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Incomplete Adoption of a Superior Innovation

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Abstract
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Introduction

Since Solow's (1956, 1957) original work on growth theory, it has been apparent that much of the economic growth that developed countries have experienced has been due to "technological innovations." These innovations may take a variety of forms, including innovations that result in more efficient ways of producing existing products (process innovations) or those that result in new products (product innovations). Innovations may occur in the final goods market or in the production of intermediate goods. Indeed, much of the recent endogenous growth theory has focused on those innovations that affect the provision of intermediate goods. As the literature on the economics of research and development (R&D) suggests, however, it is not the mere discovery of new knowledge that leads to economic progress; to realize private and/or social benefits it is necessary that innovations be adopted by firms. An innovation may be adopted directly by the discoverer or, when it is protected by intellectual property rights, the innovation may be transferred to other adopters through licensing agreements.

The literature on technology adoption has emphasized the process of "diffusion" (Karshenas and Stoneman, 1995). Diffusion refers to the widely observed phenomenon whereby new technologies are adopted slowly through time. Heterogeneity among users, uncertainty and information considerations are among the explanations that have been offered to explain the time path of adoption. More recently, attention has been devoted to the effects that licensing and strategic interactions among agents can have on the diffusion of innovations (see Reinganum, 1989, for an excellent review). Diffusion, of course, can explain why a superior innovation is not adopted immediately, and why new and obsolete technologies may coexist at any given point in time. But in most models of diffusion the premise is that, eventually, the adoption of a superior technology will be complete. Whereas we ignore the dynamic features of diffusion, our analysis can be interpreted as studying conditions that affect the limit to which the time path of technological diffusion tends. Specifically, we focus our analysis on "adoption" in a full information setting in the context of an innovation that is transferred to end-users through licensing.

Most of the literature on the licensing of innovations presumes that the right to the innovation (a patent, say) is held by a single owner (either an R&D firm or an incumbent firm) and that the license will be offered to a limited number of firms in an imperfectly competitive industry (e.g., Katz and Shapiro, 1986; Kamien and Tauman, 1986). Issues that arise in this context include the number of firms that should be licensed and the nature of the optimal license. A common and important feature of such models of technology adoption through licensing is that, in the presence of perfect information and Bertrand price competition, the adoption of a superior innovation will be complete. For example, suppose the innovation entails an improved production method that, at given input prices, lowers the costs of producing a given output for those firms that acquire the license. Then, if Bertrand competition prevails, only the more efficient firms (those that purchase the license) will actually produce output so that the adoption of the innovation is complete (though the presence of the other firms without access to the innovation typically affects the pricing strategy of innovating firms).[1]

In this paper we consider the issue of adoption of product innovations in intermediate goods in a model that relaxes an ubiquitous assumption of existing innovation adoption models, namely that the prices of all inputs (other than the innovated one) are exogenously given. The particular model that we develop considers firms which innovate in the intermediate product market but cannot directly use these inputs to produce final products. Furthermore, we assume that the final users of the innovated intermediate goods are competitive producers, and that the competitive structure of the final product

[1] Naturally, if the firms engage in Cournot competition, then those firms which do not acquire the more efficient technology will (in general) still produce, so that for this case the adoption need not be complete.

market will not be affected by the innovation. Thus, we assume the innovating firm does not have the option of exploiting the innovation directly but must license it, and licensing to a single end-user is not a viable option. A real world example for which these assumptions are appealing is offered by the U.S. agricultural sector, where an increasing number of innovations are produced by a small set of firms (in the increasingly integrated seed and chemical industry) and are adopted by numerous competitive end-users (the farmers). Farmers lack the resources, knowledge and motivation to carry out the research required to generate new innovations. Indeed, one rationale for the importance of public research in this area was precisely the inability or unwillingness of individual producers to carry out research (Huffman and Evenson, 1993). At present, however, private input suppliers (a fairly concentrated sector) are providing the larger portion of innovations to the agricultural sector, and this role is becoming increasingly important with the dawn of biotechnology (Fuglie et al., 1996). Furthermore, because innovations are often embodied in readily sold, and resold, products (such as seeds, fertilizer, herbicides and pesticides), it is difficult to imagine a pricing scheme that involves licensing plus revenue sharing; rather, the new input is made available to all end-users at the same price (as resale of the product would be difficult to preclude).

The specialized assumptions of our model, in a sense, radically simplify the analysis of the strategic interaction between innovators, and between innovators and adopters, and allow us to focus on a hitherto neglected aspect of innovation adoption. Specifically, we address the question of how the innovator's optimal pricing policy is affected when the adoption of the innovation may change the price of some other input used by final producers. Whereas it is routinely assumed that adoption of new technologies will affect the price of output, it is also equally plausible that innovation adoption will affect the equilibrium prices of some other inputs. Innovations that alter the way goods are produced (process innovations) will change not only production costs, but also the relative demands for inputs, and thus have the potential to change their equilibrium prices. For example, discussion on the rising inequality in U.S. relative wages of skilled and unskilled labor has long centered on the effects of skill-biased technological progress (Bound and Johnson, 1992). Recent agricultural biotechnology innovations such as Roundup Ready soyabeans and Bt maize, which are experiencing breathtaking adoption rates in the United States, are also having dramatic effects on the composition of farmers' demand for herbicides and pesticides. Furthermore, because yield increase is a significant attribute of these innovations, the change in profitability of these transgenic crops affects demand for land and hence its price. These agricultural biotechnology innovations also fit our licensing framework because they are patented and marketed as proprietary innovations.[2]

Previous models concerning pricing and adoption of an innovation have held other input prices constant (by assuming constant marginal cost). But, as we have argued, adoption of new technologies is likely to affect the equilibrium prices of some inputs. Because the economic viability of the innovations, in turn, depends on these input prices, an innovator pricing a proprietary discovery will rationally take that into account. Recognizing the endogeneity of input prices, in effect, transforms this standard partial equilibrium model of adoption of innovations into a general equilibrium model in which the producer of the innovated input recognizes the impact of his actions on other input prices. In this setting the main contribution of this article is to show that, due to the endogeneity of input prices, it may be optimal for the innovating firm to price its product so that the adoption of a strictly superior technology may not be complete.

I. The Model

Whereas the model we develop is applicable for an innovation in any industry which utilizes a specific factor, for concreteness our modeling will rely on the agricultural sector example discussed in the introduction whereby land denotes the input whose price is endogenously determined. Specifically, we consider an industry that is composed of a large number of competitive producers. Because of their small size, these producers do not engage in research activities aimed at improving the production technology.

[2] For example, Monsanto is marketing seeds of Roundup Ready soyabeans in the United States by charging an explicit "technology fee" for this herbicide-resistant crop. In 1999 this technology fee amounted to \$ 6.50 per lbs 50 bag, which constitutes a markup of more than 40 percent over otherwise comparable traditional soyabean varieties (Moschini, Lapan and Sobolevsky, 1999).

Instead, the relevant R&D is performed by larger firms that supply inputs to this competitive industry. The innovations are embodied in new and improved inputs (*e.g.*, seeds, herbicides, pesticides, fertilizers, machinery, etc.) that can substitute for existing inputs. Further, it is assumed that innovating firms cannot exploit their innovation by engaging directly in production of the final good. Thus, to benefit from their innovations, the firms performing this R&D must transfer the new technology to the competitive producers, i.e., they need to "license" their innovation to a competitive sector .

The problem of technology diffusion through licensing has been considered in many studies. In most models, however, licensing entails the transfer of new technology between firms that are all engaged in final production in an oligopolistic setting (Gallini and Winters, 1985; Katz and Shapiro, 1985), such that, for example, the innovating firm retains the option not to license (which we have ruled out). Alternatively, in a setting that is closer to the economic environment that we are modeling, when it is assumed that R&D is carried out by a research lab not engaged in production but licensing to downstream firms (Kamien and Tauman, 1986; Katz and Shapiro, 1986), the possibility of licensing only to a few firms (or only one firm) is still available, so that the strategic interaction between licensees is crucial.[3] For example, in the model of Kamien and Tauman (1986), an innovator that can potentially license to a competitive industry would still optimally choose to license only one firm when the innovation is drastic. In our model, on the other hand, because of reasons discussed earlier, we assume pure competition for the downstream adopting firms, and we assume that this structure is not affected by the introduction of innovations.

Because we are explicitly concerned with innovations that are necessarily embodied in inputs that can easily be resold by purchasers, we also assume that the price of the improved input is the instrument

[3] A number of related questions have been addressed in this context, including: the incentive to share innovations through licensing (Gallini and Winters, 1985; Katz and Shapiro, 1985); the effects that the possibility of licensing (and imitation) has on the incentives to innovate (Katz and Shapiro, 1985, 1986, and 1987); and the form of the optimal licensing contract (Kamien and Tauman, 1986; Katz and Shapiro, 1986; Gallini and Wright, 1990).

by which the innovating firm extracts a "license fee" for its innovation. More specifically, we consider a situation in which a large number of identical competitive agents produce a final output, denoted by q, by means of an input vector (x, z, y) where x denotes the input that is innovated (*e.g.*, seeds), z denotes the input whose price is endogenous to the industry (*e.g.*, land), and y denotes the vector of all other inputs. Let x_0 represent the old x-input, and x_1 denote the new (improved) x-input. Then final producers can choose between an 'old' technology, represented by the strictly quasi-concave production function $q = F^0(x_0, z, y)$, and a 'new' technology, represented by the strictly quasi-concave production function $q = F^1(x_1, z, y)$.[4]

Now let w_0 represent the price of x_0, w_1 represent the price of x_1, r represent the price of z, and v represent the price vector of y. Then dual to $F^0(x_0, z, y)$ and $F^1(x_1, z, y)$ there exist cost functions $C^0(q, w_0, r, v)$ and $C^1(q, w_1, r, v)$, respectively. We will assume that the two technologies exhibit constant returns to scale (at least at the industry level) with respect to all inputs.[5] Furthermore, because the prices of the input vector y are assumed to be exogenously given and play no relevant role in the analysis that follows, for notational clarity we will subsume the (constant) vector v in the cost functional. Hence, the cost functions corresponding to the (linearly homogeneous) old and new production functions are written as, respectively:

(1) $$C^0 = q\phi^0(w_0, r)$$

(2) $$C^1 = q\phi^1(w_1, r)$$

[4] This representation of innovation is not particularly restrictive as we could consider the new technology as having one more input than the old technology. The main point here is that the decision is not simply whether to adopt the new technology, but also how much to use of the input which embodies that technology.

[5] Without much change in analysis, we could allow firms to have U-shaped cost curves, but assume free entry of firms. However, because the z-input is specific to the industry in question, the endogeneity of its price (detailed below) still entails a positively sloped industry supply curve.

Thus, for given prices w_0, w_1, and r, $\phi^0(w_0,r)$ and $\phi^1(w_1,r)$ represent the unit cost of producing the final output with the old and new technology, respectively.

To simplify our analysis somewhat, we assume that the old input x_0 and the new input x_1 are both produced with a constant unit cost c.[6] Thus, we are explicitly modeling innovations that take the form of new and improved versions of a given input (a pesticide with a more effective active ingredient, an herbicide with a broader spectrum of control, a fertilizer that is better absorbed by a given plant, a more productive seed variety, a more powerful tractor, etc.). When old and new inputs are measured in the same units, their physical productions costs (that is, excluding the costs of R&D) are assumed to be the same. Among other things, we can then define the new technology as superior if:[7]

(3) $$F^1(x,z,y) > F^0(x,z,y) \quad \forall \ (x,z,y)$$

In terms of the dual costs this notion of a superior technology implies that:

(4) $$\phi^1(w,r) \leq \phi^0(w,r) \qquad \forall w,r$$

Thus, for example, if the new input were sold at the same price as the old input, per unit production costs would fall (hence, productivity increases).[8]

II. Innovation Adoption with Exogenous Input Prices

To characterize the impact of the innovation, an important condition is whether or not the innovation is "drastic" (Arrow, 1962). In our setting a drastic innovation is one in which the innovator's

[6] This assumption is not crucial, but merely simplifies the following analysis. The crucial assumption is that if both inputs are marginal cost priced, production costs with the new technology are lower.

[7] Actually, for the new technology to be valuable, it need not be globally superior, merely superior at the original set of factor prices (input vector). Allowing convex combinations of each technology to be used, then *ex post* the new isoquant must lie below the old one.

[8] In general, because the innovation creates a new x-input, the notion of a superior technology should be defined with respect to the (social) unit cost of producing the new input. Hence, the advantage of the simplifying assumption adopted -- the production cost for the new input is the same as that of the old input it replaces.

pricing decisions are not constrained by the threat of competition from the pre-existing technology; hence, the innovator can act as an unconstrained monopolist. When the innovation is not drastic, on the other hand, the innovator's pricing is constrained by the threat of competition, although, as is readily apparent, the innovator will always be able to choose a price such that she makes a positive profit (exclusive of R&D costs). Regardless of whether the innovation is drastic or not, however, for the standard case in which all other input prices are constant, the end result will be that the superior technology is adopted and totally replaces the pre-existing technology.

The assumption of the exogeneity of factor prices is difficult to defend in a general equilibrium, or "multi-market", model in which the industry affected by the innovation is a major employer of some "specific" factor. As we argued at the outset, for example, in the case of agriculture it is clear that the price of some factors, particularly land, have been significantly affected by technological innovation. Thus, in what follows we investigate the adoption of innovations when some factor prices are endogenous. Before doing that, to fix ideas, it is useful to consider the benchmark case in which all other input prices are not affected by the introduction of an innovated input.

Suppose that the price vector (r,v) is exogenously given and constant (i.e., input z is produced under constant unit costs), and also assume that the original input (x_0) is produced by a competitive industry at constant unit cost c (hence $w_0 = c$).[9] Then we expect full adoption of the new technology for this case, regardless of whether the innovation is "drastic" or "non-drastic". To illustrate, consider first the pricing of the innovation by the producer of x_1 if there were no alternative production technique, i.e., the unconstrained monopoly solution. By Shephard's lemma, the demand for the input sold by the monopolist is $q \cdot \phi^1_w(w_1, r)$. But what matters for the monopolist is the derived demand, which accounts for equilibrium in the output market. If p represents the final good price, and $D(p)$ is the final good

[9] As is apparent, the results for this case are the same as one in which the original producer of the input is also a monopolist, provided the firms engage in (Bertrand) price competition.

demand, then under the assumption of constant returns to scale and competition in the final good sector, in equilibrium the output price will equal the unit production cost under the new technology, that is:

$$(5) \qquad p = \phi^1(w_1, r)$$

Hence, under the assumption that no alternative technology exists, the derived demand for x_1 facing the innovator monopolist is:

$$(6) \qquad x_1^M(w_1) \equiv D(\phi^1(w_1, r)) \cdot \phi_w^1(w_1, r)$$

Maximizing profit for the innovator leads to the solution w_1^M:

$$(7) \qquad w_1^M = \arg\max_{w_1} \{(w_1 - c) x_1^M(w_1)\};$$

Given that the old technology is in fact available, however, the unconstrained price w_1^M may not be feasible because, at that price, producers of the final output may choose not to adopt the innovation. Specifically, define $\overline{w}_1$ as the price of the innovated input that makes final producers indifferent between the new and old technology; i.e., $\overline{w}_1$ solves $\phi^1(\overline{w}_1, r) = \phi^0(c, r)$. When prices (r, v) are constant, then for $w_1 > \overline{w}_1$ the constrained demand for x_1 is zero, so that $\overline{w}_1$ acts as an upper bound on the price the monopolist can charge. Now, if $w_1^M \le \overline{w}_1$, then the threat of competition from the alternative technology is irrelevant, and the innovation is "drastic." On the other hand, if $w_1^M > \overline{w}_1$, then the innovation is "non-drastic" and the price constraint binds; however, as long as $\overline{w}_1 > c$, as must be the case under the assumption that the new technology is superior, then the monopolist will charge $\overline{w}_1$ and the innovation will be fully adopted by all firms.[10] Thus, we obtain the well known result that, when the innovation is technologically superior, and all input prices are constant, then the innovator will price the new input to capture the whole market, i.e., adoption of the superior technology is complete. This result is hardly

[10] Strictly speaking, firms are indifferent between using the old and new technology at this price. Following standard convention, however, we assume that all firms adopt the new technology in that case (because the innovator could price x_1 a "little" below $\overline{w}_1$ in order to capture the whole market).

surprising, and it is illustrated in Figure 1. Here, the innovator-monopolist is maximizing profit given by $(w_1 - c)x_1^D(w_1)$, where $x_1^D(w_1)$ is the effective derived demand, which is defined as:

$$(8) \qquad x_1^D(w_1) \equiv \begin{cases} x_1^M(w_1) & \text{if} \quad w_1 < \overline{w}_1 \\ \in \left[0, x_1^M(\overline{w}_1)\right] & \text{if} \quad w_1 = \overline{w}_1 \\ 0 & \text{if} \quad w_1 > \overline{w}_1 \end{cases}$$

In the next section we extend the model to consider the more realistic situation in which some of the input prices are affected by the adoption of the innovation.

III. Innovation Adoption with Endogenous Input Prices

In many circumstances it is reasonable to assume that, due to a rising input supply curve for some factor, the equilibrium competitive price of that input is affected by the technology used in an industry and by the prices of other inputs. In such a case, even though firms in the final product market have constant returns to scale technology, the industry is not a constant cost industry, and the reasoning of the preceding section does not apply. Hence, the conclusion that complete adoption will be attained for a non-drastic innovation may not apply either. For the specific example of agricultural production considered earlier, it is land prices (rents, actually) that are affected by innovations in agricultural productivity, but obviously our analysis generalizes to other sectors in which one or more input prices are determined endogenously. Here, for simplicity we restrict attention to the case in which only one price, that is r (the price of z), is endogenous.

Given the endogeneity of r there is not, in general, a single threshold price $\overline{w}_1$ such that the new input captures the whole market if $w_1 \leq \overline{w}_1$ but demand for x_1 falls to zero if $w_1 > \overline{w}_1$. Thus, it will not generally be the case that the demand for x_1 is infinitely elastic at any point, as was true in the previous section with exogenous input prices. The reason for this can be understood as follows. Let $\{p^{PC}, r^{PC}\}$ denote the pre-innovation competitive equilibrium prices of output and input z, respectively (when only the original technology is used and input x_0 is priced at its marginal cost c). Now let w_1^{PC} denote the price of the new input such that, at the given price of the z input, $\phi^1\left(w_1^{PC}, r^{PC}\right) = \phi^0\left(c, r^{PC}\right)$. Hence, if the new innovation is priced at any higher price $\left(w_1 > w_1^{PC}\right)$, competitive producers will not find it desirable to adopt the new innovation and demand for x_1 will be zero, whereas at $w_1 = w_1^{PC}$ firms are indifferent as to which technology to use. If the price of z were unaffected by the adoption of the new technology, then as use of the new technology expanded firms would remain indifferent as to which technique were used, and demand for x_1 would be infinitely elastic until adoption was complete. However, if adoption of the new technology alters demand for input z and the supply of this input is not perfectly elastic, price r will change as adoption expands, meaning that firms are no longer willing to utilize both techniques unless the price of the new input also changes to maintain the equivalence of private costs on the two techniques. Hence, demand for the new input will not be perfectly elastic.

An alternative way of illustrating this point is to suppose that the monopoly firm produces a given amount of the new input x_1 and allows its price to be determined endogenously.[11] As above, if the amount supplied is zero the corresponding demand price must be at least w_1^{PC}, whereas for small (but positive) supply of x_1 the demand price will be in the neighborhood of w_1^{PC}. Furthermore, it is apparent that if the amount of x_1 supplied is "low" both techniques must be used to satisfy final demand and the price w_1 has to be determined such that production costs for the final output are the same with either technique. As the monopolist increases the amount of x_1 sold, at given prices the expanded use of the new technique and contraction of the old will, in general, change demands for all factors if these techniques have different input requirements. If all other input prices are fixed, then no change in w_1 is required to absorb the additional new input: all that happens is use of the new technique expands, use of the old contracts, and total output and all prices remain the same (until the innovation is completely

[11] In such a setting it does not matter whether the monopolist is a price setter or quantity setter.

adopted). But if the supply of some of these factors is less than perfectly elastic, then the corresponding prices must adjust as adoption of the new technology expands. Thus, in our case, the price of z will change as use of x_1 increases. However, as r changes, the value of w_1 required to make production costs on the new and old techniques the same must also change.[12] Thus, even when the old and new techniques coexist, the demand for the new input will not be perfectly elastic. This raises the possibility that it will be optimal for the monopolist to price the new input so that the adoption of the superior technique is not complete.

To characterize equilibrium when old and new technologies may coexist, let $S(r)$ denote the (upward sloping) supply of the z input to the industry, and consider first the pre-innovation equilibrium. This perfectly competitive equilibrium (labeled by the superscripted "*PC*") satisfies:

(9) $$p^{PC} = \phi^0\left(c, r^{PC}\right)$$

(10) $$q^{PC} = D\left(p^{PC}\right)$$

(11) $$q^{PC}\phi_r^0(c, r^{PC}) = S(r^{PC})$$

Equation (9) states that final product price equals marginal cost, equation (10) states that final product supply equals demand, and equation (11) specifies equilibrium in the z input market.

Now consider the effects of an innovation, and suppose at first that only the new technique can be used. In such a monopoly case, equilibrium in the final product and z input markets (labeled by the superscripted "*M*") entails:

(12) $$p^M = \phi^1\left(w_1, r^M\right)$$

(13) $$q^M = D\left(p^M\right)$$

(14) $$q^M\phi_r^1\left(w_1, r^M\right) = S\left(r^M\right)$$

[12] These adjustments must occur if the input per unit output requirements differ on the two techniques.

Solving (12)-(14) simultaneously yields $p^M(w_1)$ and $r^M(w_1)$, which represent the equilibrium prices for output and input z conditional on the price of the innovated input. Given that by Shephard's lemma input demand is $x_1 = q^M \phi^1(w_1, r)$, in this pure monopoly case the derived demand for the innovated input x_1 is:

(15) $x_1^M(w_1) \equiv D(p^M(w_1))\phi_w^1(w_1, r^M(w_1))$

This derived demand locus is sketched in Figure 2. Under the assumption of no competition from the old technology, the unconstrained monopoly solution, denoted by $\{\widetilde{w}_1^M, \widetilde{x}_1^M\}$, would be found by maximizing profit $(w_1 - c)x_1^M(w_1)$.

Because in fact the innovator-monopolist must face potential competition from the old technology, the derived demand function $x_1^M(w_1)$ is only relevant in the domain where unit production cost with the old technology is larger than unit production cost with the new technology, that is for all w_1 such that $\phi^0(c, r^M(w_1)) \geq \phi^1(w_1, r^M(w_1))$.[13] If it happens that the unconstrained monopoly solution $\widetilde{w}_1^M$ is such that $\phi^0(c, \widetilde{r}^M) \geq p^M = \phi^1(\widetilde{w}_1^M, \widetilde{r}^M)$, where $\widetilde{r}^M = r^M(\widetilde{w}_1^M)$ is the price of z under the unconstrained monopoly solution, then the innovation is "drastic" and it is completely adopted. In such a situation the presence of the alternative production technique does not constrain the monopolist's pricing behavior. However, if $\phi^0(c, \widetilde{r}^M) < p^M(\widetilde{w}^M)$, then the innovation is "non-drastic" and the monopolist's pricing (sales) decision is constrained by the presence of the original technique. To analyze a "non-drastic" innovation, we must find the relationship between w_1 and x_1 in the domain where both techniques coexist.[14] We know that if w_1 is "too high" $(w_1 \geq w_1^{pc})$ only the old technique will be used

[13] For a superior innovation we know this domain is not empty because $\phi^0(c, r) > \phi^1(c, r)$ for all r.

[14] We know this domain is non-empty since, for x_1 near zero (w_1 near w_1^{pc}) the old technique will be used. Also, the assumption the innovation is non-drastic implies this domain must be nonempty.

and the demand for x_1 will be zero. We also know that if x_1 is sufficiently large [e.g., $x_1 \geq x_1^M(c)$, so that $w_1 \leq c$] then only the new technique will be used. Thus, by continuity, there must exist a range of x_1 such that both techniques will be used simultaneously. We show below that, in general, the demand schedule will not be infinitely elastic in that domain.

To characterize the innovator's derived demand when both techniques (may) coexist, let q_1 denote total output produced using the new technique and q_0 denote total output produced using the old technique. Because by Shephard's lemma the demand for the innovated input in this domain is $x_1 = q_1\phi_w^1(w_1,r)$, to obtain the derived input demand curve we need to endogeneize output q_1 and the price of land r. To this end, the equilibrium conditions can be generalized to allow for techniques to coexist, that is:

(16) $$q_0^*\phi_r^0(c,r^*) + q_1^*\phi_r^1(w_1,r^*) = S(r^*)$$

(17) $$q_0^* + q_1^* = D(p^*)$$

(18) $$p^* \leq \phi^0(c,r^*)$$

(19) $$p^* \leq \phi^1(w_1,r^*)$$

where equation (18) holds as a strict equality if $q_0^* > 0$ and equation (19) holds as a strict equality if $q_1^* > 0$. The derived demand curve for the innovated input when both techniques (strictly) coexist, say $x_1^C(w_1) = q_1(w_1) \cdot \phi^1(w_1, r(w_1))$, where $q_1(w_1) = q_1^*$ and $r(w_1) = r^*$ are part of the solution to equations (16)-(19) in the domain for which $q_0^* > 0$ and $q_1^* > 0$. Note that the pre-innovation equilibrium discussed earlier can be obtained as a special case of equations (16)-(19) [for $q_1 = 0$ and $p = \phi^0(c,r)$]; the unconstrained monopoly demand, also discussed earlier, is another special case of equations (16)-(19) [for $q_0 = 0$ and $p = \phi^1(w_1,r)$].

To elaborate further on the nature of this demand curve, recall that $x_1^C(w_1)$ intersects the vertical axis at w_1^{PC}. As the monopolist expands (from zero) the amount of x_1 for sale, for given input (and hence output) prices, total output (demand) will be unchanged, but q_1 must increase (and hence q_0 decrease by the same amount) to absorb the additional x_1. If the supply of land is less than infinitely elastic, and the new technology uses land in a different proportion than the old technology, the equilibrium input price r will have to change, which in turns affects the price w_1 of the innovated input. For example, suppose that the amount of land used per unit output is higher for the old technology than for the new technology [that is, $\phi_r^1(w_1,r) < \phi_r^0(c,r)$ evaluated at $\phi^1(w_1,r) = \phi^0(c,r)$]. Given all input prices, and hence output price, an expansion in sales of x_1 requires q_1 to increase (and q_0 to decrease, such that $dq_0 = -dq_1$) to absorb the additional x_1. But, given the assumption on factor requirements, this implies that the demand for land falls, and hence r must decrease to restore equilibrium in the land market. Furthermore, the decrease in land prices reduces costs on both technologies, but reduces them by more on the old technology, which is land intensive; hence w_1 must decrease to maintain the competitiveness of the new technology.[15]

The foregoing conclusion about the slope of the derived demand for the innovated input admits one exception. Specifically, even when the supply of land is not perfectly elastic, if the two techniques use land in the same proportion [i.e., $\phi_r^1(w_1,r) = \phi_r^0(c,r)$ whenever $\phi^1(w_1,r) = \phi^0(c,r)$] then we can see from (16) that the demand for land, and hence the price of land, will be unaffected by the increased availability of x_1 (given $dq_0 = -dq_1$). In such a case, neither output price nor w_1 need adjust to absorb the additional x_1 and the derived demand curve for the innovated input would be infinitely elastic, until it intersects the unconstrained monopoly demand curve [at $x_1 = x_1^M\left(w_1^{PC}\right)$].

[15] Note that the conclusion would be the same if the new technology were land intensive, except land and output prices would increase as sales of x_1 expanded; however, w_1 would still decrease to offset the impact of higher land prices on the more land-intensive new technology.

Barring the (implausible) case of the two techniques having identical input requirements, it follows that if the supply of land is not infinitely elastic the derived demand for x_1 will be strictly downward sloping in the domain where the two techniques coexist [see the curve $x_1^C(w_1)$ in Figure 2]. Furthermore, because as shown in the Appendix the demand curve $x_1^C(w_1)$ is more elastic than $x_1^M(w_1)$ when the curves intersect, they must intersect at a single point, say $\{\hat{w}_1, \hat{x}_1\}$, where $\hat{w}_1$ solves $\phi^0(c, r^M(\hat{w}_1)) = \phi^1(\hat{w}_1, r^M(\hat{w}_1))$ and $\hat{x}_1 = x^M(\hat{w}_1)$. For all $w_1 \leq \hat{w}_1$ (i.e., $x_1 \geq \hat{x}_1$) the monopolist captures the whole market, and faces the downward-sloping demand curve $x_1^M(w_1)$. But for all $x_1 \in [0, \hat{x}_1]$, then $w_1^{PC} \geq w_1 \geq \hat{w}_1$ and the monopolist faces the downward sloping demand curve $x_1^C(w_1)$.[16] This derived demand schedule is shown by the solid curve in Figure 2. Depending on the elasticity of derived demand in this domain, it is therefore quite possible that the monopolist may find it optimal to price its product such that old and new technologies coexist.

To illustrate explicitly the conditions under which old and new technology will coexist, let us consider the elasticity of the derived demand for the unconstrained monopoly solution, that is $\kappa(w_1) \equiv (\partial \log x_1^M(w_1)/\partial \log w_1)$. From equations (12)-(14) we find:[17]

$$(20) \qquad \kappa = A_1 + \left(\frac{s_z}{s_x}\right)\frac{(A_2)^2}{A_3} < 0$$

where $A_1 \equiv (\varepsilon_{xw} + \eta s_x) < 0$, $A_2 \equiv (\varepsilon_{zw} + \eta s_x)$, $A_3 \equiv (\theta - \varepsilon_{zr} - \eta s_z) > 0$, $\eta \equiv (\partial \log D(p)/\partial \log p) < 0$ is the elasticity of final demand for output, $\theta \equiv (\partial \log S(r)/\partial \log r) > 0$ denotes the elasticity of supply for the z input, $\varepsilon_{zr} \equiv (\partial \log \phi_r^1(w_1, r)/\partial \log r) < 0$ denotes the own-

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[16] If the demand for x_1 is infinitely elastic in the domain where both techniques are used, then $\hat{w}_1 = w_1^{PC}$.

[17] Details on the derivation of κ and of κ^C are provided in a Reader's Appendix that is available from the authors upon request.

price elasticity of the conditional demand for input z, $\varepsilon_{xw}^{1} \equiv \left(\partial \log \phi_w^1(w_1,r)/\partial \log w_1\right) < 0$ denotes the own-price elasticity of the conditional demand for input x, $\varepsilon_{zw} \equiv \left(\partial \log \phi_r^1(w_1,r)/\partial \log w_1\right)$ denotes the cross-price elasticity of the conditional demand for input z, and $s_x \equiv w_1\phi_w^1/\phi^1$ and $s_z \equiv r\phi_r^1/\phi^1$ denote the cost shares for inputs x and z, respectively.

The elasticity of the derived demand for the improved input when the two techniques coexist, that is $\kappa^C(w_1) \equiv \left(\partial \log x_1^C(w_1)/\partial \log w_1\right)$, can be similarly obtained from equations (16)-(19), and is given by:

$$\text{(21)} \quad \kappa^C = A_1 + \frac{2A_2}{(u-1)} - \left(\frac{s_x}{s_z}\right)\frac{\left[\delta+(1-\delta)u\right]A_3}{\delta(u-1)^2} + \left[\frac{(1-\delta)u}{\delta(u-1)^2}\right]\left[\eta s_x(u-1) - \left(\varepsilon_{zr} - \varepsilon_{zr}^0\right)\right] < 0$$

where $\delta \equiv \left[q_1/(q_0+q_1)\right]$ denotes the share of total final output produced with the new technology, $\varepsilon_{zr}^0 \equiv \left(d\log\phi_r^0(c,r)\right)/d\log r$ denotes the own-price elasticity of conditional demand for input z using the old technique, and $u \equiv \phi_r^0/\phi_r^1$ denotes the relative z intensity of the old and new techniques (thus, $u > 1$ implies that, at the given factor prices, the old technique uses more of the z-input per unit output than does the new technology, whereas the opposite holds when $u < 1$).

Several things are noteworthy about the expression in (21). First, note that as $\delta \to 1$ the price elasticity of demand is strictly larger (in absolute value) when the two techniques coexist than when there is only monopoly supply, that is:

$$\text{(22)} \qquad \lim_{\delta\to 1}\left[\kappa^C - \kappa\right] = -\left[\frac{s_x}{s_z A_3}\right]\left[\frac{s_z A_2}{s_x} - \frac{A_3}{(u-1)}\right]^2 \leq 0$$

where the inequality follows because $A_3 > 0$. This result can be explained as follows. In the unconstrained monopoly case, the derived demand for x_1 responds to increases in its price because: (i) firms may substitute other inputs for x_1; (ii) the higher input prices increase output price, reduce final output and thus reduce demand for x_1; and finally because (iii) the price of land changes as w_1 increases. In the case where both techniques are used, all these factors are at work plus, as w_1 increases, firms will substitute away from the new technique back to the old technique (i.e., for a given output level, q_1 will decrease and q_0 increase). This latter effect implies that demand must be more elastic when the two techniques coexist. More importantly, note that the elasticity of demand for $x_1^C(w_1)$ is finite in this domain, with two main exceptions: when (i) the supply of z is infinitely elastic, so that r is exogenous ($\kappa^C \to \infty$ as $\theta \to \infty$); or (ii) the unit input requirement for z is the same with both techniques $(u=1)$. Case (i) represents the standard partial equilibrium model where all factor prices are treated as exogenous, and thus there is a unique price for the superior input that allows both technologies to coexist. Case (ii) arises when $u=1$ [such that $\phi^1(w_1,r)=\phi^0(c,r) \quad \Rightarrow \quad \phi_r^1(w_1,r)=\phi_r^0(c,r)$]. This means that, although factor prices are endogenous, given that production costs must be the same for the two techniques when they coexist, changes in the composition of output do not affect factor demands.[18] Clearly, case (ii) is very unlikely to hold for arbitrary changes in technology. The one situation where it will hold is when the new technology is equivalent to the old technology with a pure "input-x-only" augmenting innovation, that is $F^1(x_1,z,y) \equiv F^0(\alpha x_1,z,y)$ with $\alpha > 1$, which implies $\phi^1(w_1,r)=\phi^0(w_1/\alpha_1,r)$.

To summarize, when the price of one of the inputs is endogenous to the industry adopting the innovation, the relevant derived demand for the innovated input that the monopolist faces is:

$$x_1^D(w_1) \equiv \begin{cases} x_1^M(w_1) & \text{if} \quad w_1 \le \hat{w}_1 \\ x_1^C(w_1) & \text{if} \quad \hat{w}_1 < w_1 < w_1^{PC} \\ 0 & \text{if} \quad w_1^{PC} \le w_1 \end{cases} \tag{23}$$

Hence, based on the foregoing we can state the main result of the paper.

[18] The intuition for this special case may be strengthened by considering the analogous result of the standard two sector - two factor general equilibrium model used in trade theory (the Heckscher-Ohlin model). In that model, if factor intensities are the same in the two sectors, output supplies (and hence factor demands) are infinitely elastic; if factor intensities differ ($u \ne 1$ in our notation) the general equilibrium supply curves are positively sloped (the factor demand curves negatively sloped).

PROPOSITION 1. Suppose input prices are such that both techniques coexist; then the derived demand for the new input will not be infinitely elastic unless: (i) either the supply of all other inputs is infinitely elastic, or (ii) the unit input requirements are the same for both techniques. Thus, for a non-drastic innovation, it is possible that the innovator's optimal price for the new input is such that adoption of the innovation is not complete.

The derived demand $x_1^D(w_1)$ is illustrated in Figure 2. Because the innovator-monopolist maximizes profit given by $\pi^1 \equiv (w_1 - c)x_1^D(w_1)$, it is possible for the optimal solution to be in the interior of the domain where the relevant derived input demand is $x_1^C(w_1)$, in which case the two techniques will coexist. More specifically, we have:

$$\text{(24)} \qquad \frac{d\pi^1}{dw_1} = x_1^M(w_1)\left[1 + \left(\frac{w_1 - c}{w_1}\right)\kappa(w_1)\right] \qquad \textit{for} \quad w_1 < \hat{w}_1$$

$$\text{(25)} \qquad \frac{d\pi^1}{dw_1} = x_1^C(w_1)\left[1 + \left(\frac{w_1 - c}{w_1}\right)\kappa^C(w_1)\right] \qquad \textit{for} \quad w_1 > \hat{w}_1$$

Hence, the case of a drastic innovation occurs if:

$$\text{(26)} \qquad |\kappa(\hat{w}_1)| > \frac{\hat{w}_1}{(\hat{w}_1 - c)}$$

implying that the innovator can charge her unconstrained monopoly price. Alternatively, a non-drastic, but complete, innovation occurs if:

$$\text{(27)} \qquad |\kappa^C(\hat{w}_1)| > \frac{\hat{w}_1}{(\hat{w}_1 - c)} > |\kappa(\hat{w}_1)|$$

Thus, for example, if the (unconstrained) monopoly derived demand is inelastic, but as in the standard case all other inputs are in infinitely elastic supply $\left(\Rightarrow \quad |\kappa^C| = \infty\right)$ then the innovation always will be non-drastic, but complete. Finally, it will be optimal for the monopolist to price the input so that adoption is incomplete if:

$$(28) \qquad \left|\kappa^{C}(\hat{w}_1)\right| < \frac{\hat{w}_1}{(\hat{w}_1 - c)}.$$

The fact that the adoption is not complete means that an additional source of inefficiency arises from the monopoly pricing of the new input (technology). Traditionally, inefficiency due to monopoly pricing of the innovated input arises because: (i) the high price of the input means that input utilization on the superior technology is not efficient (i.e., the rate of technical substitution among inputs does not reflect the marginal cost of production of the inputs); and (ii) the higher price of output (due to the distorted input price) leads to too little provision of output. Here we have shown that, when the prices of some inputs used by adopters are endogenous, there may be a third source of inefficiency -- pure production inefficiency because an inferior technique is used when a superior technique is available (so that with the same input levels more output could be produced if only the new technology were used). For example, with Leontief technology $(\varepsilon_{xr} = \varepsilon_{zw} = 0)$ and completely inelastic demand for output $(\eta = 0)$, any innovation must be non-drastic. Furthermore, if other input prices were exogenous, then the innovation would be completely adopted and there would, in fact, be no inefficiency from the monopoly situation (of course, the input price would be "too high," but that would mean only a pure transfer payment between consumers and the input supplier). However, if the price of the z-input is endogenous, then it is possible that the monopolist will price the new input such that both techniques coexist, leading to inefficient production.

IV. Bertrand Competition and Incomplete Adoption

If the new technology can be protected by intellectual property rights, it is reasonable to assume the old one is patentable also. Thus, in this section we relax the assumption that the pre-innovation technology is competitively provided. Assuming the pre-innovation technology (as embodied in x_0) was owned and sold by a single firm, rather than by competitive suppliers, introduces a new strategic dimension to our analysis. In particular we now have a duopoly in the provision of the x input to the competitive end-use sector. As is well known the equilibrium outcome of such a duopoly (including the implications for adoption of the new input) depends crucially on the type of game played by incumbent and innovator firms. If the two firms supplying the x input compete in a Cournot (quantity setting) fashion, then it is apparent that equilibrium may entail both firms selling positive quantities of the input, regardless of whether or not other input prices are constant. Such an instance of incomplete adoption of the superior innovation, while interesting and potentially empirically relevant, is certainly implicit in many of the existing studies on the economics of R&D. Similarly, it is apparent that if incumbent and innovator firms engage in Bertrand (price setting) competition then, given constant prices of all other inputs, the equilibrium outcome must be characterized by the complete adoption of the superior innovation. But we will show below that, when the price of some other input is endogenous to the industry adopting the innovation, under Bertrand competition it is quite possible that adoption of the superior innovation is not complete. Hence, the result derived earlier under competitive production of the old x input does generalize to a much richer set of admissible strategic interactions.

To analyze the Bertrand competition case, let w_0 denote the price at which the input x_0 is sold; in the previous section we assumed $w_0 = c$, whereas when a duopolist supplies the old input the restriction is $w_0 \geq c$. Now consider the case in which r is exogenous. Because in this situation the two inputs are essentially perfect substitutes, we can show only the new technology will be used. To do so, define the threshold price $t^1(w_0;r)$ such that $\phi^1\left(t^1(w_0;r),r\right) = \phi^0(w_0,r)$. For any $w_1 < t^1(w_0;r)$ the innovator captures the whole market, whereas for any $w_1 > t^1(w_0;r)$ the innovator makes no sales. Thus, the demand for x_1 is infinitely elastic at $t^1(w_0;r)$. Similarly, define $t^0(w_1;r)$ such that $\phi^0\left(t^0(w_1;r),r\right) = \phi^1(w_1,r)$. By the same argument, if $w_0 < t^0(w_1;r)$, the incumbent firm captures the entire market, while if $w_0 > t^0(w_1;r)$ it makes no sales. Given that the firms engage in price competition, and given that the demands are infinitely elastic when both firms have positive sales, the only possible equilibrium is one in which the innovator captures the whole market. Otherwise, for a set of prices (w_1', w_0') such that both firms make positive sales (with $w_0' > c$), either firm can increase its profits by lowering its price slightly, thereby capturing the whole market. Thus, the possibilities are: (i) the innovating firm charges its unconstrained monopoly price w_1^M if $\phi^1(w_1^M, r) \leq \phi^0(c, r)$; or, (ii) the innovating firm captures the whole market by charging $t^1(c;r)$ if $t^1(c;r) < w_1^M$. Thus, when r is exogenous and the firms engage in Bertrand price competition, the equilibrium is the same as when the incumbent input producers are competitive.

Next, consider the case when r is endogenous. Under this structure, the derived demand for each firm's input is determined, as before, by Shephard's lemma in conjunction with the equilibrium conditions (16)-(19) [but with w_0 replacing c in the unit cost function $\phi^0(.,r)$]. The solution to this system of equations determines the functions $r(w_1, w_0)$, $q_1(w_1, w_0)$, $q_0(w_1, w_0)$, and $p(w_1, w_0)$. Thus, the derived demands for the new and old inputs are $x_1^D(w_1, w_0) = q_1(w_1, w_0) \cdot \phi_w^1(w_1, r(w_1, w_0))$ and $x_0^D(w_0, w_1) = q_0(w_0, w_1) \cdot \phi_w^0(w_0, r(w_0, w_1))$, respectively. The profit functions for the two firms are:

(29) $$\pi^1(w_1, w_0) = (w_1 - c)x_1^D(w_1, w_0)$$

(30) $$\pi^0(w_0, w_1) = (w_0 - c)x_0^D(w_0, w_1)$$

Clearly, because $w_0 \geq c$ the innovator can capture the whole market by charging $w_1 \leq \hat{w}_1$ (where $\hat{w}_1$ is as defined earlier). Thus, the condition both for a drastic innovation, and a non-drastic innovation that is completely adopted, remain the same. Specifically, if

(31) $$\lim_{w_1 \to \hat{w}_1 -} \left\{ \frac{d\pi^1}{dw_1} \right\} \Bigg|_{w_0 = c} < 0$$

then the innovation is drastic. Similarly, if

(32) $$\lim_{w_1 \to \hat{w}_1 -} \left\{ \frac{d\pi^1}{dw_1} \right\} \Bigg|_{w_0 = c} > 0 > \lim_{w_1 \to \hat{w}_1 +} \left\{ \frac{d\pi^1}{dw_1} \right\} \Bigg|_{w_0 = c}$$

then the innovation is non-drastic but complete (because if the incumbent firm charges $w_0 = c$, the new firm's best response is $\hat{w}_1$, and if the new firm charges $\hat{w}_1$, the old firm cannot make any positive sales at a profit.)[19] Finally, if

(33) $$\lim_{w_1 \to \hat{w}_1 +} \left\{ \frac{d\pi^1}{dw_1} \right\} \Bigg|_{w_0 = c} > 0,$$

then for $w_0 = c$, the innovating firm's best response is to charge a price which exceeds $\hat{w}_1$, implying the incumbent will make some sales (though no profits) at $w_0 = c$. Thus, the incumbent firm has an incentive to raise price above c, as it can make some sales at a positive profit. The resulting equilibrium will be one in which the two firms both make positive sales and positive profits.[20] Thus, we can state the following result.

PROPOSITION 2. Under the conditions that give rise to incomplete adoption of a superior innovation when the innovator faces competitive suppliers of the old technology, incomplete adoption is preserved even if the competitive suppliers of the old technology are replaced by a monopolist and the suppliers of new and old technologies engage in Bertrand competition.

[19] If $w_1 \leq \hat{w}_1$, any response $w_0 \geq c$ is equally good for the old incumbent since its sales, and profits, will be zero. Thus, $\{\hat{w}_1, c\}$ would be part of the solution for this Bertrand game. A solution with complete adoption and $w_1 > \hat{w}_1$ is not possible, as the incumbent firm would have an incentive to lower price to capture some sales.

[20] Define $g(w_0)$ to be the solution for w_1 of $t^1(w_0; r(w_1, w_0)) \equiv w_1$, such that for $w_1 \leq g(w_0)$ the innovating firm captures the entire market whereas for $w_1 > g(w_0)$ the incumbent makes some sales; thus, the price limit $\hat{w}_1$ defined earlier satisfies $\hat{w}_1 = g(c)$. Clearly, no Bertrand equilibrium is possible

The remarkable feature of this result is that both duopolists make positive sales, despite Bertrand competition and constant marginal production costs for their products. In essence, the endogeneity of the input price r has transformed the outputs of the two firms (x_0 and x_1) from perfect substitutes into imperfect substitutes. Naturally, the actual equilibrium prices, in the case of incomplete adoption, will differ between the competitive and Bertrand cases. In particular, the old input will be sold at a higher price in the Bertrand case. Furthermore, assuming the two prices are strategic complements (i.e., $\partial^2\pi^1/\partial w_0 \partial w_1 > 0$), then the innovator will also charge a higher price than in the competitive case. Thus, Bertrand competition will lead to higher prices than if the incumbent sector is competitive. However, the welfare implications are not transparent. Presumably the higher price for the older input (which leads to the higher price for the newer input) means that, in the Bertrand situation, the innovating firm will gain a larger market share than in the competitive case, so that this aspect of production inefficiency will be diminished.

V. Conclusion

In this paper we have developed a simple model of technology adoption through licensing that allows for the price of some industry-specific inputs to be affected by the adoption of new technology. Specifically, we have studied the equilibrium outcomes when an innovator-monopolist can license its new technology to competitive end-users while facing the threat of competition from an old technology that is either competitively supplied or supplied by an incumbent firm that engages in Bertrand competition. The main result that is derived is that, in this context, adoption of a superior technology may not be complete. In other words, the discoverer may find it profitable to price its innovation such that some potential adopters will not switch away from the old technology. As the model has illustrated, this

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with $w_0 > c$ and $w_1 \in (\hat{w}_1, g(w_0))$, because with w_1 in this domain the incumbent firm can make positive sales (and positive profits) by charging a price w_0' such that $c < w_0' < w_0$.

somewhat surprising result is due to the endogeneity of the price of some other input that affects the derived demand for the innovated input.

The fact that innovators exploit the monopoly position granted by intellectual property rights in general implies some ex-post economic inefficiency, because the price of the innovated input is "too high" (so that not enough of this input is used, relative to other inputs) and because "not enough" of the final output is produced (due to the distorted price for the innovated input). Our analysis here has uncovered a third potential source of ex-post inefficiency in the context of technology adoption through licensing: pure production inefficiency because the superior technique is not used for all the final output that is produced. Whether the "general equilibrium" effect that we have studied can explain widespread instances of incomplete technology adoption in the real world is an open question. But the fact that technology transfer through licensing is becoming increasingly relevant for a number of sectors, and the fact that there are real welfare implications of incomplete adoption, suggest that more attention to the endogeneity of some prices may be important for modeling the economics of R&D.

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Figure 1. Derived Demand for Innovated Input Given Constant Prices of Other Inputs

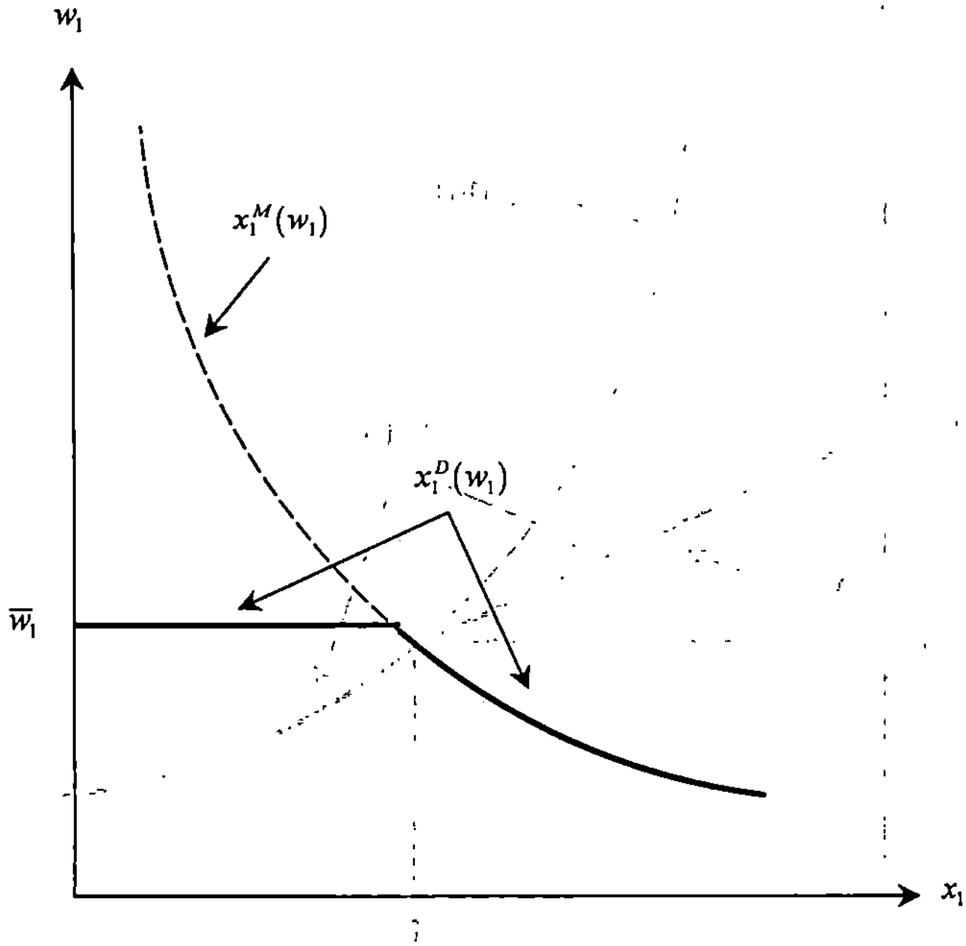

Figure 2. Derived Demand for Innovated Input
with Endogenous Prices of Other Inputs