payoff if at least one more innovative rival also waits. Firm 1's waiting payoff is larger because its leadership position guarantees that, if it waits, then it cannot be excluded from the new product market in the next period. The other firms, with no such guarantee, can have a larger incentive to adopt first because their waiting payoff is smaller. In general, initial adoption by $k \geq 1$ firms, but not including the first k firms to move, can be a subgame perfect Nash equilibrium.

A third interesting result is that innovative leadership is always beneficial in this model. The expected payoff of the most innovative firm 1 is at least as great as the expected payoff of firm 2, and so on. There is a distinct advantage to the first mover, although in equilibrium that advantage may take the form of waiting, not adopting. Therefore, one reasonable interpretation is that innovative leadership may, by its very nature, be transitory. If the order of moves is based on past experience (e.g., the order in which the firms adopted the last innovation), then an early adopter of past innovations may rationally decide not to be an early adopter of the current innovation. This provides an explanation for the empirical phenomenon of a firm, or country, apparently becoming less innovative over time. Once it has become an innovative leader, it has a larger incentive to take a wait-and-see approach, and free ride on the information provided by its rivals' adoption.

Finally, these results are robust in two ways. They do not depend on a ranking based on past behavior or on whether firms make their decisions sequentially or simultaneously. For example, suppose firms are heterogeneous and firm1 has the highest production profit (or lowest R&D cost), firm 2 has the next highest profit (lowest cost), and so on. Then, *ceteris paribus*, firm 1's adoption payoff is always greater that the other firms' adoption payoffs. Nevertheless, it still may not be a first adopter because, as above, its waiting payoff is also greater than the other firms' waiting payoffs. And if firms move simultaneously in each period, then there are many more equilibria, but they still include those from the sequential move game examined.

Section 2 presents the adoption game. Section 3 analyzes initial adoption behavior. Section 4 examines alternative approaches to leadership. Section 5 concludes, and the Appendix contains proofs of technical results.

2 A Two-Period Stochastic Game of Innovation Adoption

Consider $N \geq 3$ firms deciding whether to use an innovation in each of two production periods. A firm cannot use the innovation unless it first adopts it. Adoption requires the payment of a one-time, lump-sum cost $I>0$. Profit from the use of the innovation is stochastic. In each period, any firm using it has either a good experience or a bad experience (good news or bad news), and every firm using it has the same experience. The true probability of good news is $p^* \in [0,1]$. No firm knows p^*, so each initially estimates it by $p \in [0,1]$. These facts are common knowledge. Formally, this is a common values problem in which experience is a Bernoulli random variable Z that equals 1 with probability p^*. The true distribution of p^*, denoted F, has support [0,1] and mean p. The game begins with a random draw from F that is not revealed, so each firm estimates it by p.

For ease of exposition, consider the case of a new product, the demand for which can be high or low in each period. Demand can be stochastic for reasons either related to the new product, such as consumers needing to learn about it from experience, or unrelated to it, such as stochastic income. Producing the new product in the first few periods does not reveal if its average demand is large enough to allow profitable production by one or more firms (p^* can be learned only in the limit, with probability 1, if demand has been observed often enough that the strong law of large numbers applies).

Assume that a firm that does not use the innovation in a period earns zero profit. That is, the period profit of a firm that does not adopt is normalized to zero. Further assume that all firms are identical as producers and make their product market choices simultaneously. Then a producer's expected profit per period depends only on the total number of producers, k ($1 \leq k \leq N$), and the current estimate of high demand, p, and so can be written as $\pi(k,p)$. If p=0, so demand is certainly low in every period, then any producer expects a loss, even as a monopolist. If p=1, so demand is certainly high in every period, assume product market behavior that allows all N firms to earn positive expected profit, but only M firms ($2 \leq M \leq N$) to earn positive expected profit net of the adoption cost. Then it is natural to also assume that this expected profit is increasing in the current estimate and decreasing in the number of producers.

Assumption 1. A producer's expected profit per period, $\pi(k,p)$, is continuous and increasing in p, decreasing in k, and satisfies $\pi(1,0)<0$, $\pi(N,1)>0>\pi(N+1,1)$, and $\pi(M,1)>I>\pi(M+1,1)$ for some integers N and M such that $2 \leq M \leq N$. A firm that does not produce earns zero profit.[4]

It follows immediately that if k firms produce, then each producer expects positive profit if and only if the current estimate is high enough: for each k=1,...,N, there exists a unique $\rho_k \in (0,1)$, given by $\pi(k,\rho_k)=0$, such that $\pi(k,p) \gtrless 0$ if and only if $p \gtrless \rho_k$. Similarly, each producer expects positive profit net of the adoption cost if and only if the estimate is high enough: for k=1,...,M, there is a unique $\alpha_k \in (0,1)$, given by $\pi(k,\alpha_k)=I$, such that $\pi(k,p) \gtrless I$ if and only if $p \gtrless \alpha_k$. Note that ρ_k and α_k are increasing in k, and that $\rho_k<\alpha_k$ for k=1,...,M.

It is useful to provide an algebraic example of this market model. Assume the firms are considering adoption of a homogeneous new good with demand $P=A+p\theta-Q$, where P is price, Q is market quantity, $A>0$ is a constant, and the random variable θ takes on the values $\theta^*>0$ with probability p^* and 0 with probability $1-p^*$. Marginal cost is a constant $c>0$ and there is a fixed cost $K>0$ in any period the good is produced. Under Cournot quantity competition, expected profit is $\pi(k,p)=[(A+p\theta^*-c)^2/(k+1)^2]-K$, and the critical probabilities are $\rho_k=[(k+1)K^{1/2}-A+c]/\theta$ and $\alpha_k=[(k+1)(K+I)^{1/2}-A+c]/\theta$.

Now assume a common knowledge ranking of firms, based on past behavior toward innovations, such that firm 1 is the most innovative, firm 2 is the next most innovative, and so on. That is, in the sequel one firm is said to be more innovative than another if it has a lower number. In practice, innovative reputations do exist and are usually based on past behavior (see, e.g., Mansfield [13], Rogers [21], and Stoneman [23], [24]). All that matters herein is that such a ranking exists, and that it gives the more

[4] Zero profit for a firm that does not produce the innovation implies that this firm either has no profit from other sources or such profit is not affected by the adoption of its rival(s).

innovative firms an advantage in the form of a type of Stackelberg leadership in which the firms make their decisions sequentially in the order determined by this ranking.

Assumption 2. In period one, the firms move sequentially in deciding to adopt (pay I) or not in the order determined by their numbers: firm 1 moves first, firm 2 moves second, and so on. Each firm observes the actions taken in all preceding moves before making its decision. The firms that adopted then make their production[5] choices simultaneously (and collect expected profits). After production, all firms observe if demand was high or low. In period two, firms that adopted in period one (incumbents) move sequentially in deciding whether to continue or not in the order determined by their numbers. Firms that did not adopt in period one (waiters) then move sequentially in deciding to adopt or not in the order determined by their numbers. Firms that have continued or adopted then make their production choices simultaneously, after which all firms observe if demand was high or low.

In the context of the example, adoption in period one means to incur the adoption cost I and the fixed production cost K, and production means to generate the gross expected production profit $(A+p\theta^*-c)^2/(k+1)^2$. In period two, continue means to incur the fixed production cost K, adoption again means to incur the adoption cost I and the fixed production cost K, and production means to generate the gross expected production profit $(A+p\theta^*-c)^2/(k+1)^2$.

The analysis focuses on the subgame perfect Nash equilibria (SPNE) both within and between each period. It is worth noting that the assumption that all incumbents move before waiters in period two is made simply because it seems natural. All the qualitative results that follow would also hold under the assumption that the firms move in the order determined by their numbers in both periods.

2.1 Subgames in Period Two

Because all firms observe the period-one outcome, every subgame is characterized by a record of the choices of the firms in period one and a (possibly updated) estimate of high demand, say q. Let s_i denote firm i's period one (pure) strategy, where s_i=a if it adopts and s_i=w if it waits. Also let s_i^* denote the equilibrium strategy chosen by firm i in period one. The history of the game in period two is then this record of moves in period one, $h=(s_1^*,\ldots,s_N^*)$. The state variable for each firm in period two is then the history of the game and the current estimate of high demand, (h,q).

In period two, an incumbent first must decide whether to continue or not, while a waiter must decide

[5] Although the discussion proceeds in terms of production, the same results occur if firms produce

whether to adopt or not. Recall that, by Assumption 2, each subgame is a sequential-move game in which the incumbents move first, in the order of their numbers, and then the waiters move, also in the order of their numbers. Thus, the history of the game determines the order of moves in period two. For example, if h=(w,a,w,a,a,w,a), then in the resulting period-two subgame, firm 2 moves first, followed by firms 4, 5, 7, 1, 3, and 6.

Suppose no firm adopted in period one, so h=(w,...,w) and the estimate remains p. If $p<\alpha_1$, no firm adopts in period two because the adoption cost exceeds expected profit for any number of producers, $\pi(k,p)<I$ for all k. If $p\in[\alpha_k,\alpha_{k+1})$ for k=1,...,M−1, then k firms adopt because expected profit exceeds the adoption cost if and only if k or fewer firms produce. The adopters are the k most innovative firms, those numbered 1 to k. Finally, if $p\geq\alpha_M$, then firms 1 to M adopt.

Note that multiple equilibria occur when the marginal firm is indifferent. For example, if none have adopted and $p=\alpha_k$, then adoption by firms 1 to k−1 is an equilibrium, but adoption by firms 1 to k is also an equilibrium; $\pi(k-1,\alpha_k)>I=\pi(k,\alpha_k)$, so firm k is indifferent between adopting or not. There is no loss of generality in focusing on equilibria in which the maximum number of firms adopt.

<u>Assumption 3</u>. Only pure strategy equilibria in which the maximum possible number of firms adopt are considered in any period.

Now suppose $n\geq1$ firms adopted initially and the period-two estimate is $q\in[0,1]$. For brevity's sake, let N=M=3. If $q<\rho_1$, no incumbents continue and no waiters adopt. If $q\in[\rho_1,\rho_2)$ and $\rho_2\leq\alpha_1$, the most innovative incumbent continues, but no other incumbents continue and no waiters adopt. This is also the equilibrium if $\alpha_1<\rho_2$ and $q\in[\rho_1,\alpha_1)$. But if $\alpha_1<\rho_2$ and $q\in[\alpha_1,\rho_2)$, then firm 1 either continues or adopts, because it can adopt as long as no rival continues, and no incumbent can continue once it adopts. Similarly, if $q\in[\rho_2,\rho_3)$ and $\rho_3\leq\alpha_2$, there are two possibilities. If $n\geq2$, the two most innovative incumbents continue, but no other incumbents continue and no waiters adopt. If n=1, the lone incumbent continues, but no waiters adopt. These are also the equilibrium possibilities if $\alpha_2<\rho_3$ and $q\in[\rho_2,\alpha_2)$. But if $\alpha_2<\rho_3$ and $q\in[\alpha_2,\rho_3)$, then firms 1 and 2 either continue or adopt. There are six possibilities if $q\geq\rho_3$. If n=3, all incumbents continue. If n=2, both incumbents continue, but the waiter adopts if and only if $q\geq\alpha_3$. If n=1, $\alpha_2>\rho_3$, and $q\in[\rho_3,\alpha_2)$, the incumbent continues, but no waiters adopt. If n=1 and $q\geq\alpha_2$, the incumbent continues, the most innovative waiter adopts, but the other waiter adopts if and only if $q\geq\alpha_3$ as well.

It is impractical to provide a detailed summary of the SPNE in all possible subgames. Fortunately, this is not necessary. For each period two state (h,q), Assumptions 1-3 guarantee there is a unique SPNE for the resulting subgame. Thus, each firm i's period-two SPNE payoff is uniquely defined as a function of

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differentiated products and compete in prices.

the state, and so can be written as $V_i(h,q)$. In the example of the preceding paragraph, suppose $q\varepsilon[\alpha_2,\alpha_3)$ and firm 1 adopted in period one. Then in period two, firm 1 continues, firm 2 adopts, and firm 3 waits, so $V_1((a,w,w),q)=\pi(2,q)$, $V_2((a,w,w),q)=\pi(2,q)-I$, and $V_3((a,w,w),q)=0$. However, if firm 3 adopted in period one, then in period two firm 1 adopts, firm 2 waits, and firm 3 continues, so $V_1((w,w,a),q)=\pi(2,q)-I$, $V_2((w,w,a),q)=0$, and $V_3((w,w,a),q)=\pi(2,q)$. Clearly, as noted above, the period-two SPNE payoff for any firm depends on the specific firms that adopted in period one, as well as the total number of adopters.

2.2 Payoffs in Period One, Given SPNE Behavior in Period Two

Now consider the expected payoffs from adopting and waiting in period one, conditional on SPNE behavior in period two. Let $s=(s_1,...,s_N)$ be a vector of period-one strategies, one for each firm, and s_{-i} be the $(N-1)$-vector of the strategies of firm i's rivals, formed from s by deleting s_i. From firm i's perspective, then, the history of the game in period two is written as $h=(a,s^*_{-i})$ if it adopted and $h=(w,s^*_{-i})$ if it waited.

Recall that, if any firm adopts, then all firms observe the experience and update p using Bayes rule. Assume p is updated up to g(p) given good news (high demand) and down to b(p) given bad news (low demand), where g and b map [0,1] into [0,1], g(p) and b(p) are increasing functions of p, and $0\leq b(p)<p<g(p)\leq 1$ for $p\in(0,1)$. Formally, each updated estimate is the mean of the posterior of p* derived from the prior F and the realization of Z. A common example is a beta (μ,ν) prior, for which the mean is $p=\mu/(\mu+\nu)$ and the updated estimates are $g(p)=(\mu+1)/(\mu+\nu+1)=[(\mu+\nu)p+1]/(\mu+\nu+1)$ and $b(p)=\mu/(\mu+\nu+1)=(\mu+\nu)p/(\mu+\nu+1)$.

Define $R_i(a;s_{-i},p)$ as firm i's expected payoff if it adopts in period one, given the estimate p, rival strategies s_{-i}, and SPNE behavior in period two under Assumptions 1-3. If n(s) is the number of producers in period one given the strategy s and $\delta\in(0,1)$ is the discount factor, then

$$R_i(a;s_{-i},p)=\pi(n(s),p)-I+\delta[pV_i((a,s_{-i}),g(p))+(1-p)V_i((a,s_{-i}),b(p))]. \quad (1)$$

Similarly define $R_i(w;s_{-i},p)$ as firm i's expected payoff from waiting in period one, given p, σ_{-i}, and SPNE behavior in period two. Then

$$R_i(w;s_{-i},p)=\delta[pV_i((w,s_{-i}),g(p))+(1-p)V_i((w,s_{-i}),b(p))] \text{ if } n(s)>0, \quad (2)$$

and

$$R_i(w;s_{-i},p)=\delta V_i((w,s_{-i}),p) \text{ if } n(s)=0. \quad (3)$$

Because these payoffs embody SPNE behavior in stage two, the SPNE of the entire game are determined by finding the SPNE of the "reduced-form" sequential-move game in period one in which firm 1 moves first, firm 2 moves second, and so on, and the payoffs are given by (1)-(3). Given this period-one outcome, summarized in the state (h,q), the corresponding period-two SPNE is then determined as noted above. In general, the SPNE can have period one outcomes with adoption by any number of firms or by none. No firm adopts in either period if p is low enough, but all firms adopt initially if p is high enough. Otherwise, some but not all firms adopt, in which case there are three types of period two outcomes: some incumbents continue but others do not; all incumbents continue but no waiters adopt; and all incumbents continue and some or all waiters adopt. The remainder of the paper, however, focuses on properties of initial (period-one) adoption in the SPNE.

3 Initial Adoption Behavior

One interesting result is that an increase in the initial estimate of high demand can decrease the SPNE number of initial adopters. The reason is that an increase in the initial estimate is accompanied by an increase in the updated estimates. These increases in the updated estimates may induce adoption by an additional waiter in period two. If so, then the higher initial estimate decreases an incumbent's period two SPNE payoff, and so also decreases its adoption payoff. In fact, this decrease takes the form of a downward, jump discontinuity in the adoption payoff function. Hence, an increase in the initial estimate can result in a decrease the SPNE number of initial adopters whenever there is at least one waiter that can adopt in period two.

Consider the outcome if $p=\gamma_2$, where γ_2 is defined by $g(\gamma_2)=\alpha_2$. If firm i adopts and gets good news, then it continues and one waiter adopts in period two. Also assume $b(\gamma_2)<\rho_1$, so if firm i adopts and gets bad news, then no firms continue or adopt in period two. Thus, its payoff from lone adoption is $R_i(a;(w,...,w),\gamma_2)=\pi(1,\gamma_2)-I+\delta\gamma_2\pi(2,\alpha_2)$. However, now consider the outcome for any p just below γ_2. If firm i adopts and gets good news, then in period two it continues but no waiter adopts because $g(p)<\alpha_2$ for $p<\gamma_2$. Now its lone adoption payoff is $R_i(a;(w,...,w),p)=\pi(1,p)-I+\delta p\pi(1,g(p))$. The period-two payoff given good news is discontinuous at $p=\gamma_2$, where it decreases from (almost) expected monopoly profit $\pi(1,\alpha_2)$ to expected duopoly profit $\pi(2,\alpha_2)$, so the lone adoption payoff is also discontinuous at $p=\gamma_2$.[6] It is, therefore, possible that this adoption payoff is positive for p just below γ_2, but negative at γ_2, so the SPNE is one firm adopts for p just below γ_2, but no firm adopts if $p=\gamma_2$. This is depicted in Figure 1, where $R_i(a;(w,...,w),p)>0>R_i(a;(w,...,w),\gamma_2)$ for such p.

(FIGURE 1)

However, as p rises above γ_2, the lone adoption payoff must become positive again, certainly for $p>\alpha_1$, where $\pi(1,p)>I$. Thus, lone adoption can be a SPNE on two disjoint intervals of estimates. In fact, it

[6] It is worth noting that Assumption 2 does not cause this discontinuity. It merely guarantees that the payoff function is continuous from the right whenever such a discontinuity occurs.

can be a SPNE on as many as M disjoint intervals of estimates. In general, discontinuities in the adoption payoff can occur at estimates of the form $p=\gamma_k$ where $g(\gamma_k)=\alpha_k$ whenever there is at least one waiter that can adopt in period two, or $k<M$. If so, then an increase in p can decrease the SPNE number of adopters from k to $k-1$, and adoption by k firms can be a SPNE on disjoint intervals of p, for any $k=1,...,M-1$.

Theorem 1. In the SPNE, an increase in the initial estimate of high demand can decrease the number of initial adopters. Furthermore, initial adoption by $k<M$ firms can occur on two or more disjoint intervals of estimates.

For example, if N=M=3, then as F changes so that p increases from 0 to 1, the equilibrium number of initial adopters can be 0, 1, 0, 1, 2, 1, 2, 3. If the prior is beta (μ,ν), one can do this by fixing μ, so that p, g(p), and b(p) all increase as ν decreases. This allows one to determine the SPNE as F varies so that p rises from 0 to 1. For this prior, the critical estimates at which discontinuities can occur are given by $\gamma_k=[(\mu+\nu+1)\alpha_k-1]/(\mu+\nu)$ for $k<M$. In the algebraic market model given above, let $\theta^*=9$, A=c, K=2.25, I=.99, and $\delta=.95$. Then $\pi(k,p)=[81p^2/(k+1)^2]-2.25$, $\rho_1=1/3$, $\alpha_1=.4$, $\rho_2=.5$, $\alpha_2=.6$, $\rho_3=2/3$, and $\alpha_3=.8$. Fix $\mu=.4$, and start with an $\nu\geq 2.8$, so $g(p)\leq\rho_1$ and no firms adopt. As ν decreases and p increases, the SPNE have initial adoption by: no firms if p=2/9, firm 1 if p=.298 and g(p)=.598, no firms if p=.3 and g(p)=.6, firm 2 if p=4/11 and g(p)=2/3, firm 1 if p=4/9 and g(p)=.737, firms 1 and 2 if p=.5 and g(p)=7/9, firm 1 if p=8/15 and g(p)=.8, firms 1 and 2 if p=.6 and g(p)=.814, and all firms if p=.8 and g(p)=.933.

Notice that a necessary condition for this result is that adoption does not immediately reveal if the innovation is a success. If adoption immediately reveals the true state to all firms, as assumed in the preceding strategic studies, then the updated good news estimate is g(p)=1 for all p. Thus, good news induces all remaining firms to adopt in the next period. The result of Theorem 1 cannot hold with instantaneous learning because an increase in the initial estimate cannot further increase the updated good news estimate, and thus induce adoption by an additional waiter in the next period.

Another necessary condition is that good news increases the estimate of high demand more than the distance between the critical adoption probabilities. Consider an initial estimate p such that $p<\alpha_{k-1}$ and $g(p)=\alpha_k$. If $k-1$ firms adopt at p, then each suffers a loss in period one because $p<\alpha_{k-1}$ implies $\pi(k-1,p)<I$. Thus, adoption by $k-1$ firms cannot be a SPNE unless the period-two SPNE payoff is large enough to offset this loss. But there is a downward jump discontinuity in the period-two payoff at p, because good news induces adoption in period two by a k^{th} firm. This is why it is possible that adoption by $k-1$ firms is not profitable at p, but is profitable for slightly lower estimates p', where $g(p')<\alpha_k$ and so good news does not induce the k^{th} firm to adopt in period two. Hence, this result requires that $p<\alpha_{k-1}<\alpha_k\leq g(p)$, or $g(p)-p\geq\alpha_k-\alpha_{k-1}$.

How does the condition $g(p)-p \geq \alpha_k - \alpha_{k-1}$ vary with parameters in the model? A mean-preserving increase in the variance of F (e.g., for a beta prior) increases the extent to which good news raises the estimate of high demand, $g(p)-p$. Such an increase in variance is usually interpreted as greater uncertainty, or greater risk, associated with the new good. Next, note that the difference between critical probabilities, $\alpha_k - \alpha_{k-1}$, is decreasing in the number of producers k if increased competition decreases each firm's expected profit at a decreasing rate, or $\pi(k,q)-\pi(k-1,q)$ is decreasing in k. Because α_k is increasing in k, higher initial estimates correspond to larger values of α_k, and so smaller values of $\alpha_k - \alpha_{k-1}$. Last, consider a change such as a decrease in adoption cost or an increase in production profit that increases the number of firms that can profitably adopt a success from M to M+1. Denote the new values where expected profit equals I by β_k. Then one expects $\beta_{k+1}-\beta_k<\alpha_{k+1}-\alpha_k$ (simply because $0<\alpha_1<...<\alpha_M<1$ before the change, but $0<\beta_1<...<\beta_M<\beta_{M+1}<1$ after), in which case the result is more likely after this change. These last two possibilities do hold for reasonable explicit market models, including the one introduced above with $\pi(k,p)=[(A+p\theta^*-c)^2/(k+1)^2]-K$. The next result follows immediately.

Corollary. An increase in the initial estimate of high demand is more likely to decrease the SPNE number of initial adopters, in the sense that $g(p)-p$ increases relative to $\alpha_k-\alpha_{k-1}$, if: (i) the new product is riskier; (ii) the initial estimate is higher; or (iii) the number of firms that can profitably adopt a success is larger.

Recall the specific market model presented after Theorem 1, in which α_1=.4 and α_2=.6. In this case, $\gamma_2=[.6(\mu+\nu)-.4]/(\mu+\nu)$ for any beta (μ, ν). If the prior is a beta (1,1.5), then $p=.4<\gamma_2=.44$ and $g(p)=.57<\alpha_2=.6$. Hence, as the initial estimate increases from below to α_1=.4, the payoff to lone adoption does not suffer a downward jump discontinuity because a second firm will not adopt in the next period at $g(\alpha_1)$. Reducing μ and ν proportionately to obtain a beta (.8,1.2) results in a mean-preserving increase in the variance of the prior, as now $p=\gamma_2=.4$ and $g(p)=\alpha_2=.6$. As the initial estimate increases to α_1=.4, the payoff to lone adoption does suffer a downward jump discontinuity because a second firm adopts in the next period at $g(\alpha_1)=\alpha_2$. Increasing the risk of the innovation, by a mean-preserving increase in the variance of the prior on the probability of high demand, increases the extent to which good news changes the initial estimate from .17 to .2, and generates the result that an increase in the initial estimate decreases the SPNE number of initial adopters.

Now recall that Assumption 2 gives the most innovative firm the advantage of deciding to adopt before its rivals do. An intriguing result is that the most innovative firm is not always one of the first adopters. Recall that a firm adopts initially if and only if its adoption payoff exceeds its waiting payoff. Naturally, this advantage gives a firm an adopting payoff at least as large as that of any less innovative rival. However, it also gives a firm a waiting payoff at least as large as that of any less innovative rival. For example, suppose that if some firms adopt and get good news, then in period two all incumbents continue, but only one of several waiters adopts. Then the most innovative waiter adopts in period two and so has a positive waiting payoff, but all the other waiters do not adopt and so have a zero waiting payoff. Therefore, the most innovative firm may not be one of the first adopters because its waiting payoff is larger. Note well that this argument requires at least three firms: one to adopt initially, so good news is possible, and two others to wait, only one of which can adopt in period two.

Consider, therefore, the SPNE in an example with three firms, N=M=3. Assume the estimates satisfy $p<\alpha_1$, $g(p)\in(\alpha_2,\alpha_3)$, and $b(p)<\rho_1$. The good news estimate is chosen so that at least two firms continue or adopt in period two, but the third firm would not adopt. The bad news estimate is chosen so that no firms continue or adopt in period two. Then the adoption payoff to any firm i is

$$R_i(a;w,w,p)=\pi(1,p)-I+\delta p\pi(2,g(p)) \tag{4}$$

if it adopts alone, and

$$R_i(a;a,w,p)=R_i(a;w,a,p)=\pi(2,p)-I+\delta p\pi(2,g(p)) \tag{5}$$

if it and one rival adopt. If the adoption payoff is positive if one firm adopts but negative if two firms adopt, $\pi(1,p)-I+\delta p\pi(2,g(p))>0>\pi(2,p)-I+\delta p\pi(2,g(p))$, then the SPNE involves initial adoption by one firm, with adoption by one waiter in period two given good news.

That lone adopter, however, may not be firm 1. If it waits, then whether firm 2 or 3 adopts, it is the one waiter that adopts in period two given good news, so its waiting payoff is

$$R_1(w;a,w,p)=\delta p[\pi(2,g(p))-I]. \tag{6}$$

Therefore, firm 1 waits if $\delta p[\pi(2,g(p))-I]>\pi(1,p)-I+\delta p\pi(2,g(p))$. In this event, however, firm 2 cannot afford to wait. If it waits, then firm 3 adopts and its waiting payoff is $R_2(w;w,a,p)=0$ because, given good news, firm 1 is the one waiter that adopts in period two. The unique SPNE in this case has initial adoption by only firm 2. Firm 1 is not the first adopter in this case because it has a larger waiting payoff, while all firms have the same adoption payoff. Firm 1 has a positive waiting payoff because its leadership position guarantees it is the lone adopter in period two, given good news. Firms 2 and 3 have a zero waiting payoff because they have no such guarantee.

Moreover, there are also unique SPNE in which the k most innovative firms are not initial adopters for any k<M. Suppose $p<\alpha_m$, $b(p)<\rho_1$, and $g(p)\in(\alpha_{m+k},\alpha_{m+k+1})$. If $m\leq M-k$ firms adopt initially and get good news, then in period two all incumbents continue, the k most innovative waiters adopt, but no other waiters adopt ($m\leq M-k$ implies $g(p)>\alpha_{m+k}$ is possible). Hence, all firms have the same adoption payoff, firms numbered 1 to k have a positive waiting payoff, but firms numbered k+1 to N have a zero waiting payoff.

The unique SPNE, therefore, can be firms numbered k+1 to k+m adopt initially, but all other firms wait.

Theorem 2. If, and only if, there are at least three firms ($N \geq M \geq 3$), there exist SPNE in which initial adoption occurs, but the adopters do not include the k most innovative firms (for k=1,...M−1).

Again recall the example after Theorem 1. If $p=4/11<\alpha_1=.4$ and $g(p)=2/3>\alpha_2=.6$, we have $R_1(w;a,w,p)=\delta p[\pi(2,g(p))-I]=.262>R_i(a;w,w,p)=\pi(1,p)-I+\delta p\pi(2,g(p))=.041>R_2(w;w,a,p)=0$ and $R_i(a;a,w,p)=\pi(2,p)-I+\delta p\pi(2,g(p))=-1.446<0$. As noted above, the unique SPNE in this case is firm 2 adopts in period one. Then in period two, firm 1 adopts and firm 2 continues given good news in period one, but no firm adopts or continues given bad news.

Hence, if innovative leadership comes from past behavior, the first adopters in the past need not be the first adopters of a current innovation. That is, innovative leadership may, by its nature, be transitory in that yesterday's leaders need not be today's leaders. This interpretation is somewhat problematic, of course, because the analysis also shows the most innovative firms often are first adopters. Nevertheless, it is accurate to say the advantages of innovative leadership include not only a larger adoption payoff, but also a larger waiting payoff that can dominate and thereby preclude the most innovative firms from initial adoption.

Whether a firm adopts first or not, however, its expected SPNE payoff is greater than or equal to that of any less innovative rival. The logic of this result is simple. Suppose firm 1 waits initially. Because it moves first in period two, it adopts if any waiter does, and so its total waiting payoff is no less than that of any other waiter. Similarly, if firm 1 adopts initially, it continues in period two if any incumbent does, and so its adoption payoff is no less than that of any other initial adopter. Hence, firm 1's SPNE payoff is no less than that of any other firm. Analogously, firm 2's SPNE payoff is no less than that of any other firm except possibly firm 1, and so on. This proves the following result.

Theorem 3. Any firm's SPNE payoff is greater than or equal to that of any less innovative rival.

This result says the SPNE payoffs are nonincreasing in the numbering of the firms. This is worth noting because some studies have found that, in sequential move games with two firms, the leader may have a disadvantage in that it earns a smaller payoff than the follower. In Gal-Or [7], for example, this occurs because the leader may produce less than the full-information Cournot output in an attempt to mislead the follower about its private information on the state of demand. Because all information is public in this model, such an effect is not possible. Hence, the fact that firm 1 is not one of the initial adopters does not mean there is a first-mover disadvantage, but rather that the first-mover advantage takes the form of a larger waiting payoff.

Two remarks should be made in concluding this section. First, no attempt has been made to characterize all the equilibria of the entire game. This is essentially a hopeless task due to the large number of possibilities. There are two sources of difficulty. First, the rankings of the critical probabilities are not clear. Although $\alpha_k<\alpha_{k+1}$ and $\rho_k<\rho_{k+1}$, and $\rho_k<\alpha_k$ for all k, the ranking of α_k and ρ_{k+1} is not given. The possibilities range from $\rho_1<\alpha_1<\rho_2<\alpha_2<\rho_3<\alpha_3$, and so on, to $\rho_N<\alpha_1$. As seen in Section 2, uncertainty about these rankings results in the need to consider many possibilities even for the simple case of three firms. Second, even given a fixed ranking of critical probabilities, the variable extent to which good and bad news change the initial estimate creates difficulties. Given $p\in(\alpha_k,\alpha_{k+1})$, all we can conclude is that $g(p)>p>b(p)$. The possibilities include everything from $\alpha_k<b(p)<g(p)<\alpha_{k+1}$ to $b(p)<\rho_1<\max\{\alpha_M,\rho_N\}<g(p)$.

This multiplicity of equilibrium possibilities will only increase exponentially if the analysis is extended to more than two periods. Nevertheless, the main results should carry over to adoption problems of this type with more than two periods. For example, consider the simple extension to three periods. Now an increase in p results in not only a higher g(p) in period two, but also a higher g(g(p)) in period three. Thus, an increase in the initial estimate results in higher updated estimates that could induce adoption by additional firms in both periods two and three. Next, recall the example of Theorem 2 when firm 2 adopts initially and firm 1 adopts in the next stage, given good news. It should be simple to extend this to a three-period example in which firm 3 adopts initially, then firm 2 adopts in period two given good news, and then firm 1 adopts in period three given more good news. Finally, Theorem 3 continues to hold because it follows from the sequence of moves within periods.

4 Alternative Assumptions on Innovative Leadership

It is natural to ask if these results depend critically on the form of innovative leadership. There are two issues. First, do the results hold without leadership in adoption decisions as defined in Assumption 2? Second, do they hold when leadership is derived from a current advantage such as differences in adoption costs or production profits?

The obvious alternative to leadership in adoption decisions is to assume that firms decide to adopt (or continue) or not simultaneously in both periods. More precisely, we could consider replacing Assumption 2 with the following.

<u>Assumption 2'</u>. In period one, the firms simultaneously decide to adopt (pay I) or not. Each firm then observes these actions, and the firms that adopted then make their production choices simultaneously (and collect expected profits). After production, all firms observe if demand was high or low. In period two, all firms move simultaneously in deciding whether to continue or adopt. Firms that have continued or adopted then make their production choices simultaneously, after which all firms observe if demand was high or

low.

There are multiple SPNE under this assumption. For example, if all firms adopt initially, get bad news, and $b(p)\in[\rho_{k-1},\rho_k)$, then the period-two Nash equilibria are any $k-1$ incumbents continue. One might argue any reasonable notion of innovative leadership should imply continuation by the $k-1$ most innovative (lowest numbered) incumbents is the focal point equilibrium. In any event, this outcome is a Nash equilibrium of the subgame. Also, when some but not all waiters adopt in period two, adoption by the most innovative waiters is a Nash equilibrium. Hence, one SPNE of the two-period adoption game with simultaneous adoption decisions can be found by assuming the same period-two SPNE behavior used above for the game with sequential adoption decisions. It then follows that the results of Theorem 1 and its Corollary hold in this game because they depended on only the discontinuity in the period-two expected payoff.

Now consider period one when firms decide to adopt or not simultaneously in period one and period-two behavior is given as above. Suppose N=M=3, $p<\alpha_2$, $g(p)\in(\alpha_2,\alpha_3)$, and $b(p)<\rho_1$. Let $S_i(a;s_j,s_k,p)$ and $S_i(w;s_j,s_k,p)$ be the adopting and waiting payoffs in this game given p and rival strategies (s_j,s_k). Given bad news, no incumbents continue and no waiters adopt in period two. If two firms adopt and get good news, then in period two they continue, but the waiter does not adopt. Similarly, if one firm adopts and gets good news, then in period two it continues and the more innovative waiter adopts, but the other waiter does not adopt. Hence, for any firm i,

$$S_i(a;a,w,p)=S_i(a;w,a,p)=\pi(2,p)-I+\delta p\pi(2,g(p)) \quad (7)$$

$$S_i(w;a,w,p)=S_i(w;w,a,p)=S_i(w;a,w,p)=\delta p[\pi(2,g(p))-I], \quad (8)$$

and

$$S_i(w;w,a,p)=S_i(w;a,w,p)=S_i(w;w,a,p)=0. \quad (9)$$

The SPNE has firms 2 and 3 adopt initially, but firm 1 waits, if $S_2(a;w,a,p)>S_2(w;w,a,p)$, $S_3(a;a,w,p)>S_3(w;a,w,p)$, and $S_1(a;a,w,p)<S_1(w;a,w,p)$ (notice that the last inequality implies $S_1(a;s_2,a,p)<S_1(w;a_2,a,p)$ for all s_2). This occurs if $\delta p[\pi(2,g(p))-I]>\pi(2,p)-I+\delta p\pi(2,g(p))>0$, which is possible because $\pi(2,p)<I$. Firm 1 will not adopt with either firm 2 or 3 because, given that one rival adopts, its waiting payoff exceeds its adopting payoff. The same is true for firm 2 if the rival that adopts is firm 1. However, if the rival that adopts is firm 3, then firm 2's total waiting payoff is 0, less than its adopting payoff, because firm 1 is the lone adopter in period two given good news. Firm 3's waiting payoff is similarly 0 if either firm 1 or 2 is the rival that adopts. Again, firm 1 is not an initial adopter because its waiting payoff is higher. Notice firm 1's SPNE payoff (its waiting payoff) is greater than those of firms 2 and 3 (their adopting payoffs), so Theorem 3 holds here also.

Naturally, Theorems 2 and 3 cannot hold for all SPNE of the entire game with simultaneous adoption decisions in each period. However, this is a moot point because examining all SPNE discards any notion of leadership. The main point is that, in any equilibrium where some but not all firms will adopt in the future, those firms which are "guaranteed" leadership in the future have a greater waiting payoff, and thus have a smaller incentive to adopt immediately. In these cases the initial adopters may be those firms not guaranteed leadership in the future.

Finally, note well that these results do not require a ranking based on past behavior only. For example, the ranking of firms as innovators could be based on lower numbered firms having lower R&D costs or higher expected profits. Firm i could have R&D cost I_i, where $I_1<...<I_N$, or expected profit $\pi_i(k,q)$, where $\pi_1(k,q)>...>\pi_N(k,q)$. It is evident that the examples above for both the simultaneous and sequential move games can be used to obtain the same results as long as the differences in R&D costs or expected profits are sufficiently small.

Return to the explicit market example following Theorem 1, now with simultaneous moves in each period. As p increases, the SPNE have initial adoption by: no firms if p=2/9, firm 1 if p=2/7 and g(p)=7/12, no firms if p=.3 and g(p)=.6, firm 1 if p=4/11 and g(p)=2/3, firms 2 and 3 if p=.5 and g(p)=7/9, firm 1 if p=8/15 and g(p)=.8, firms 1 and 2 if p=.6, and all firms if p=.8. This shows Theorems 1 and 2 are not vacuous for this adoption game.

Finally, modify this example by assuming firm i has adoption cost I_i, and $I_1=.9<I_2=.99<I_3=1.3$ is the basis for the innovative ranking. Then, again, initial adoption by firm 2 is the unique SPNE of the sequential move game if p=4/11 and g(p)=2/3, and initial adoption by firms 2 and 3 is a SPNE of the simultaneous move game if p=.5 and g(p)=7/9.

5 Concluding Remarks

This paper has examined innovation adoption when uncertainty about its profitability persists over some time, rather than being resolved instantaneously by the initial adoption. In this case, favorable information from some firm's adoption may induce future adoption by other firms, but in general will not induce adoption by all remaining firms. This leads to somewhat more realistic dynamics in the sense that a favorable experience by one firm does not imply the diffusion is completed in the next instant. Although only two periods were analyzed, one can see how an extension to additional periods would allow outcomes where the innovation realistically diffuses through the industry (i.e., some but not all remaining firms adopt at future dates as the estimates probability of success increases over time with the observation of more favorable experiences).

One interesting implication of this non-instantaneous learning approach is that an increase in the initial estimate of high demand can reduce the initial number of adopters. The reason is that an increase in the initial estimate also increase the estimate to which all firms would update in the next period if the adopters had favorable experiences. Hence, such an increase in the estimate can decrease the future profit expected from adoption by inducing an additional firm to adopt tomorrow. This obviously cannot happen in an instantaneous learning model where a favorable experience leads to adoption by all remaining firms in the next period.

Another interesting result is that innovative leadership (in the form of a first-mover advantage) does not guarantee that the most innovative firms always adopt first. Innovative leadership need not imply first adoption because it can give the leader a larger incentive to wait and free ride on its rivals' experience. The conditions that imply this result are not pathological. They are: a more innovative firm decides whether to adopt before less innovative rivals do (at least at the last decision date); profit from the innovation is stochastic; a waiter can learn from rival adoption; and if at least one firm adopts, then some but not all waiters adopt in the next period (i.e., at least three firms). The result therefore also can hold in a game with any finite number of periods as long as there is a terminal subgame in which there are at least two waiters, not all of whom can adopt. Moreover, the result is also sensible because more innovative firms earn larger expected payoffs from the current innovation than do their less innovative rivals.

6 Appendix

6.1 Proof of Theorem 1

For $k=1,...,M-1$, define γ_k by $g(\gamma_k)=\alpha_k$, so $g(p) \gtrless \alpha_k$ if and only if $p \gtrless \gamma_k$. Let F be a prior such that $b(p)<\rho_1$ and $\rho_k<p<\gamma_{k+1}<\alpha_k$, which implies $g(p)\in(\alpha_k,\alpha_{k+1})$. If k firms adopt initially, then each has total adoption payoff $\pi(k,p)-I+\delta p\pi(k,g(p))$ because in period two all k incumbents continue and no waiters adopt given good news, but no incumbents continue and no waiters adopt given bad news. Similarly, if $m>k$ firms adopt initially, then by Assumption 1 each has a maximum possible total adoption payoff of $\pi(m,p)-I+\delta p\pi(k,g(p))$. Assume that $\pi(k,p)-I+\delta p\pi(k,g(p))>0$, but $\pi(m,p)-I+\delta p\pi(k,g(p))<0$ for all $m>k$. Then initial adoption by some k firms must be a SPNE. Now change F so that $p=\gamma_{k+1}$ and $g(p)=\alpha_k$. Also assume that $b(\gamma_k)<\rho_1$ (this is convenient, not necessary). Now if k firms adopt initially, each has total adoption payoff $\pi(k,\gamma_{k+1})-I+\delta\gamma_{k+1}\pi(k+1,\alpha_{k+1})$ because in period two all k incumbents continue, the most innovative waiter adopts by Assumption 3, but no other waiters adopt given good news (again no incumbents continue and no waiters adopt given bad news). By Assumption 1, it is possible that both $\pi(k,\gamma_{k+1})-I+ \delta\gamma_{k+1}\pi(k,\alpha_{k+1})>0$ and $\pi(k,\gamma_{k+1})-I+\delta\gamma_{k+1}\pi(k+1,\alpha_{k+1})<0$ hold simultaneously. If so, then for arbitrarily small $\varepsilon>0$, the SPNE is k firms initially adopt if $p=\gamma_{k+1}-\varepsilon$. However, at $p=\gamma_{k+1}$, the SPNE is $k-1$ firms adopt if $\pi(k-1,\gamma_{k+1})-I+\delta\gamma_{k+1}\pi(k+1,\alpha_{k+1})>0$. And if $\pi(k-1,\gamma_{k+1})-I+\delta\gamma_{k+1}\pi(k+1,\alpha_{k+1})<0$ and $\pi(k-2,\gamma_{k+1})-I+\delta\gamma_{k+1}\pi(k+1,\alpha_{k+1})>0$, then the SPNE is $k-2$ firms adopt (and so on). The example in the text shows this is possible.

Now change F so $p=\alpha_k$, $g(\alpha_k)\in(\alpha_{k+1},\alpha_{k+2})$, and $b(\alpha_k)<\rho_1$. Because $\pi(k,\alpha_k)=I$ and period two expected payoffs are nonnegative, any firm's total adopting payoff is nonnegative if k firms adopt initially. Hence, at least k firms must adopt initially in the SPNE. If $m>k$ firms adopt initially, then any firm's maximum possible total adopting payoff is $\pi(m,\alpha_k)+\delta p\pi(k+1,g(\alpha_k))$ because at least k+1 firms continue or adopt in period two given good news. So, if $\pi(m,\alpha_k)+\delta p\pi(k+1,g(\alpha_k))<0$, which is possible because $\pi(m,\alpha_k)<\pi(k,\alpha_k)=I$ for all $m>k$, then initial adoption by more than k firms cannot be a SPNE. Adoption by k firms is a SPNE at $p=\gamma_{k+1}-\varepsilon$ and $p=\alpha_k$, but not at $p=\gamma_{k+1}\in(\gamma_{k+1}-\varepsilon,\alpha_k)$.

6.2 Proof of SPNE in Example for Theorem 2

The SPNE for the entire game are found by computing the SPNE in period one using (1)−(3). This is done by inducting backward in period one, starting with firm 3, who observes if firms 1 and 2 adopted or not. Notice no incumbents continue and no waiters adopt in period two given bad news because $b(p)<\rho_1$. Suppose firms 1 and 2 adopted. If firm 3 adopts and there is good news, then in period two firms 1 and 2 continue because $g(p)>\rho_2$, but firm 3 does not continue because $g(p)<\rho_3$. If firm 3 waits and there is good news, then in period two firms 1 and 2 continue, but firm 3 does not adopt because $g(p)<\alpha_3$. Next suppose either firm 1 or 2 (but not both) adopted. If firm 3 adopts and there is good news, then in period two it and the other incumbent continue, but the waiter does not adopt. If firm 3 waits and there is good news, then in period two the incumbent continues, the other waiter adopts, but firm 3 does not adopt. Now suppose firms 1 and 2 wait. If firm 3 adopts and gets good news, then in period two it continues, firm 1 adopts, but firm 2 does not adopt. If firm 3 waits, so all wait in period one, then no firm adopts in period two because $p<\alpha_1$. Hence,

$$R_3(a;a,a,p)=\pi(3,p)-I+\max\{\delta p\pi(3,g(p)),0\},$$

$$R_3(a;a,w,p)=R_3(a;w,a,p)=\pi(2,p)-I+\delta p\pi(2,g(p)),$$

$$R_3(a;w,w,p)=\pi(1,p)-I+\delta p\pi(2,g(p)),$$

and $R_3(w;s_1,s_2,p)=0$ for all (s_1,s_2). Recall $R_3(a;a,w,p)<0$ by assumption. This and Assumption 1 imply that $R_3(a;a,a,p)<0$. And because $R_3(a;w,w,p)>0$ by assumption also, firm 3 adopts if and only if firms 1 and 2 both wait.

Next consider firm 2's decision, after observing firm 1's choice and knowing (as determined above) how firm 3 will behave after it moves. If firm 1 adopts, then firm 2 knows that, whatever its decision, firm 3 waits. If firm 2 adopts and there is good news, then in period two it and firm 1 continue, but firm 3 does not adopt, so $R_2(a;a,w,p)=R_3(a;a,w,p)$. If firm 2 waits and there is good news, then in period two it adopts, firm 1 continues, but firm 3 does not adopt, so

$$R_2(w;a,w,p)=\delta p[\pi(2,g(p))-I].$$

Suppose instead firm 1 waits. If firm 2 adopts and there is good news, then in period two it continues, firm 1 adopts, but firm 3 does not adopt, so $R_2(a;w,w,p)=R_3(a;w,w,p)$. If firm 2 waits (so firm 3 adopts) and there is good news, then in period two firm 3 continues, firm 1 adopts, but firm 2 does not adopt, so $R_2(w;w,a,p)=0$. Because $R_2(a;a,w,p)<0$ and $g(p)>\alpha(2)$ implies $R_2(w;a,w,p)>0$, firm 2 waits if firm 1 adopts. But because $R_2(a;w,w,p)>0$, firm 2 adopts if firm 1 waits. Hence, firm 2 adopts if and only if firm 1 waits.

To finish the induction, consider firm 1's decision, knowing how firms 2 and 3 will behave after its choice (as determined above). If firm 1 adopts and gets good news, then in period two it continues, firm 2 adopts, but firm 3 does not adopt, so $R_1(a;w,w,p)=R_3(a;w,w,p)$. If firm 1 waits, then firm 2 adopts. If there is good news, then in period two firm 1 adopts, firm 2 continues, but firm 3 does not adopt, so $R_1(w;a,w,p)=R_2(w;a,w,p)$. Again note that $R_1(w;a,w,p)>0$ because $g(p)>\alpha_2$. Hence, the conditions $\delta p[\pi(2,g(p))-I]>\pi(1,p)-I+\delta p\pi(2,g(p))>0$, which certainly can hold simultaneously because $\pi(1,p)<I$, imply that $R_1(a;w,w,p)<R_1(w;a,w,p)$, in which case the unique SPNE is firm 2 adopts alone initially.

6.3 Proof of Theorem 2

For any $m=1,\ldots,M-1$, assume a prior F such that $p<\alpha_m$, $b(p)<\rho_1$, and $g(p)\in(\alpha_{m+1},\alpha_{m+2})$. Also assume $\pi(n,p)-I+\delta p\pi(m+1,g(p))<0$ for all $n>m$. Then because each firm's maximum possible total adopting payoff if $n>m$ firms adopt initially is $\pi(n,p)-I+\delta p\pi(m+1,g(p))<0$ and the minimum possible total waiting payoff is 0, initial adoption by m+1 or more firms is not a SPNE. Next assume $\delta p[\pi(m+1,g(p))-I]>\pi(m,p)-I+\delta p\pi(m+1,g(p))>0$. This is possible because $\pi(m,p)<I$, but $\pi(m+1,g(p))>I$. Then initial adoption by firms numbered 2 through m+1, but waiting by firm 1 and firms numbered m+2 to N (if $N\geq M+1$) is the unique SPNE. To see this, notice if m firms adopt initially, then only the most innovative waiter adopts in period two given good news. Hence, firm 1's total waiting payoff is $\delta p[\pi(m+1,g(p))-I]$. Moreover, if firm 1 waits, firms 2 through m+1 adopt initially because they have a total waiting payoff of 0, and the total adopting payoff to each firm is $\pi(m,p)-I+\delta p\pi(m+1,g(p))>0$. Finally, firm 1's total waiting payoff is greater because $\delta p[\pi(m+1,g(p))-I]>\pi(m,p)-I+\delta p\pi(m+1,g(p))$. This proves the "if" part for the case where firm 1 is not one of $m\leq M-1$ initial adopters. The proofs for the cases where firms 1 to k are not the $m\leq M-k$ initial adopters are entirely analogous.

The “only if” part is proved by showing that if N=M=2, then firm 2 adopting initially cannot be the unique SPNE. If firm 2 adopts alone, then firm 1’s total waiting payoff is 0 if $g(p)<\alpha_1$, $\delta p[\pi(2,g(p))-I]$ if $b(p)<\alpha_1\leq g(p)$, and $\delta[p\pi(2,g(p))+(1-p)\pi(2,b(p))-I]$ if $b(p)\geq\alpha_1$. This is also firm 2’s total waiting payoff if firm 1 adopts alone (because, unlike the example in Section 3, there is no firm behind firm 2 to adopt initially and exclude if from adopting in period two). Hence, because its total lone adoption payoff is less than or equal to firm 1’s by Theorem 3, firm 2 adopting alone cannot be the unique SPNE.

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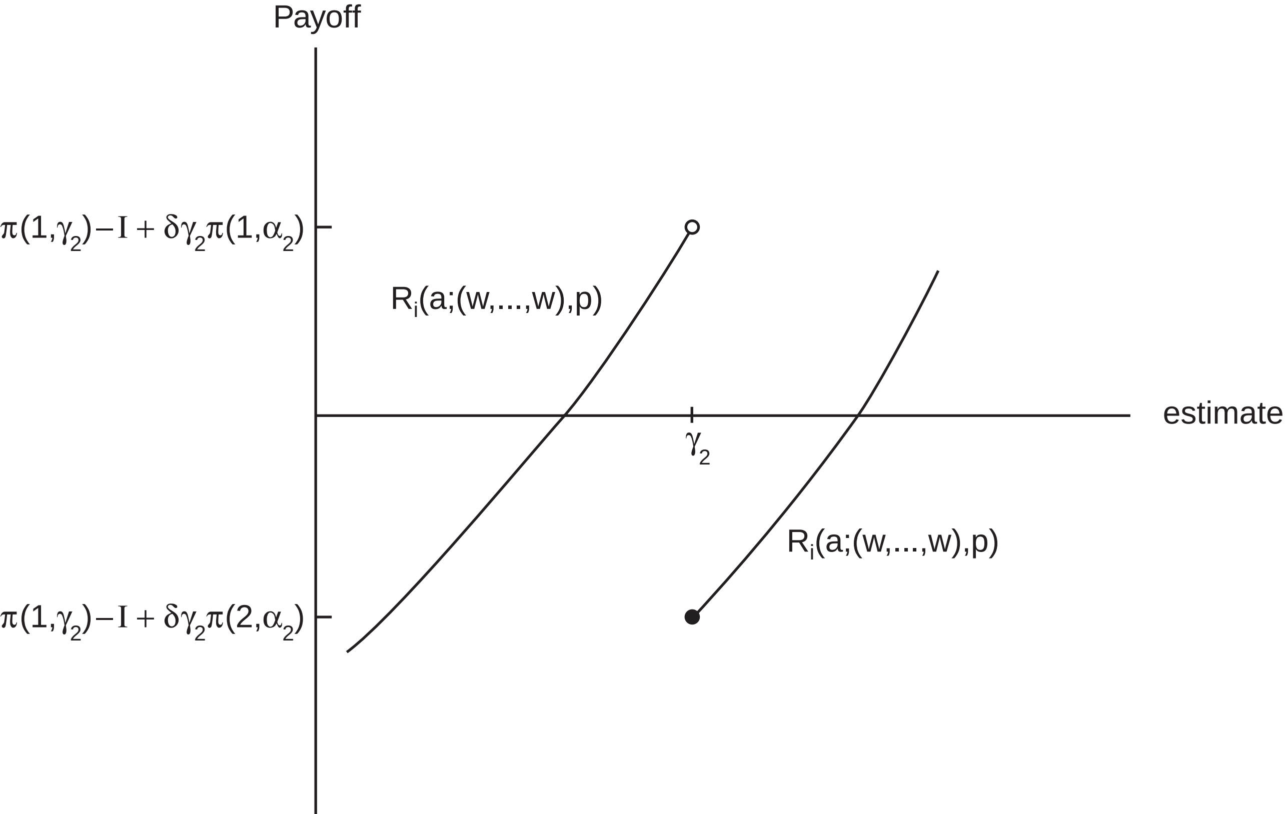
Payoff
π(1,γ2)−I + δγ2π(1,α2)
π(1,γ2)−I + δγ2π(2,α2)
Ri(a;(w,...,w),p)
Ri(a;(w,...,w),p)
γ2
estimate