A Dynamic Pricing Game in a Model of New Product Adoption with Social Influence

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***Abstract*—We examine a pricing game between firms that produce differentiated products and in which consumer preferences evolve in response to the market shares of the available products. One of the products is new and a subset of consumers (early adopters) have a relatively strong preference for it, while the remaining consumers are influenced by the relative market shares of the two products, being drawn to the product with the higher market share. We use a system of PDEs to specify the evolution of the preferences for the alternative goods. This system is nonlinear due to the influence of existing consumption choice on the distribution of preferences. The pricing game allows firms to react to the changing distribution of consumer preference. We find that allowing for the evolution of consumer preference in this way results in interesting dynamics for prices. In particular, price paths can be non-monotonic over time.**

***Keywords*-product adoption; price game; social influence**

I. Introduction

Firms' pricing decisions are key to understanding the adoption of products by consumers. These decisions take on additional complexity when consumers' preferences are subject to social influence: the value of adopting a product depends on the extent to which other consumers are also adopting the product. A particular difficulty that is raised by looking at social influence in consumer choice is that preferences themselves become dynamic as they are affected by past decisions of other consumers. We examine a pricing game in which two firms must set prices for their products when preferences are affected by social influence. We allow consumer preferences to evolve depending on market shares of the available products and examine a pricing game between two firms producing differentiated products.

The analysis of new product adoption has become more socially significant in recent years as the desire to lessen the environmental impact of consumption decisions has increased. New product adoption is important as new generations of products have more benign environmental impacts. Examples range from automobiles to household appliances. A common feature of new, environmentally friendly products is that consumers often do not have much if any experience with them, often resulting in a barrier to their adoption in addition to any price or advertising influences.

We model individual consumer behavior at any given time using the standard characteristics approach to a differentiated product market developed in [1] and [2]. The standard model however, considers consumer preferences as static in that they do not change in response to the introduction of new or innovative products. Consequently, these models are silent on the rate of adoption of new products. We differ from this standard approach in that we allow the distribution of consumer preferences over product characteristics to evolve over time. In this way, we provide a micro-foundation for the aggregate choice dynamics in the innovation adoption literature. In particular, we examine two types of agents: "adopters," whose preferences gravitate towards new products, and "followers", who have preferences that evolve towards products that are popular.

There is a large literature on the adoption and diffusion of innovation which has been applied to the adoption of new products. Early models of product adoption built upon the Bass model of innovation diffusion, [3], which models the proportion of the population adopting the innovation as following a differential equation in which the rate of adoption is influenced by the current level of adoption. Price was incorporated into this model in [4] and [5], [6] who examine the price dynamics of a single firm. The model was extended to allow competition among firms in [7], [8], and [9]. Alternative ways to model social influence in these models was examined in [10] and [11] .

A number of papers examine diffusion paths when consumers are uncertain about product quality. In this case market share can be used by consumers as a signal about product quality, generating S-shaped adoption curves: [12], [13], [14], [15] are contributions using this approach. In contrast, in our model consumers are perfectly informed about product characteristics and the dynamics are generated through social influence.

It is well known that many of the new products offered never attain any sizable market share. When these new products are socially desirable (such as having lower environmental impact) there is interest in government policy to foster adoption. This has been examined by [16], [17], [18], and [19]. The models we develop are particularly useful for analysis of subsidies for environmentally friendly products or taxes on environmentally harmful products on the relative adoption of these products.

In what follows, we first describe the model we use for the dynamics of consumer preferences and then the pricing game played by firms. We then present some results from simulation of the model, examining the effects of price flexibility, the extent of differentiation, and cost differentials on the equilibrium price and market share paths.

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II. Evolving Consumer Preferences

In this section we first describe the method we use to model the time-evolution of consumer preferences and then present our application of this method to two consumer types.

A. Time-Dependent model of consumer preferences

We extend the standard model of consumer preferences over differentiated products of [2], to allow for preferences to evolve depending on what products other consumers are choosing. The main components of the static model are the same as in [2]:

1) The interval $[0, L]$ is the characteristics space, where we place two products at unique locations.
2) Consumers are distributed in $[0, L]$ according to a continuous and strictly positive density function $f(z,t)$. A consumer's location indicates its most preferred variant of the product.
3) Each consumer purchases the variant that provides them the greatest utility, given by
$$U_i(z, p_i) = \alpha_i - p_i - \gamma(z - z_i)^2, \quad i = 1, 2 \qquad (1)$$
for a consumer located at z, with α_i representing a one-dimensional quality index of variant i, and p_i its price. The parameter γ adjusts the dis-utility of purchasing a product other than the most preferred.
4) The *market space* of variant i is
$$\begin{aligned} M_i(p) = \{z \in \mathbb{R}^m : U_i(z, p_i) \geq 0,\\ U_i(z, p_i) \geq U_j(z, p_j), \quad i, j = 1, 2\}. \end{aligned} \qquad (2)$$
Consumers may choose to buy neither of the available variants if the utility received from both is negative.
5) The *demand for variant i* is
$$X_i(p) = \int_{M_i(p)} f(z,t)dz \qquad (3)$$

where $p = (p_1, p_2)$.

We wish to allow the distribution of consumer preferences, $f(z)$, to vary over time in response to social influences, so the density becomes $f(z,t)$. To that end, we postulate a flux, $\phi(z,t)$, which measures the movement of consumers across the point z at time t. It is through the specification of this flux function that we allow for social influence on preferences.

Consider any range $a \leq z \leq b$ for $a, b \in [0, L]$. The mass of consumers on this range is given by
$$\int_a^b f(z,t)dz.$$
This mass can only change by consumers moving across the boundaries a and b, as measured by $\phi(a,t)$ and $\phi(b,t)$. We then have
$$\frac{d}{dt}\int_a^b f(z,t)dz = \phi(a,t) - \phi(b,t). \qquad (4)$$
We have that
$$\phi(a,t) - \phi(b,t) = -\int_a^b \phi_z(z,t)dz \qquad (5)$$
as long as ϕ has continuous first partial derivatives. If f also has continuous first partial derivatives (4) can be written as
$$\int_a^b [f_t(z,t) + \phi_z(z,t)]dz = 0. \qquad (6)$$
Since this must be true for any (a, b), the distribution of consumer preferences must satisfy
$$f_t(z,t) + \phi_z(z,t) = 0. \qquad (7)$$
Given an initial distribution, $f(z, 0)$, (7) describes the evolution of $f(z,t)$. Note that (6) implies
$$\int_0^L [f_t + \phi_z]dz = 0 \qquad (8)$$
or
$$\frac{d}{dt}\int_0^L f(z,t)dz = \phi(0,t) - \phi(L,t). \qquad (9)$$
In order for the population of consumers to remain constant, the left hand side of (9) must be zero. Consequently, the flux function must satisfy
$$\phi(0,t) = \phi(L,t) \qquad \forall t \qquad (10)$$
for the population of consumers to not change.

In summary, to find the distribution of consumers at any time, t, we solve the PDE (7) with boundary conditions (10) and initial condition $f(z, 0)$.

B. Application to two consumer types

Consider the population of consumers as consisting of two general types: Adopters (A) and Followers (F). The density of consumer preferences is then given by
$$f(z,t) = f^A(z,t) + f^F(z,t), \forall t \in [0, T] \qquad (11)$$
where $f^A(z,t)$ is the distribution of Adopters and $f^F(z,t)$ is the distribution of Followers. The two personality types differ in how their preferences evolve over time. We express this evolution via a partial differential equation for each type. In particular, the density of each type follows the following convection-diffusion equation:
$$f_t^j + \left[v^j(z,t)f^j(z,t)\right]_z = \beta f_{zz}^j \qquad (12)$$
with $j \in A, F$, where the $v^j(z,t)$ term governs the evolution of the density of personality type j. The diffusion term, βf_{zz}^j maintains heterogeneity in consumers preferences. Without the diffusion component consumers preferences would become identical over time. In order to maintain a constant population of consumers, or (equivalently) that consumer's preferences remain within $[0, L]$, we impose the following boundary conditions on (12):
$$f_z^j(0,t) = f_z^j(L,t) = 0, \qquad \forall t \in [0, T] \qquad (13)$$

We examine only two goods here, so these velocity functions are given by

$$v^A(z,t) = \delta_A \frac{z(z-z_2)(z-L)}{((z-z_2)^2+L)^2} \tag{14}$$

$$v^F(z,t) = \delta_F \left[X_1 \frac{z(z-z_1)(z-L)}{((z-z_1)^2+L)^2} + X_2 \frac{z(z-z_2)(z-L)}{((z-z_2)^2+L)^2} \right] \tag{15}$$

where z_1 is the location of product one and z_2 is the location of product two. We consider product 2 to be the newer product, so adopters gravitate toward its location, while the movement of followers depends on the relative market shares of the two goods. The larger the market share of a good, the more strongly Followers are pulled towards it. The parameters $\delta_A > 0$ and $\delta_F > 0$ allow us to control the speed of adjustment of the two types of consumers. Finally, by ensuring that the velocities are zero at the bounds of the characteristic space, these functional forms allow the boundary conditions to be satisfied. These boundary conditions ensure that the population of consumers remains constant over time.

III. Pricing Game

Given the dynamic behavior of consumers, we now specify the pricing game played by the two firms. We assume that firms behave myopically: each firm sets price to maximize its current profit given the price of its rival. Profit is given by

$$\Pi_i(p_1,p_2,t) = p_i X_i(p,t) - C_i(X_i(p,t)), \tag{16}$$

where $C_i(X_i)$ is the cost function for firm i.[1] Computing the market space for each firm is straightforward:

$$M_i(p) = \{z \in \mathbb{R}^m : U_i(z,p_i) \geq 0, U_i(z,p_i) \geq U_j(z,p_j)\}. \tag{17}$$

Using (1), we have

$$M_1(p) = \{z : z \in [z_1 - \sqrt{(\alpha_1 - p_1)/\gamma}, z_1 + \sqrt{(\alpha_1 - p_1)/\gamma}]\} \cap \{z : z \leq z^*\} \tag{18}$$

and

$$M_2(p) = \{z : z \in [z_2 - \sqrt{(\alpha_2 - p_2)/\gamma}, z_2 + \sqrt{(\alpha_2 - p_2)/\gamma}]\} \cap \{z : z > z^*\} \tag{19}$$

where

$$z^* = \frac{(\alpha_1 - \alpha_2) + (p_2 - p_1) + \gamma(z_2^2 - z_1^2)}{2\gamma(z_2 - z_1)}. \tag{20}$$

A consumer located at z^* is indifferent between consuming either product. Note that the market spaces do not depend on time explicitly, they only depend on the current prices of the two firms. Assuming $z_2 > z_1$ we have

$$X_1(p,t) = \int_{M_1(p)} f(z,t)dz = \int_{a_1(p)}^{b_1(p)} f(z,t)dz \tag{21}$$

[1]Since these products embody different characteristics and are thought to be developed at different points in time, we allow for different cost functions for each firm.

and

$$X_2(p,t) = \int_{M_2(p)} f(z,t)dz = \int_{a_2(p)}^{b_2(p)} f(z,t)dz. \tag{22}$$

where

$$a_1(p) = \max\left[0, z_1 - \sqrt{(\alpha_1 - p_1/\gamma)}\right],$$
$$b_1(p) = \min\left[z^*, z_1 + \sqrt{(\alpha_1 - p_1/\gamma)}\right],$$
$$a_2(p) = \max\left[z^*, z_2 - \sqrt{(\alpha_2 - p_2/\gamma)}\right],$$
$$b_2(p) = \min\left[L, z_1 + \sqrt{(\alpha_1 - p_1/\gamma)}\right].$$

The optimal static price choice for a firm must satisfy

$$\frac{\partial \Pi_i}{\partial p_i} = X_i(p,t) + (p_i - C_i'(X_i(p,t)))\frac{\partial X_i(p,t)}{\partial p_i} = 0 \quad i = 1,2 \tag{23}$$

with

$$\frac{\partial X_1(p,t)}{\partial p_1} = \frac{\partial X_2(p,t)}{\partial p_2} = -\frac{f(z^*,t)}{2\gamma(z_2 - z_1)}. \tag{24}$$

For our game, we have firms maximize instantaneous profit $\Pi_i(p)$, and do not allow them to adjust their price at arbitrary $t \in [0,T]$, but only at certain times t_k, $k \in \{0,\ldots,s\}$ where

$$0 = t_0 < t_1 < \ldots < t_s = T \tag{25}$$

The price on each interval $[t_k, t_{k+1})$, $k \in \{0,\ldots,s-1\}$ must remain constant, and are obtained solely based on the population distribution at the time t_k. Essentially, we are modelling two firms who choose their prices so as to maximize their profits at given times t_k. We could also say that they try to maximize their profit under the assumption that the demand for their product (and that of their competitor's) will remain constant over (t_k, t_{k+1}), or equivalently that they do not know how their choice of price will affect future demand.

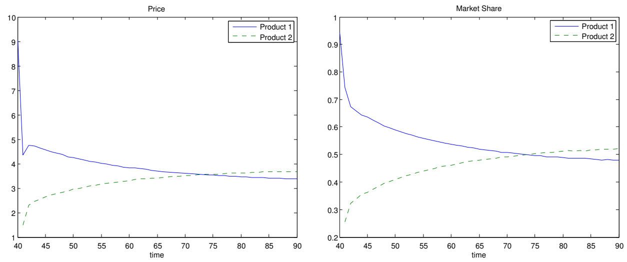
IV. Simulations

We begin by presenting a baseline model in which firms set price in a simultaneous move game each "period". Between periods t and $t+1$, the PDE is solved to provide the distribution of consumers for the $t+1$ game.[2] For this baseline model, we use the parameter values: $z_1 = 4$, $z_2 = 6$, $L = 10$, $\beta_1 = \beta_2 = 0.05$, $\alpha_1 = \alpha_2 = 10$, $c_1 = c_2 = 0$, $\delta_A = 5$ and $\delta_F = 1$. The proportion of the population that are Adopters is 10%.

A useful initial condition for the price game is to run the model with just firm one active for a number of periods (we use 40) prior to the introduction of the new product. This allows both consumers' tastes and the incumbent firm's price to adjust to the monopoly level. Hence, the distribution of consumer preferences upon the entry of firm two (the start of the game) is consistent with monopoly behavior by firm one.

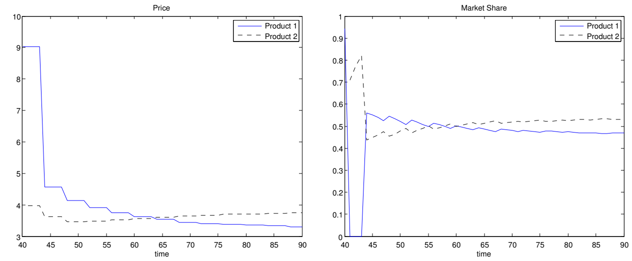
In Figures 1a and 1b we plot the prices and market shares for the two firms for 50 periods following the entry of the new product. The price for product one in period 40 is the monopoly price charged by firm one. Firm two initially sets

[2]We solve the PDEs using Matlab's "pdepe" solver.



(a) Price (b) Sales

Fig. 1: Price and Sales: Baseline



(a) Price (b) Sales

Fig. 2: Price and Sales: Scenario 2

a relatively low price ($p_2 \approx 1.5$) since it has few consumers located near it. This forces firm one to cut its price in half from its monopoly level. The market share for firm two rises quickly immediately following its entry resulting in it raising its price steeply after entry. Initially this allows firm one to raise its price as well, but over time, consumers gravitate towards the location of product two as its market share builds. This allows firm two to continue raising price while still gaining sales. In contrast, firm one loses sales even as it reduces price. Ultimately, the market settles with firm two enjoying a larger market share and a higher price than firm one.

Figures 1a and 1b illustrate behavior that is common to most of our simulations. A firm's price and sales are positively correlated over time: firm one's sales fall as it lowers its price while firm two's sales increase as it increases its price. This effect is due to the movement of consumers preference. As product two gains market share, the mass of consumers moves closer to product two's location. This increased mass of consumers located near product two allows firm two to increase its price without losing market share. Firm one faces the opposite force: as the mass of consumers moves away from the location of product one, it must lower its price as consumers are more and more located further away from its product. These forces have a second implication for prices in that the prices of the two firms are largely negatively correlated over time. In Figure 1a the price of product one falls over time as the price of product two rises, which is contrary to the usual prediction of models of price competition in which prices are strategic complements. While prices in this game are strategic complements in the myopic game played in each period, the evolution of consumers' preferences causes firms prices to be negatively correlated over time.

A. Reducing price flexibility

Scenario 2: In this scenario, we keep all parameters at the same values as in the baseline case, but we lengthen the time between price changes. Firms now play the price game every fourth period.

We examine the effects of reducing price flexibility by lengthening the time for which a firm's price is fixed (reducing the frequency at which a firm can vary price). We plot the price and market shares for this scenario in Figures 2a and 2b. The initial price of product 2 now higher, as firm one's price is fixed, but firm one makes a larger price response when it is first able to change its price.[3] By delaying its ability to respond the the entry of the new product, the distribution of consumers has shifted more in firm 2's favor, resulting in firm one needing to charge a lower price in response. This shift in consumer preference is seen dramatically in Figure 2b where firm one's sales actually drop to zero before it is able to adjust its price. In contrast, when firm one can respond immediately following entry of the new product, it is able to stem the loss in market share (Figure 1b).

The decreasing flexibility of pricing has a dramatic effect on the shape of the path of firm 2's price. The immediate competition from firm one in the baseline model results in firm two entering with a relatively low price, whereas when firm one's price is fixed for a couple of periods following entry, firm two enters with a higher price which it then lowers as firm one reduces its price. Once firm two builds sufficient market share, it is able to increase its price again. Note that firm two's price in Figure 2a remains above its initial price that it sets in the baseline scenario (Figure 1a). Although firm one responds more strongly in this scenario, it does so later, which allows firm two to generate larger market share and consequently speeds the movement of consumers towards product two. This effect results in substantially higher profit for firm two at firm one's expense.

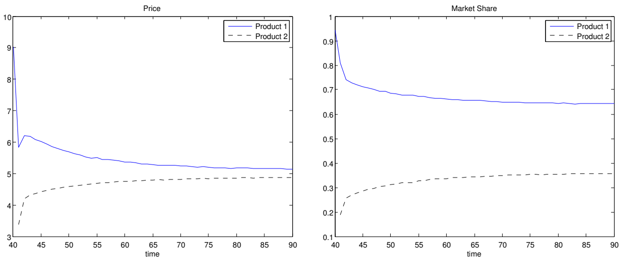
Also striking is that the volatility of market shares increases and as the flexibility of pricing is reduced. Ultimately though, the final levels of sales and prices are not significantly affected.

B. Cost differentials

So far we have assumed symmetric (and zero) costs of production of the alternative products. However, when a new product represents an innovation, often its cost of production is higher than the existing one.[4] To see the effects of cost differentials on the equilibrium, we modify Scenario 1 by having firm two produce product two at a cost of $2 per unit, maintaining firm one's production cost at zero.

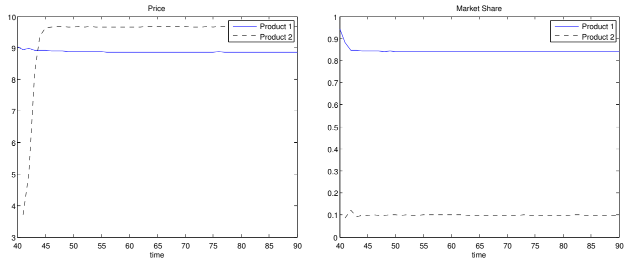
[3]While the game is symmetric following the introduction of the new product, in the period of introduction firm two is able to set its price while firm one's price remains fixed at the pre-entry level.

[4]If there are learning-by-doing effects, the unit cost of the new product will fall over time with cumulative production.



(a) Price (b) Sales

Fig. 3: Price and Sales: Scenario 3



(a) Price (b) Sales

Fig. 4: Price and Sales: Scenario 4

Scenario 3: New product costs more to produce ($c_2 = 2$ vs. $c_2 = 0$).

Price and market share for this scenario are plotted in Figures 3a and 3b. Compared to the baseline, the cost disadvantage faced by the new product causes it to enter with a higher price and consequently gain market share more slowly, ultimately resulting in it gaining a substantially lower market share than in the baseline case (36% vs. 52%). It also reduces the "competitiveness" of the market as a whole: firm one is able to maintain a substantially higher price due to the higher cost of the new product (roughly $p_1 = 5$ vs. 3.5). The general pattern of prices is the same as in the baseline case, the only difference is that both firms charge higher prices resulting in firm one performing better as it retains a higher market share at a higher price. Not surprisingly, higher costs for firm two means that firm one earns substantially higher profits than in the baseline case, while firm two earns substantially lower profits.

C. Combining cost differentials with more distance between products

Scenario 4: Cost differentials with more distance between products. ($c_1 = 0$, $c_2 = 2$, $z_1 = 4$, $z_2 = 7$)

It is interesting to combine the cost differentials of scenario 3 with the a larger distance between the two products3. Figures 4a and 4b plot the prices and sales for this case, in which we end up with two monopolies operating independently of each other. With the products further apart, the distributions of Adopters and Followers separates. Firm two now sets the maximal price it can and still make sales to the Adopters. No Followers purchase good two and firm two contents itself with the 10% market share of Adopters only. Firm one does lower price slightly given the loss of the Adopters from its demand, however its price remains close to what is chose prior to entry of the new product. Maintaining a high price and market share means that firm one's profitability is the highest in this scenario, while firm two's profitability is the lowest.

Scenario 5: Smaller cost differential ($c_1 = 0, c_2 = 0.5$, $z_1 = 4$, $z_2 = 7$)

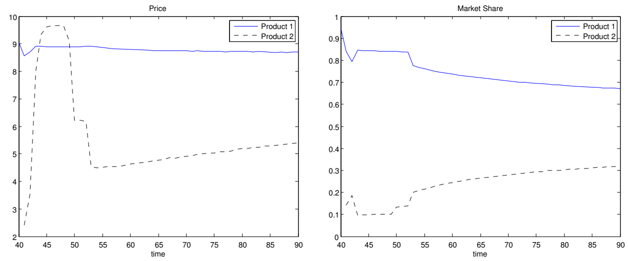
For smaller cost differentials interesting behavior occurs as we see in Figures 5a and 5b for Scenario 5, where firm two's unit production cost is 0.5 (vs. 2 in Scenario 4). In an initial phase following the introduction of product two, firm two acts the same as it does in the case with the higher production cost: it enters with a low price and quickly raises it once Adopters have moved to its location. It then maintains this price and only sells to Adopters, acquiring a 10% market share for several periods. After the initial couple of periods, firm one's market share has nearly stabilized as well, although it slowly loses market share. After 10 periods a threshold is crossed where firm two now finds it profitable to lower price dramatically and increasingly make sales to Followers, after which market share is slowly accumulated by firm two enabling it to slowly increase its price.

The pattern of adoption of the new product in this case is interesting in that between two and 15 periods after the introduction of the new product, adoption follows the familiar S-curve that is often seen in the adoption of innovation literature.

V. Conclusion

By allowing the tastes of a large proportion of consumers to be affected by the market shares of the alternative products, we have shown that this type of social influence can have interesting effects on the dynamics of price and new product adoption in a market. In general, a new product is introduced at a relatively low price, which then rises to the extent that increasing sales cause Followers to view the new product more favorably. Conversely, the incumbent firm lowers price in tandem with falling sales. The net effect is that over time prices of the new and old products move in opposite directions even though in the price game of any given period, the firms' actions are strategic complements as the game is a standard one of price competition with differentiated products.

Furthermore, we find a range of interesting outcomes depending on the extent of any price disadvantage faced by the new product and the extent to which the new product differs from the old. In particular, we show that an equilibrium might entail the entrant maintaining a high initial price for some length of time, selling largely to the Adopters, after which it lowers it price aggressively to sell to increasing numbers of Followers. In this situation the market share of the new product follows a pattern similar to the familiar S-shape of the innovation adoption literature, although here it is largely an endogenous result due to the pricing behavior of the entrant.



(a) Price (b) Sales

Fig. 5: Price and Sales: Scenario 5

We found fairly rich behavior even though firms behaved myopically, not considering the results of their pricing decisions on the future dynamics of consumer tastes. A interesting extension to this work is to relax this assumption. Although it would require a substantial increase in the complexity of the computational routines, this extension would allow the analysis of interesting alternative behavior, such as limit pricing by the incumbent to forestall the acquisition of substantial market share by the entrant.

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